COMMISSIONS 27 AND 42 OF THE IAU
INFORMATION BULLETIN ON VARIABLE STARS

Number 6086

Konkoly Observatory
Budapest
2 December 2013

HU ISSN 0374 – 0676

STANDARD UBV PHOTOMETRY AND IMPROVED PHYSICAL PROPERTIES OF TW Dra

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1 Introduction

The semi-detached eclipsing binary TW Dra (HD 139319, HIP 76196, SAO 16767, BD+64°1077A; $V = 7^{\mathrm{m}}.3$-$9^{\mathrm{m}}.2$) is the brighter member of the visual binary ADS 9706. The fainter component ADS 9706B has a Hipparcos H_{p} magnitude of $9^{\mathrm{m}}.887$ and is separated only $3''$ from the eclipsing binary. Consequently, the light contribution from ADS 9706B affects any usual photoelectric observations of TW Dra and must be considered as a third light in the system.

The history of investigation of TW Dra was summarized by Zejda, Mikulášek and Wolf (2008) or Tkachenko, Lehmann and Mkrtichian (2010) and we shall restrict ourselves to only a few relevant citations.

The interest in the study of this system was renewed when rapid photometric variations with a period of $0^{\mathrm{d}}.0556$ and a full amplitude of only $0^{\mathrm{m}}.004$ were discovered (in addition to deep binary eclipses) by Kusakin (2001) and later confirmed by Zejda et al. (2006). Kim et al. (2003) found a period of $0^{\mathrm{d}}.0528$, which is a 1-d alias of the original period. Rapid multiperiodic line-profile changes were then reported by Lehmann et al. (2008) and Lehmann, Tkachenko and Mkrtichian (2009). They were unable to detect the periods reported from photometry but found three still shorter periods.

Table 1. Comparison and check stars of TW Dra.

	Name	V	$B-V$	$U-B$	Number of obs.	Comment
comp	HD 139549	$9^{\mathrm{m}}.131\pm0^{\mathrm{m}}.010$	$0^{\mathrm{m}}.413$	$-0^{\mathrm{m}}.042$	211	all–sky
check	HD 139703	$9^{\mathrm{m}}.292\pm0^{\mathrm{m}}.010$	$0^{\mathrm{m}}.939$	$0^{\mathrm{m}}.580$	174	all–sky
		$9^{\mathrm{m}}.292\pm0^{\mathrm{m}}.009$	$0^{\mathrm{m}}.938$	$0^{\mathrm{m}}.581$	542	differential

Rather complicated changes of the orbital period have been studied in detail by Zejda, Mikulášek and Wolf (2008), who also summarized previous studies on this topic.

A very detailed and careful study of a superb series of electronic spectra and determination of reliable orbital elements was carried out by Tkachenko, Lehmann and Mkrtichian (2010).

There are several complete light curves of TW Dra, but a multicolour light curve, transformed to a standard system in a reliable way, was still missing. This led us to obtain a complete UBV light curve at Hvar. Its solution, along with the spectroscopic elements by Tkachenko, Lehmann and Mkrtichian (2010), allowed us to improve the knowledge of the basic physical properties of the system, which might be helpful for the future studies of the nature of this binary, its rapid changes or period changes of the system.

2 Observations and their reduction

Differential photoelectric observations of TW Dra in the UBV filters were obtained with a single–channel photometer, equipped with an EMI9789QB tube attached to the 0.65 m Cassegrain reflector of the Hvar Observatory. The observations cover the time interval JD 2453517–2455804. HD 139549 = BD+64°1078 served as the comparison star while HD 139703 = BD+64°1079 was used as the check star and was observed as frequently as the variable. Altogether, 430 individual measurements were secured over 22 nights. The observations were reduced and transformed to the standard Johnson UBV system with the program HEC22 (Harmanec and Horn 1998). The transformation is based on nonlinear formulæ and on numerous observations of standard stars during the whole observing season (see Harmanec, Horn and Juza 1994 for the details). The latest rel. 18 of the program was used, which also allows modelling of variable extinction during individual observing nights. The mean Hvar all-sky UBV magnitudes of the comparison and check stars are listed in Table 1. For all observations the UBV magnitudes of the comparison listed in that Table were added to the magnitude differences var-comp and check-comp. To illustrate the quality of our transformation to the standard system, we also tabulate the mean differentially derived UBV magnitudes of the check star. The individual differential UBV observations of TW Dra with their heliocentric Julian dates are given in Tables 3, 4 & 5, published in electronic form only.

