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

Number 6016

Konkoly Observatory
Budapest
6 March 2012

HU ISSN 0374 – 0676

ZZ Cyg – FUNDAMENTAL PARAMETERS

NELSON, ROBERT H.[1,2]

[1] 1393 Garvin Street, Prince George, BC, Canada, V2M 3Z1; email: b-o-b.nelson@shaw.ca [remove dashes]

[2] Guest investigator, Dominion Astrophysical Observatory, Herzberg Institute of Astrophysics, National Research Council of Canada

Variability of ZZ Cyg (GSC 3576-0244, V∼11.0) was discovered by Williams (1907) using a 4″ portrait lens to obtain a large number of photographs. Two photographic minima, as well as 12 visual minima were reported. The data were sufficient to determine an accurate position, visual magnitudes, primary eclipse depth, and a period of 0.6286135 days. Although he plotted a visual light curve around a minimum, he did not furnish any other data but went on to classify the system as an Algol, presumably because of the apparent flatness of the light curve between eclipses. Shapley (1913) provided an early summary of the orbits of 87 eclipsing binaries – including ZZ Cyg – listing rough periods, magnitudes, amplitudes, spectral types and the results of various model fittings. Hall and Weedman (1971) performed UBV photometry on 19 eclipsing binaries with close companions – including ZZ Cyg. For ZZ Cyg, they listed the (AB-C) separation as 9″ in 1971. The V, $B-V$, and $U-B$ magnitudes of ZZ Cyg's close companion were provided (12.63 ± 2, 0.61 ± 1, and 0.15 ± 2, respectively), but alas, no infrared observations were possible at that time. They did list the spectral type of the Algol system as F7 + K5 IV. Hall and Cannon (1974) published their UBV data and performed an analysis based on the rectification method. They concluded that the visual companion (quoted as 5.″8 distant) was not physically connected. They also suggested that the primary, as observed between eclipses, underwent 0.05 magnitude fluctuations of period 0.1 days. Brancewicz & Dworak (1980) provided estimates of fundamental parameters of eclipsing binaries based on some simple equations. Following upon suggestions that ZZ Cyg had a δ Scuti variability in the primary component, Frolov et. al. (1982) undertook B and V photoelectric observations of ZZ Cyg obtained over 7 nights and saw no evidence of δ Sct varability in their published light curves. Shaw (1994) provided a list of 128 systems – including ZZ Cyg – that fell into his newly-defined class of near contact binaries (periods $<$ 1 day, evidence of tidal interaction, facing sides separated by $< 0.1 \times$ orbital radius, but not in contact like the EW-types). ZZ Cyg was listed as an Algol-type. However, he pointed out the difficulty in distinguishing between that class and that of contact binaries (and presumably also semi-detached).

From 1965 to the present, there have been many publications with times of minima and period studies (see Nelson, 2011), but surprisingly, there have been none with radial velocity data or modern light curve analysis.

Accordingly, photometric observations were undertaken by the author at his private observatory in Prince George, BC, Canada in June of 2003. Obtained were a total of

Table 1: Details of variable, comparison and check stars.

Type	GSC 3576-	R.A. J2000	Dec. J2000	V (Tycho) Mags	$B-V$ Mags
Variable	0244	$20^h23^m52\overset{s}{.}944$	$46°55'14\overset{''}{.}666$	10.98	0.582
Comparison	0964	$20^h23^m38\overset{s}{.}139$	$46°56'53\overset{''}{.}899$	11.11	0.100
Check	0702	$20^h23^m32\overset{s}{.}522$	$46°56'52\overset{''}{.}142$	11.31	0.437

Table 2: Log of DAO observations

DAO Image #	Mid Time (HJD−2400000)	Exposure (sec)	Phase at Mid-exp	V_1 (km/s)	V_2 (km/s)
13214	54000.7465	3600	0.847	82.5	−175.0
19121	55102.6356	3600	0.728	83.8	−213.3
19176	55104.8590	3600	0.265	−76.1	197.6
19178	55104.8989	3177	0.329	−73.9	194.1
17461	55476.6949	3600	0.780	87.4	−189.8

92 frames and 90 in the I_C (Cousins) band. Standard reductions were then applied. See Nelson (2004) for details. The comparison and check stars are listed in Table 1 (coordinates and magnitudes are from the GSC catalogue).

