

LETTER TO THE EDITOR

## Tidal synchronisation of the subdwarf B binary PG 0101+039<sup>★,★★</sup>

S. Geier<sup>1</sup>, S. Nesslinger<sup>1</sup>, U. Heber<sup>1</sup>, S. K. Randall<sup>2</sup>, H. Edelmann<sup>3</sup>, and E. M. Green<sup>4</sup>

<sup>1</sup> Dr.-Remeis-Sternwarte, Institute for Astronomy, University Erlangen-Nürnberg, Sternwartstr. 7, 96049 Bamberg, Germany  
e-mail: geier@sternwarte.uni-erlangen.de

<sup>2</sup> ESO, Karl-Schwarzschild-Str. 2, 85748 Garching, Germany

<sup>3</sup> McDonald Observatory, University of Texas at Austin, 1 University Station, C1402, Austin, TX 78712-0259, USA

<sup>4</sup> Steward Observatory, University of Arizona, Tucson, AZ 85721, USA

Received 5 October 2007 / Accepted 30 October 2007

### ABSTRACT

*Aims.* Tidally locked rotation is a frequently applied assumption that helps to measure masses of invisible compact companions in close binaries. The calculations of synchronisation times are affected by large uncertainties, in particular for stars with radiative envelopes, calling for observational constraints. We aim to verify tidally locked rotation for the binary PG 0101+039, a subdwarf B star + white dwarf binary from its tiny (0.025%) light variations measured with the MOST satellite (Randall et al. 2005).

*Methods.* Binary parameters were derived from the mass function, apparent rotation and surface gravity of PG 0101+039 assuming a canonical mass of  $0.47 M_{\odot}$  and tidally locked rotation. The light curve was then synthesised and was found to match the observed amplitude well.

*Results.* We verified that the light variations are due to ellipsoidal deformation and that tidal synchronisation is established for PG 0101+039.

*Conclusions.* We conclude that this assumption should hold for all sdB binaries with orbital periods of less than half a day. Hence the masses can be derived from systems that are too faint to measure tiny light variations.

**Key words.** binaries: spectroscopic – subdwarfs – stars: rotation

### 1. Introduction

The masses of compact objects like white dwarfs, neutron stars and black holes are fundamental to astrophysics, but very difficult to measure. Close binary systems consisting of a visible primary and an invisible compact object are very useful to this end, as the companion mass can be constrained from the radial velocity and the light curve of the primary if the primary mass and the orbital inclination are known. The latter can be measured in systems that are eclipsing or show tidally locked rotation. If the mass of the primary can be estimated, the companion mass can then be derived. The assumption of tidally locked rotation has often been used to determine the masses of neutron stars and black holes in known X-ray binaries (see Charles & Coe 2003 for a review). The same technique has recently been applied to KPD 1930+2752, a short period binary consisting of a subluminous B star and a white dwarf (Geier et al. 2007)<sup>1</sup>.

Subluminous B stars (sdBs) are core helium burning stars with very thin hydrogen envelopes and masses around  $0.5 M_{\odot}$

(Heber et al. 1986). A large proportion of the sdB stars are members of short period binaries (Maxted et al. 2001; Napiwotzki et al. 2004). For these systems, common envelope ejection is the most probable formation channel (Han et al. 2002). The companions of sdBs in these systems are predominantly white dwarfs, implying that the system has undergone two phases of common envelope ejection.

To establish bound rotation for an sdB star the synchronisation time scale has to be smaller than its evolutionary life time ( $t_{\text{EHB}} \approx 10^8 \text{ yr}$ ). Two theoretical concepts for computing synchronisation times have been developed by Zahn (1977) and Tassoul & Tassoul (1992). While the mechanism proposed by Zahn is not efficient enough to fully fit the observed levels of synchronisation, the more efficient mechanism of Tassoul & Tassoul is matter of a controversy, given its free parameter dependence (see Claret et al. 1995, 1997, and references therein). The predictions of the two models at hand can differ by orders of magnitude, especially in the case of hot stars with radiative envelopes, where tidal forces are less effective in synchronising the stars. All prior studies were undertaken to match observations of hot main sequence stars. Hot subdwarf stars have similar temperatures to B-type main sequence stars, but are much smaller and the internal structure of these helium core burning objects is different. In addition, the fraction of sdBs residing in close binary systems is among the highest known of all types of stars. Observations of hot subdwarfs could provide a new benchmark to study the yet unresolved problem of tidal dissipation in radiative stellar envelopes.