3 The light-curve solution and properties of the system

3.1 The initial ephemeris

Since Zejda, Mikulášek and Wolf (2008) found complicated period changes from their analysis of the orbital-period changes and minima timings of TW Dra over the past 150 years, it was necessary to decide, which ephemeris we should use to begin the solution in `PHOEBE`. The formulæ they derived permit the determination of the instantaneous values of the orbital period and the epoch of primary minimum and these were used by Tkachenko, Lehmann and Mkrtichian (2010). As the Hvar observations were secured during and shortly after the spectroscopic observations by Tkachenko et al., we first tried to adopt their linear ephemeris

$$T_{\rm min.\,I} = {\rm HJD}\,2\,454\,400.97997 + 2\overset{\rm d}{.}8068491 \times E, \tag{1}$$

but we found that it leads to a small phase shift in the phase diagram. We therefore decided to allow also convergence of the epoch and local value of the period during the light curve solution.

Table 2. The final light curve solutions obtained with `PHOEBE`. All epochs are in RJD = HJD − 2400000. Probable elements and their error estimates are provided. L_j ($j = 1, 2, 3$) are the relative luminosities of the components in individual photometric passbands, normalized in such a way that $L_1 + L_2 + L_3 = 1$. The magnitudes of the individual components refer to the orbital phase 0.25.

Element		Primary	System	Secondary
P	(d)		2.806791 ± 0.000003	
$T_{\rm min.I}$	(RJD)		55703.33053 ± 0.00008	
e			0 fixed	
a	$(R_\odot)$		12.2 fixed	
q			0.430 ± 0.002	
i	(°)		87.08 ± 0.03	
r_{pole}	(a)	0.2152 ± 0.0006		0.2881 ± 0.0001
r_{side}	(a)	0.2168 ± 0.0006		0.3004 ± 0.0001
$T_{\rm eff}$	(K)	7815 ± 92		4442 ± 32
M	$(M_\odot)$	2.16 ± 0.11		0.93 ± 0.05
R	$(R_\odot)$	2.64 ± 0.04		3.66 ± 0.06
$M_{\rm bol}$	(mag.)	1.327 ± 0.062		3.163 ± 0.048
$\log g$	[cgs]	3.928 ± 0.026		3.314 ± 0.026
$L_{\rm V}$	V band	0.7924 ± 0.0004		0.0962 ± 0.0004
$L_{\rm B}$	B band	0.8639 ± 0.0004		0.044 ± 0.0004
$L_{\rm U}$	U band	0.8812 ± 0.0004		0.018 ± 0.0004
V	(mag.)	7.582 ± 0.001		9.870 ± 0.005
$(B-V)$	(mag.)	0.213 ± 0.001		1.148 ± 0.011
$(U-B)$	(mag.)	0.094 ± 0.001		1.076 ± 0.026
V_{1+2+3}	(mag.)		7.323	
B_{1+2+3}	(mag.)		7.630	
U_{1+2+3}	(mag.)		7.752	
			Third light	
L_3	V band		0.111 ± 0.002	
L_3	B band		0.092 ± 0.001	
L_3	U band		0.100 ± 0.001	
$^2V_3$	(mag.)		9.713 ± 0.006	
$^2(B-V)_3$	(mag.)		0.517 ± 0.009	
$^2(U-B)_3$	(mag.)		0.017 ± 0.010	

[1] The higher uncertainty bar of variables (a, $r_{\rm side}$, $T_{\rm eff}$, q) was used to propagate the uncertainty of the parameter.

[2] The errors of magnitudes and colours were derived from the formal errors of luminosities.

3.2 The light-curve solution

We derived the solution based on our new UBV light curves using the program `PHOEBE` (Prša and Zwitter, 2005, 2006). Our approach was the following: we first adopted the principal results from the spectroscopic study by Tkachenko, Lehmann and Mkrtichian (2010) as the input values for the `PHOEBE` iteration, adopting the circular orbit. These authors, using spectra disentangling (Hadrava 1995, 1997, 2004) and the Shellspec07 inverse program (Budaj and Richards 2004), derived the semiamplitudes of the radial-velocity curves of 64.05±0.02 and 156±1 km s^{-1} (implying the mass ratio of 0.411±0.004), semimajor axis of (12.2 ± 0.2) $R_\odot$, and zero eccentricity. Note, however, that their result from the KOREL disentangling led to different values: semiamplitudes of 64.05 ± 0.34 and 150.0 ± 2.3 km s^{-1}, semimajor axis of (12.10 ± 0.47) $R_\odot$ and a mass ratio of 0.427 ± 0.011. Comparing the disentangled spectra to synthetic ones, they also derived the effective temperatures of 8160 ± 15 and 4538 ± 11 K for the primary and secondary, respectively.