Examination of Digitized Sky Survey (DSS) images and also ST-7 images revealed an elongated shape to ZZ Cyg. As it was unresolvable into component images, apertures large enough to enclose the entire shape were used.

In September of the years 2006, 2009 and 2010 the author took five medium resolution (reciprocal dispersion = 10 Å/mm, resolving power = 10 000) spectra at the Dominion Astrophysical Observatory (DAO) in Victoria, British Columbia, Canada; he then used the Rucinski broadening functions (Rucinski, 2004) to obtain radial velocity (RV) curves (see Nelson, et al. (2006) and Nelson (2010b) for details). The spectral range was approximately 5000-5260Å. A log of DAO observations and RV results is presented in Table 2. The results were corrected (2.9% up in this case) to allow for the small phase smearing. (One simply divides by the factor $f = \frac{\sin(X)}{X}$, where $X = \frac{2\pi t}{P}$ and t=exposure time, P=period. For spherical stars, the correction is exact; in other cases, it can be shown to be close enough for any deviations to fall below observational errors.)

The author used the 2004 version of the Wilson-Devinney (WD) light curve and radial velocity analysis program with the Kurucz atmospheres (Wilson and Devinney, 1971, Wilson, 1990, Kallrath, et al., 1998) as implemented in the Windows software WDwint (Nelson, 2010a) to analyze the data. To get started, a spectral type F7 (Hall and Weedman, 1971) and a temperature $T_1 = 6381 \pm 66$ K were initially used; interpolated tables from Cox (2000) gave $\log g = 4.346$; an interpolation program by Terrell (1994, available from Nelson 2010b) gave the Van Hamme (1993) limb darkening values; and finally, a logarithmic (LD=2) law for the extinction coefficients was selected, appropriate for temperatures < 8500 K (ibid.). (The stated error in T_1 corresponds to one half spectral sub-class.) For some reason, the author started with mode 2 (detached). Convergence by the method of multiple subsets was reached in a small number of iterations. At first, a radiative envelope was chosen for star 1, (appropriate for hotter stars) and convective for the other, but shifting to convective envelopes for both stars gave a much better fit. The limb darkening coefficients are listed in Table 3.

Early on, it was discovered that T_1 = 6381 (F7) gave a poor fit. Higher values,

Table 3: Limb darkening values from Van Hamme (1993)

Quantity —	T_1=6650 Star 1	T_2=4307 Star 2	Error —	T_1=6514 Star 1	T_2=4264 Star 2
x (bol)	0.640	0.612	[fixed]	0.639	0.616
y (bol)	0.243	0.178	[fixed]	0.251	0.171
x (V)	0.705	0.795	[fixed]	0.710	0.797
y (V)	0.280	0.034	[fixed]	0.275	0.014
x (Ic)	0.548	0.680	[fixed]	0.553	0.682
y (Ic)	0.275	0.176	[fixed]	0.276	0.164

corresponding to earlier spectral types, gave a much better fit. F5 (T_1 = 6650 K) and F6 (T_1 = 6514 K) gave similar, better residuals; therefore, the results of both models are presented (as Models A & B, resp.). Since there was a known extra star, 3rd light was used. In any case, its inclusion improved the fit. A single spot on star 2 was required to account for the dip in light intensity from phase 0.6 to 0.9, approximately. Alternate configurations (dark spot on star 1, bright spots) were tried with no success. Next, non-zero eccentricity was tested for; a value of 0.0016 ± 0.0012 resulted. This is a very low value and is worth ignoring.

Mode 5 (Algol, where the secondary fills the Roche lobe) was then tried, resulting in marginally better residuals. The results are presented as Models C & D, respectively, in Table 4. Since the corresponding values are very close, an extra digit is included to show the tiny differences.