Independent observational constraints are needed to prove or disprove synchronised rotation in hot subdwarf stars. Ellipsoidal

<sup>★</sup> Based on data from MOST, a Canadian Space Agency mission operated jointly by Dynacon, Inc., the University of Toronto Institute of Aerospace Studies, and the University of British Columbia, with assistance from the University of Vienna.

<sup>★★</sup> Based on observations collected at the Centro Astronómico Hispano Alemán (CAHA) at Calar Alto, operated jointly by the Max-Planck Institut für Astronomie and the Instituto de Astrofísica de Andalucía (CSIC).

<sup>1</sup> The companion is so massive that the system mass may exceed the Chandrasekhar mass, making the system a viable Supernova Ia progenitor candidate in the double degenerate scenario.

variations can be used to verify synchronisation of the stellar surface because the light variations would then have to occur at exactly half the orbital period. Two sdB + white dwarf binaries are known to show ellipsoidal variations at half of the orbital period (KPD 0422+5421, Orosz & Wade 1999; KPD 1930+2752, Geier et al. 2007). However, both systems have short orbital periods of about 0.1 d and theory predicts synchronisation times much smaller than the evolutionary time scale. As the synchronisation time strongly increases with increasing period, we expect an upper limit to the period to exist, at which the assumption of tidally locked rotation breaks down. To this end, it would be of utmost importance to find ellipsoidal variations in an sdB binary of longer period and to provide a stringent test for the theory of synchronisation.

Recently a suitable object has been found. PG 0101+039, an sdB+WD binary ( $P = 0.567$  d, Maxted et al. 2001) was discovered to show very weak luminosity variation at half the orbital period in a 16.9 day long, almost uninterrupted light curve obtained with the MOST satellite (Randall et al. 2005).

In order to verify that we indeed see ellipsoidal variations, we have to show that the observed light curve can be consistently modelled. Beforehand, we have to derive the complete set of system parameters. As the spectrum is single lined, the analysis of the radial velocity curve yields the mass function only. Complementing it with an estimate of the sdB mass and with measurements of the sdB's projected rotational velocity, as well as its gravity, allows one to solve for all binary parameters and compute the light curve.

## 2. Binary parameters

### 2.1. Radial velocity curve

Based on spectra obtained in 1998, Moran et al. (1999) determined the period  $P = 0.569908 \pm 0.000007$  d. However, these ephemerides are not accurate enough to phase the MOST photometry, because the time span of six years between spectroscopic and photometric observations is too long. Therefore we combined the velocities of Moran (1999) with those from eight MMT-spectra taken in 1996, 1997 and 2002 (Randall et al. 2005) and five spectra obtained with the Steward 2.3 m Bok telescope from 2000. The latter were determined using the double-precision version of the IRAF fxcor package, against the combined template for the star. In addition we obtained three high resolution spectra ( $R = 30\,000$ ) in 2000 at the 2.2 m telescope at the German-Spanish Astronomical Center (DSAZ) equipped with the FOCES-spectrograph. RVs were determined by cross correlation with a model spectrum at rest wavelength.

This provided us with 57 velocities distributed between 1996 and 2000. A sine curve was fitted to the observed velocities using an  $\chi^2$  minimising method and the power spectrum was generated (Napiwotzki et al. 2001). The orbital parameters were measured:  $\gamma = 7.3 \pm 0.2$  km s<sup>-1</sup>,  $K = 104.5 \pm 0.3$  km s<sup>-1</sup>,  $P = 0.569899 \pm 0.000001$  d and HJD(0) = 2452 545.064275. The period error was derived with a bootstrapping algorithm. The period is sufficiently accurate to allow the MOST photometry to be phased properly. However, it should be kept in mind that the error quoted is a purely statistical one. To investigate possible systematic errors, which can occur when radial velocities obtained with different instruments are combined, we also used another method to verify our results. In this case the fitting was performed with the system velocity  $\gamma$  as an additional free parameter for every individual dataset. The results using

both methods were perfectly consistent within the quoted errors. However, additional systematic effects may still be present.