As already mentioned, we could not exclude the close companion of TW Dra, ADS 9706B from our photoelectric observations and the third-light contribution had to be considered during the solution. To get some initial estimate how large the third light could be, we started with the only reliable photoelectric determination obtained by the Hipparcos satellite and published in the 2nd Tycho catalog, $H_\mathrm{p} = 9\overset{\mathrm{m}}{.}887 \pm 0\overset{\mathrm{m}}{.}047$. We adopted the F7 spectral class of the third body after Meisel (1968) and its colors $B-V = 0\overset{\mathrm{m}}{.}49$ and $U-B = 0\overset{\mathrm{m}}{.}00$ on the premise it is a main-sequence object from the compilation by Golay (1974). Then we could transform the observed H_p magnitude to the Johnson V using the transformation formula by Harmanec (1998). Having the Johnson UBV values for the third star in the system, it was then possible to calculate the relative luminosities L_j (j=1-3) in the units of the total luminosity of the system outside the eclipses $(L_1 + L_2 + L_3 = 1)$ for all three components from the light curves. We took into account the fact that the primary eclipse is a total one. For the input values of the fractional luminosity of the third body we got $L_\mathrm{3V} = 0.095$, $L_\mathrm{3B} = 0.081$ and $L_\mathrm{3U} = 0.090$.

The bolometric albedos for both components of the close binary system were estimated from Claret (2001) and kept fixed during iterations at $A_1 = 0.94$ and $A_2 = 0.78$. The values for gravity–darkening coefficients were estimated from Claret (1998) as $g_1 = 0.95$ and $g_2 = 0.36$.

A linear limb–darkening law was adopted and the limb–darkening coefficients were interpolated every iteration from the 2010 pre-calculated tables, available with a recent *devel* version of the program `PHOEBE`, which we used. They were calculated by Dr. Prša on the basis of Castelli and Kurucz (2004) model atmospheres.

Using the scripter enviroment of `PHOEBE` (version 0.31), we explicitly assumed a semi-detached configuration and a circular orbit. The free parameters during iterations were: the orbital inclination i, the orbital period P, the epoch of the primary mid-eclipse, the mass ratio q, the effective temperatures of both components T_eff1 and T_eff2, the surface potential of the primary Ω_1 and the luminosities of the components L_j, (j=1-3). We have chained five hundred minimizations of the cost function together, starting each minimization at the minimum found in the previous run. The solution converged to the surroundings of the final solution in less than ten iterations. The solution having the lowest cost function value was adopted as the final one.

We also carried out the calculations for the initial values of relative luminosities for the spectral class of the third body in the range from F4 to G0. The best fit, according to the cost function value, has been obtained for the spectral types F6 and F7, which makes the choice of Meisel's value legitimate.

The results of the solution are summarized in Table 2 and the light curves are plotted in Figure 1&2. Figure 1 shows a complete V-band light curve, residua from it and also the phase plot of individual differential observations of the check star to characterize the scatter of the data. Figure 2 is a zoomed part of the UBV light curves and their residua from the solution at the phases around both minima.