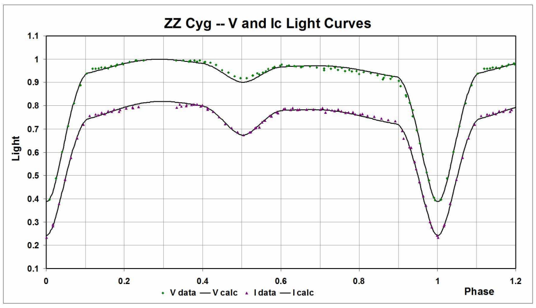

Figure 1. ZZ Cyg: V and I_C Light Curves – Data and WD Fit (all models)

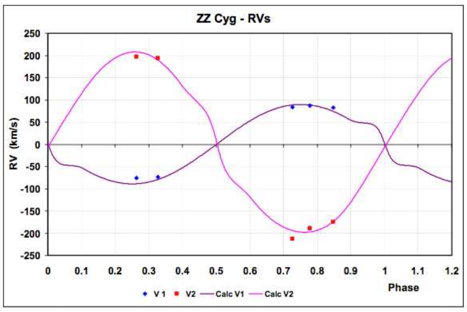

Figure 2. ZZ Cyg: Radial Velocity Curves – Data and WD Fit.

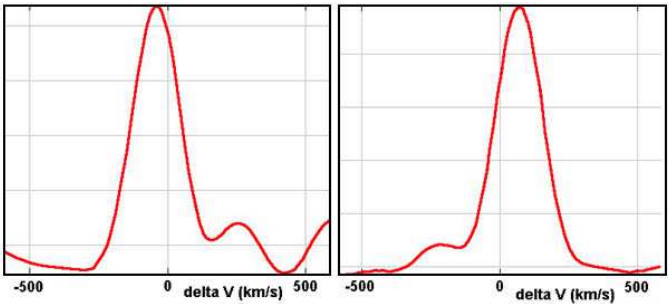

Figure 3. Representative broadening functions, at phases 0.265 and 0.728, resp.

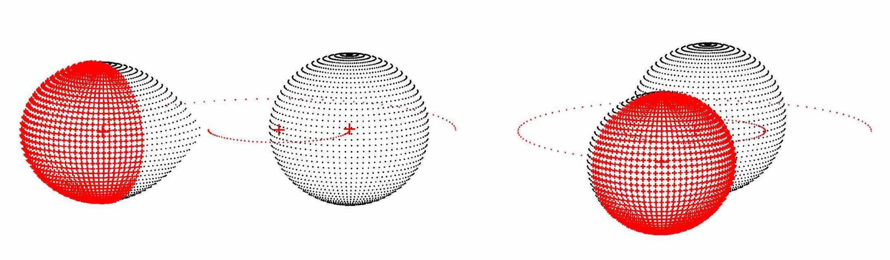

Figure 4. Binary Maker 3 representation of the system – at phases 0.75 and 0.97.

A plot of the V and I_C light curves, and WD fit are shown in Figure 1. Since the visual appearances of the four different models are virtually indistinguishable, only one plot is presented. The RVs are shown in Fig. 2 (again, for the same reason, only one plot is presented). Two representative examples of the broadening functions (Rucinski, 2004 and Nelson, 2010b) are depicted in Figure 3. These functions – in velocity space – represent the agents that would alter the sharp and unshifted lines from a non-rotating spherical star to those observed. In both of these cases, the peak of the large hump is at the primary RV and the weaker less distinct one, the secondary. The velocities, of course, need to be converted to heliocentric ones. A three dimensional representation from Binary Maker 3 (Bradstreet, 1993) is shown in Fig. 4.

The WD output fundamental parameters and errors are listed in Table 5 and – for comparison – the corresponding values of zero age main sequence stars (Cox, 2000). Most of the errors are output or derived estimates from the WD routines. The error in q was derived from the rms deviations of points from the best-fit double sine curves. In estimating the distance, galactic extinction was allowed for using the formula $A_V = 3E(B-V) = R \times [(B-V)_{data} - (B-V)_{tables}]$.