### 2.2. Gravity and projected rotational velocity

Low resolution spectra obtained by Randall et al. (2005) and Maxted et al. (2001) were used to derive the atmospheric parameters. Particular attention should be paid to the gravity determination as it provides a mass-radius-relation, and its error propagates into the mass determination (see. Sect. 4).

Synthetic line profiles calculated from metal line-blanketed LTE model atmospheres with solar metal content (Heber et al. 2000) were matched to the observed Balmer and helium line profiles using a  $\chi^2$  fit procedure described by Napiwotzki et al. (1999). The resulting parameters are  $T_{\text{eff}} = 27\,700$  K,  $\log g = 5.55$ ,  $\log N(\text{He})/N(\text{H}) = -2.62$  from the spectra of Randall et al. (2005) and  $T_{\text{eff}} = 27\,300$  K,  $\log g = 5.50$ ,  $\log N(\text{He})/N(\text{H}) = -2.71$  from the spectra of Maxted et al. (2001) with formal statistical fitting errors of less than 100 K, 0.02 dex and 0.02 dex, respectively, which are unrealistically low. The true uncertainties are dominated by systematic inaccuracies in both the observations and model atmospheres, and can be estimated from repeated observations and the use of different model grids. Taking into account the discussion of typical systematic errors obtained when applying this method in Geier et al. (2007), we adopt  $T_{\text{eff}} = 27\,500 \pm 500$  K,  $\log g = 5.53 \pm 0.07$ ,  $\log N(\text{He})/N(\text{H}) = -2.66 \pm 0.1$ .

In order to derive  $v_{\text{rot}} \sin i$  and the elemental abundances, we compared the observed high resolution spectra with rotationally broadened, synthetic line profiles. The projected rotational velocity was measured simultaneously with the elemental abundances to  $v_{\text{rot}} \sin i = 10.9 \pm 1.1$  km s<sup>-1</sup> using 17 suitable metal lines.

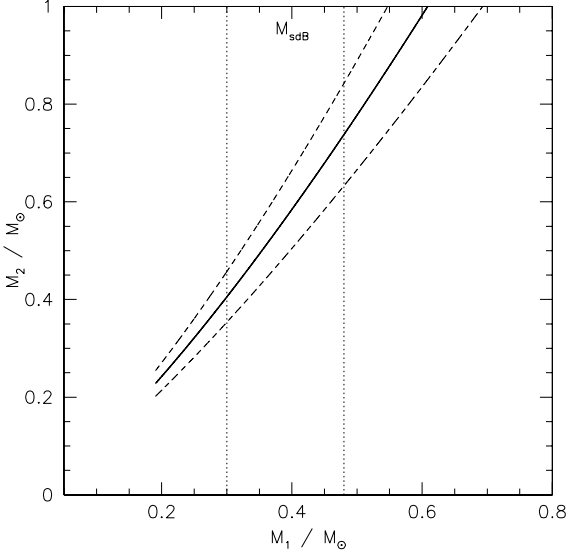
### 2.3. Analysis

The analysis strategy is the same as for KPD 1930+2752 and therefore is described here only briefly. For details we refer the reader to Geier et al. (2007).

Since the spectrum of PG 0101+039 is single-lined, it contains no information about the orbital motion of the companion, and thus only the mass function  $f_m = \frac{M_{\text{comp}}^2 \sin^3 i}{(M_{\text{comp}} + M_{\text{sdB}})^2} = \frac{PK^3}{2\pi G}$  can be calculated. Although the RV semi-amplitude  $K$  and the period  $P$  are determined by the RV curve,  $M_{\text{sdB}}$ ,  $M_{\text{comp}}$  and  $\sin^3 i$  remain free parameters.

Nevertheless, the masses can be constrained by assuming tidal synchronisation. Combining the orbital parameters with an estimate of the sdB mass, and with the measurements of its  $v_{\text{rot}} \sin i$  and gravity, allows the mass of the invisible companion to be constrained tightly. The mass of the sdB primary is constrained from the population synthesis models (Han et al. 2002) that predict a mass range of  $M_{\text{sdB}} = 0.30\text{--}0.48 M_{\odot}$  for sdBs in binaries, which experienced a common envelope ejection. The mass distribution shows a sharp peak at a mass of about  $0.47 M_{\odot}$ .