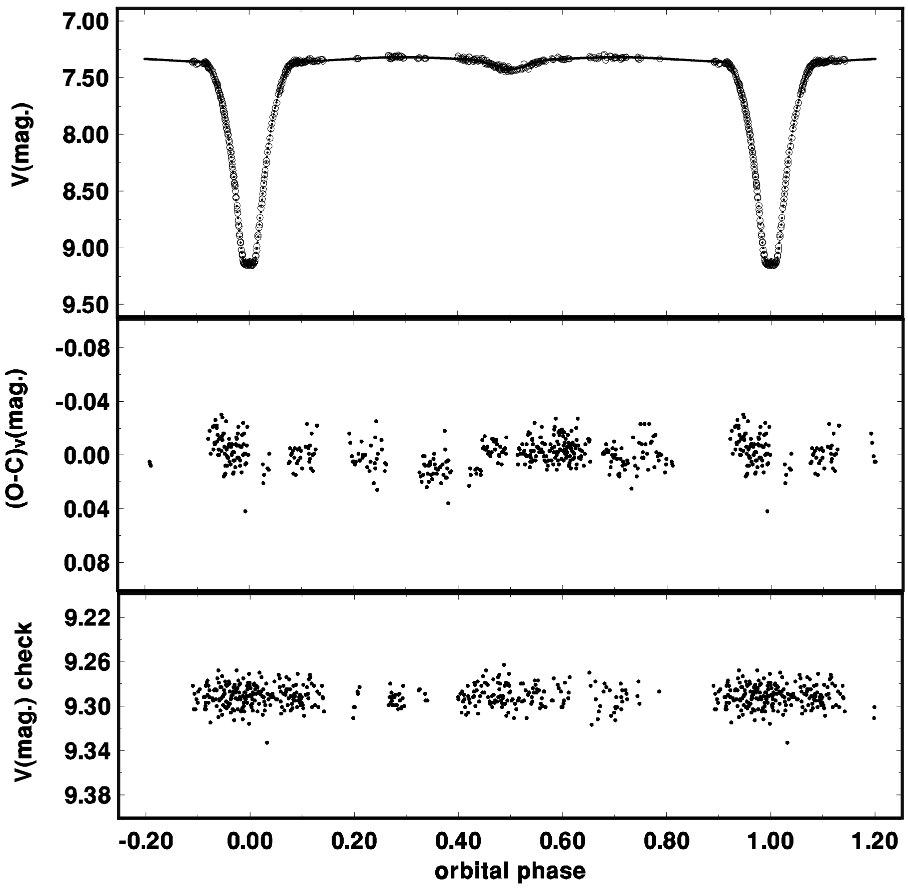

Figure 1. The V magnitude light curve of TW Dra and the final solution are shown in the upper panel. The residua from the solution are in the middle panel while the individual differential observations of the check star are shown in the bottom panel to illustrate the data accuracy.

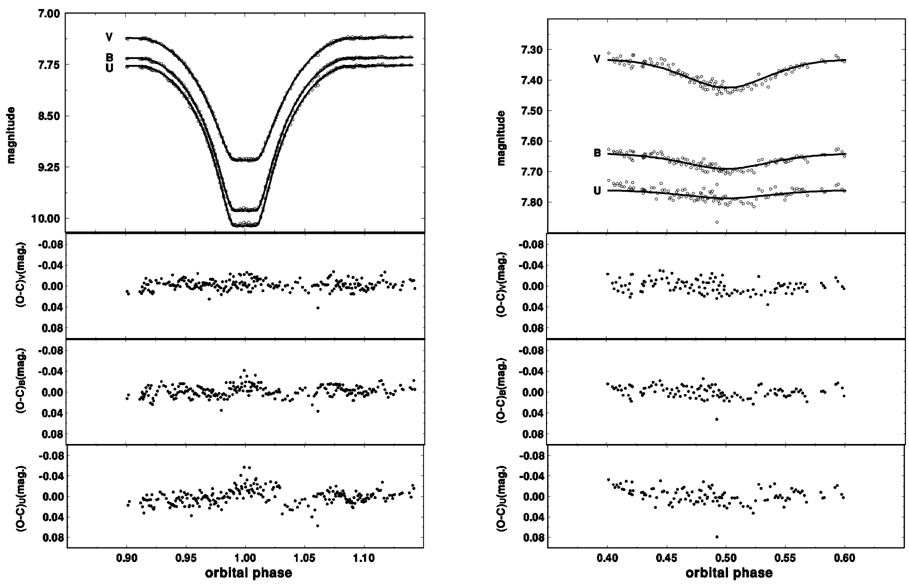

Figure 2. The UBV light curves of TW Dra and the final PHOEBE solution in the neighbourhood of the primary minimum (left) and the secondary minimum (right). The UBV residua from the solution are shown in the bottom panels.

The errors of all fitted parameters given in Table 2 are the formal errors derived in PHOEBE from a covariance matrix.

3.3 Basic properties of the system

There are several things worth mentioning in our new solution:

1. The $O-C$ residua in Fig. 2 show a slight central brightening around the primary mid-eclipse, with an amplitude increasing towards shorter wavelengths. The referee has pointed out that it might be caused by a poor theoretical spectral energy distribution over the Balmer jump region, where even small deviations can accumulate into a significant effect. Even though V light curve should not be affected, there seems to be similar brightening, hence it may also be related to the temperature distribution over the surface of the donor star.