In conclusion, it is impossible to distinguish between the detached state where the secondary very nearly fills its Roche lobe and the Algol state (where the secondary star completely fills its Roche lobe), although the latter is favoured. In terms of the physical parameters, there is very little difference. More importantly, it was difficult to settle on the spectral type (and temperature T_1) of the primary. A re-determination of the primary spectral type from a high S/N classification is highly desirable for this interesting system. The main sequence values corresponding to single stars, but, since it is very likely

Table 4:

Wilson-Devinney Quantity	Model A Detached Value	Model B Detached Value	A.B Detached Error	Model C Algol Value	Model D Algol Value	C.D Algol Error
T_1 (K)	6650	6514	67	6650	6514	67
T_2 (K)	4362	4297	78	4333	4283	84
Ω_1	3.627	3.623	0.040	3.627	3.623	0.034
Ω_2	2.717	2.718	0.018	2.678	2.672	—
$q = M_2/M_1$	0.4143	0.4143	0.0047	0.3999	0.3972	0.0080
i (deg)	79.79	79.79	0.44	79.79	79.79	0.36
$L_1/(L_1+L_2)$ (V)	0.9134	0.9160	0.0013	0.9165	0.9169	0.0012
$L_1/(L_1+L_2)$ (I_C)	0.8414	0.8445	0.0022	0.8448	0.8492	0.0019
a (solar radii)	3.964	3.965	0.038	3.946	3.951	0.036
V_γ (km/s)	0.4	0.4	1.4	0.4	0.4	1.3
r_1 (pole)	0.3095	0.3099	0.0038	0.3082	0.3084	0.0037
r_1 (point)	0.3255	0.3260	0.0048	0.3235	0.3235	0.0046
r_1 (side)	0.3164	0.3168	0.0042	0.3149	0.3150	0.0041
r_1 (back)	0.3219	0.3223	0.0045	0.3201	0.3202	0.0044
r_2 (pole)	0.2834	0.2831	0.0039	0.2825	0.2820	0.0016
r_2 (point)	0.3817	0.3798	0.0317	0.4070	0.4064	0.0070
r_2 (side)	0.2952	0.2949	0.0046	0.2945	0.2940	0.0017
r_2 (back)	0.3267	0.3262	0.0074	0.3272	0.3266	0.0017
Spot co-latitude	90	90	[fixed]	90	90	[fixed]
Spot longitude	215.8	214.0	5.2	215.5	215.4	5.0
Spot radius	88.3	88.3	8.0	88.5	88.5	7.5
Spot temp factor	0.9090	0.9090	0.0082	0.9060	0.9075	0.0083
3^{rd} light (V)	0.0010	0.0010	0.016	0.0017	0.0010	0.016
3^{rd} light (I_C)	0.0397	0.0397	0.015	0.0414	0.0397	0.014
$\Sigma\omega^2_{res}$	0.00564	0.00563	—	0.00547	0.00541	—