If the companion is synchronised the rotational velocity  $v_{\text{rot}} = \frac{2\pi R_{\text{sdB}}}{P}$  can be calculated. The radius of the primary is given by the mass radius relation  $R = \sqrt{\frac{M_{\text{sdB}} G}{g}}$ . The measurement of the projected rotational velocity  $v_{\text{rot}} \sin i$  therefore allows us to constrain the inclination angle  $i$ . With  $M_{\text{sdB}}$  as a free parameter the mass function can be solved, and both the inclination angle and the companion mass can be derived. Because of  $\sin i \leq 1$  a



**Fig. 1.** Companion mass as a function of primary (sdB) mass. The dotted vertical lines mark the theoretical sdB mass range for the common envelope ejection channel (Han et al. 2002). The dashed lines mark the error limits of the companion mass.

lower limit for the sdB mass is given by  $M_{\text{sdb}} \geq \frac{(v_{\text{rot}} \sin i)^2 P^2 g}{4\pi^2 G}$ . There are no visible spectral signatures of the companion. A main sequence companion with a mass higher than  $0.45 M_{\odot}$  can therefore be excluded because its luminosity would be sufficiently high to be detectable in the spectra.

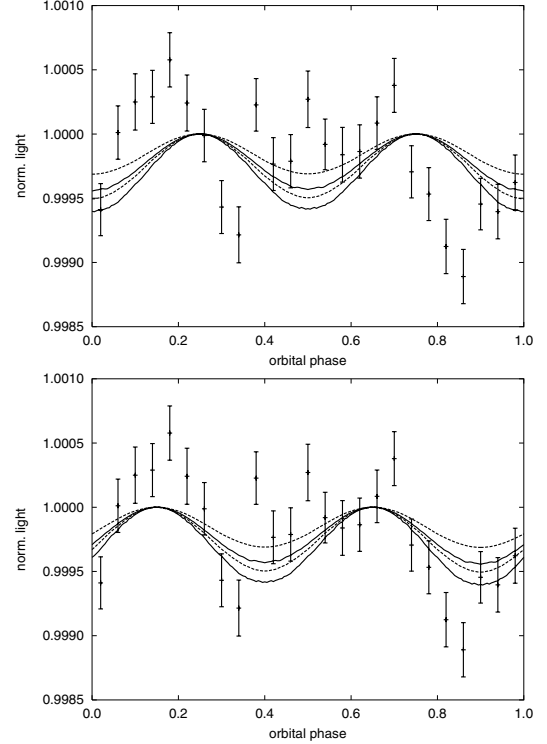
The relationship between the primary and the secondary mass is shown in Fig. 1. The allowed mass range for the companion is consistent with that of a white dwarf and therefore consistent with the common envelope ejection scenario. For the most likely sdB mass of  $0.47 M_{\odot}$  the binary parameters are:  $R_{\text{sdb}} = 0.19 \pm 0.02 R_{\odot}$ ,  $M_{\text{WD}} = 0.72 \pm 0.10 M_{\odot}$ , inclination  $i = 40 \pm 6^{\circ}$  and separation  $a = 3.1 \pm 0.4 R_{\odot}$ .

### 3. Light curve and ellipsoidal variations

The MOST photometric data were folded on the orbital period and re-binned to get a better signal to noise ratio (see Fig. 2). As PG 0101+039 is a pulsating sdB star of V1093 Her type, the light curve had to be pre-whitened for the pulsational frequencies beforehand.

Each bin contains more than 400 original measurements. Light curve variations at half the orbital period with a semi-amplitude of 0.025% were detected. Therefore PG 0101+039 shows the smallest ellipsoidal variation ever measured. In order to compare with synthetic light curves, we had to phase the photometry properly, taking the zero point from the orbital solution. Because the amplitude of the variation is very low, Doppler boosting arising from the orbital motion affects the lightcurve significantly. A resulting factor of  $(1 - v(t)/c)$  was applied to the total flux to correct for this effect.