2. Given a rather small distance to the system, the reddening is insignificant and the observed colours of all three components can be directly compared to the standard ones. Miner (1966) indeed found $E(B-V) = 0.0$ for TW Dra. Thanks to the fact that our observations are carefully transformed to the standard UBV system, the light-curve solution allows determination of colour indices of binary components and contains therefore information about photometric effective temperatures of both stars. We have used such an approach for a long time – cf, e.g., Mayer et al. (1991). The possibility to converge both effective temperatures using calibrated photometry was later realised by Prša, A. & Zwitter, T. (2005, 2006), who implemented it to the scripter environment of PHOEBE and the referee encouraged us to use this option in our light-curve solution. It is clear that this requires standardised photometry

of superb quality. In our case the situation is more favourable due to the fact that the temperatures of both components differ substantially from each other. We find the fact that it resulted in reasonable values notable. It represents one of the very first practical attempts along this line. Note that an even more elaborate attempt at the determination of both effective temperatures was carried out by Wilson & Raichur (2011). Referring again to the compilation by Golay (1974), we found the photometric spectral types of A6–A8V, K1–2III, and F8V for the primary, secondary, and tertiary, respectively. For comparison, deriving colour indices of the primary and secondary from the standard UBV values at maximum light and from relative luminosities in individual passbands correspond to $T_{\rm eff1} = 7700$ K and $T_{\rm eff2} = 4560$ K if Flower's (1996) calibration is used, and to 7600 and 4215 K if Popper's (1980) calibration is used.

3. The linear ephemeris, which follows from our solution and applies to the time interval JD 2455594-2455804 (the single night of observations secured in 2005 was obtained at maximum light and has little impact on the accurate determination of the orbital period; a solution without this night remains almost unaltered) is

$$T_{\rm min.\,I} = {\rm HJD}\,2\,455\,703.3305280(28) + 2\overset{\rm d}{.}806790(0) \times E, \tag{2}$$

i.e. significantly shorter than the ephemeris used by Tkachenko et al. (2010). Zejda, Mikulášek and Wolf (2008) demonstrated the damping $O-C$ variations with a cycle of some 20 years which they attributed to the quadrupole moment variations in the system. One can speculate that the period decrease found by us could indicate an increase in the mass–transfer rate. The small–amplitude 6.5-year variation due to a hypothetical low–mass third body proposed by Wolf (1990) and Zejda, Mikulášek and Wolf (2008) is not sufficient to explain the large discrepancy between observed and expected value of the period.

4. Taken at face value, the mass of the primary of 2.2 $M_\odot$ would correspond to an A0-A1 main-sequence object (see Harmanec 1988), which strongly disagrees with the spectral class A5 found by Tkachenko, Lehmann and Mkrtichian (2010) or A6–A8 derived by us. One possibility is that the primary is somewhat evolved from the zero-age main sequence. However, we wish to offer an alternative possibility. TW Dra is an emission-line star seen edge-on (Richards and Albright 1999). In that case, we have a situation reminiscent of cases of the inverse correlation between the brightness and emission strength discussed by Harmanec (1983). The matter flowing from the contact secondary towards the primary may form *a pseudophotosphere*, which – seen equator-on – mimics a later spectral subclass than that, which one would get for the primary if it could be observed pole-on or totally without such a pseudophotosphere. In other words, we might not be observing an evolutionary effect but an effect of the densest parts of circumstellar matter projected against the disk of the primary.

   The idea might be worth testing via dedicated spectral observations. In passing we note that the continuing mass exchange in TW Dra seems to be supported by a recent study by Ibanoğlu et al. (2012), who found evidence of carbon deficiency, indicative of inflow of CNO reprocessed material into the atmosphere of the primary. Notably, these authors estimate the effective temperature of the primary from the Strömgren photometry to be 10800 K.

Acknowledgements: We acknowledge the use of the latest *devel* version of the `PHOEBE` program, written and freely distributed by Dr. A. Prša. A constructive criticism of the previous version of this paper by the referee, Dr. A. Prša, helped to improve the paper. This research was supported from the grants P209/10/0715 of the Czech Science Foundation and 101-10/253289 of the Charles University in Prague and from the Research Program MSM0021620860 of the Ministry of Education, Youth and Sports of the Czech Republic. We profited from the use of the electronic database from CDS Strasbourg and electronic bibliography maintained by the NASA/ADS system.

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*This version of the paper contains corrections, and differs from the one appeared on-line originally. Date of last modification: Dec 6 14:04:16 CET 2013