Table 5: WD Output Values

Fundamental Quantity	Tabular value	Mdl A WD	Mdl C WD	Tabular value	Mdl B WD	Mdl D WD	Error WD
Eclipsing type	—	EB	Algol	—	EB	Algol	—
Sp. Type, star 1	F5	F5	F5	F6	F6	F6	—
Temperature (K), 1	6650	6650	6650	6514	6514	6514	67
Mass ($M_\odot$), 1	1.40	1.500	1.495	1.32	1.501	1.504	0.15
Radius ($R_\odot$), 1	1.30	1.25	1.24	1.26	1.26	1.24	0.006
$M_{\rm bol}$, 1	3.36	3.69	3.70	3.52	3.77	3.79	0.08
$\log g$ (cgs), 1	4.356	4.42	4.42	4.360	4.42	4.43	0.002
Luminosity ($L_\odot$), 1	2.97	2.75	2.73	2.56	2.56	2.51	0.19
Sp. Type, star 2	K5	K5	K5	K6	K6	K6	—
Temperature (K), 2	4410	4362	4333	4290	4297	4283	59
Mass ($M_\odot$), 2	0.67	0.622	0.598	0.63	0.622	0.597	0.036
Radius ($R_\odot$), 2	(0.72)	1.20	1.19	(0.69)	1.20	1.19	0.006
M bol, 2	(6.63)	5.61	5.65	(6.788)	5.68	5.70	0.08
Log g (cgs), 2	(4.549)	4.07	4.06	(4.557)	4.07	4.06	0.002
Luminosity ($L_\odot$), 2	(0.176)	0.47	0.45	(0.147)	0.44	0.43	0.03
Distance (pc)	—	90	90	—	87	86	10

that mass transfer occurred as some point, the comparison is mute (especially for the secondary).

No evidence of the 0.05-amplitude, 0.1-day delta Scuti variation was detected, confirming the conclusion of Frolov et al. (1982).

Reference to the $O-C$ relation (Nelson, 2011) reveals a more or less constant period decrease from 1965 to 2002; however, the large scatter in the data in that range prevents any definitive conclusions. Indeed, data since 2002 suggest that the period is constant. As is often the case, more accurate data and a longer time base are required. Also, a re-examination of the conclusion of Hall and Cannon (1974) – that the visual companion is not physically connected – might be worth re-examining.

Acknowledgements:
It is a pleasure to thank the staff members at the DAO (especially Dmitry Monin and Les Saddlemyer) for their usual splendid help and assistance.

References:

Bradstreet, D.H., 1993, "Binary Maker 2.0 - An Interactive Graphical Tool for Preliminary Light Curve Analysis", in Milone, E.F. (ed.) Light Curve Modelling of Eclipsing Binary Stars, pp 151-166 (Springer, New York)

Brancewicz, H.K., Dworak, T.Z., 1980, *Acta Astron.* **30**, 501.

Cox, A.N., ed, 2000, Allen's Astrophysical Quantities, 4th ed., (Springer-Verlag, New York, NY).

Frolov, M.S., Pastukhova, E.N., and Mironov, A.V., 1982, *IBVS* **2117**

Hall, D.S. and Weedman, S.L., 1971, *Publ. Astron. Soc. Pac.* **83**, 69

Hall, D.S. and Cannon, R.O., 1974, *Acta Astron.* **24**, 79

Kallrath, J., Milone, E.F., Terrell, D., and Young, A.T., 1998, *ApJ* **508**, 308.

Nelson, R.H., 2004, *IBVS* **5493**

Nelson, R.H., Terrell, D., and Gross, J., 2006, *IBVS* **5715**

Nelson, R.H., 2010a, Software, by Bob Nelson, http://members.shaw.ca/bob.nelson/software1.htm

Nelson, R.H., 2010b, "Spectroscopy for Eclipsing Binary Analysis" in The Alt-Az Initiative, Telescope Mirror & Instrument Developments (Collins Foundation Press, Santa Margarita, CA), R.M. Genet, J.M. Johnson and V. Wallen (eds)

Nelson, R.H., 2011, Bob Nelson's O-C Files, http://www.aavso.org/bob-nelsons-o-c-files

Rucinski, S.M., 2004, *IAU Symp.* **215**, 17

Shapley, H., 1913, *ApJ*, **38**, 158

Shaw, J.S., 1994, *Mem. Soc. Astron. Ital.* **65**, 95

Terrell, D., 1994, Van Hamme Limb Darkening Tables, vers. 1.1.

Van Hamme, W., 1993, *Astron. J.* **106**, 2096

Williams, A.S., 1907, *Astron. Nachr.* **174**, 9

Wilson, R.E., and Devinney, E.J., 1971, *Astrophys. J.* **166**, 605

Wilson, R.E., 1990, *Astrophys. J.* **356**, 613