The light curve was modelled with the light curve synthesis and solution code MORO, based on the model by Wilson & Devinney (1971). The details of the Bamberg implementation are given by Drechsel et al. (1995). The software uses a modified Roche model for light curve synthesis. It is capable of simulating the distortions of the stars induced by a companion. Light curves for different component masses and orbital inclinations were synthesised. For typical values of  $M_{\text{sdb}}$  appropriate



**Fig. 2.** Lightcurve data with superimposed models. The two solid curves confine the best fit models with parameters and associated uncertainties derived from spectroscopy under the assumption of orbital synchronisation and  $M_{\text{sdb}} = 0.3 M_{\odot}$ . The two dotted curves confine models for  $M_{\text{sdb}} = 0.7 M_{\odot}$ . Phasing the data to the orbital solution results in a significant phase shift (*upper panel*). In the *lower panel* the model lightcurve is shifted by  $-0.1$  in phase.

ranges of  $\sin i$  and  $R_{\text{sdb}}$  values were computed as described in Sect. 2, covering the full parameter space (including error limits) allowed by the spectroscopic analysis.

We used sdB masses from  $0.3$ – $0.7 M_{\odot}$  to calculate the model light curves and compared the models to the observations in Fig. 2. The synthetic light curve matches the semi-amplitude of the observed light curve quite well. Taking into account the extremely low amplitude of the variation, the consistency with the model is remarkable. However, there is a significant phase shift between the observed and the predicted light curve. The best fit to the data is phase shifted by  $-0.1$  with respect to the model calculated with proper orbital phase (see Fig. 2). Despite our efforts to derive a high precision orbital period, we can not rule out completely the possibility that this shift is caused by systematic effects when RV measurements from different instruments are combined. To match the observed light curve would require the period to differ by  $0.00008$  d from our results. Given the overall consistency of our orbital parameter determination, such a large deviation ( $80\times$  period error) seems to be rather unlikely.

### 4. Discussion

Tidally locked rotation in close binary systems has been assumed to measure masses of invisible compact companions, in particular in X-ray binaries. The synchronisation time is very difficult to calculate for stars with radiative envelopes, and is plagued with large uncertainties. Therefore, observational constraints are of utmost importance. Ellipsoidal variations can be used to verify the assumption, at least for the surface layers. We applied this technique to the sdB/WD binary PG 0101+039, for which

a very weak luminosity variation at half the orbital period has been discovered in a 16.9 day long, almost uninterrupted light curve obtained with the MOST satellite.

From spectroscopy we measured the mass function, apparent rotation and surface gravity of PG 0101+039. Stellar evolution models suggest that the sdB mass is close to  $0.47 M_{\odot}$ . Assuming tidally locked rotation, this information is sufficient to solve for all parameters of the binary system. The companion mass is found to be  $M_{WD} = 0.72 \pm 0.10 M_{\odot}$ , typical for a white dwarf. The light curve was then synthesised and was found to match the observed amplitude well. However, a problem with the phasing of the light curve to the radial velocity curve became apparent. Due to a six-year difference between the MOST photometry and published radial velocities, the phase errors were far too large for any conclusion to be drawn. Therefore we added 16 radial velocities from three observatories. The statistical error of the period decreased sufficiently to enable proper phasing of the photometry. The synthesised light curve was found to be offset by 0.1 cycles from the observed one, indicating that our systematic error estimate may be overly optimistic. Alternative explanations, like supersynchronous rotation of the sdB that may cause the observed phase shift, seem to be unlikely because a deviation of 10% from equilibrium would require fast rotation of the sdB. In this case the inclination would be very low and the companion mass would rise dramatically.

A simultaneous measurement of the radial velocity curve and a high precision light curve would be necessary to solve this problem since the theoretical understanding of angular momentum transfer in hot stars with radiative envelopes is still very limited. In conclusion, we found a strong indication that the surface rotation of the sdB star PG 0101+039 is tidally locked to its orbit.

The synchronisation times for any given type of primary depend strongly on the orbital period (Zahn 1977; Tassoul & Tassoul 1992). Hence, other sdB stars in close binaries should also be synchronised if their orbital period is less than that of

PG 0101+039 ( $P = 0.567$  d). We conclude that tidally locked surface rotation is established in sdB binaries with orbital periods of less than half a day. The assumption of tidally locked rotation can be safely applied to such systems, even if they are too faint to measure such extremely small light variations as observed here.

*Acknowledgements.* S.G. is supported by the Deutsche Forschungsgemeinschaft under grant He1354/40-3. We would like to thank P. F. L. Maxted and T. Marsh for providing us with the radial velocity measurements of C. Moran. Furthermore we thank H. Drechsel for his kind advice.

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