Analysis of multicolour light curves of the eclipsing binaries AQ Tuc and AY Vel

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Abstract. First multicolour photoelectric light curves of the eclipsing binaries AQ Tuc and AY Vel obtained in 1965 and 1969 at the Leiden Southern Station using Walraven *VBLU* filters were analyzed by the Wilson-Devinney's code. Our analysis confirmed the contact configuration for AQ Tuc and revealed that AY Vel is an almost contact system with $q \approx 3$. The absolute radii of the components of AQ Tuc derived from the combination of our photometric and available spectroscopic elements are $R_1 = 2.03 \pm 0.11\ R_\odot$ and $R_2 = 1.30 \pm 0.07\ R_\odot$.

Key words: eclipsing binaries - photometry - orbital elements

1. Introduction

In 1965-78 the second author (CJvH) initiated a program for obtaining multicolour photoelectric light curves of eclipsing variables observed in the southern hemisphere using the 0.9 m telescope of the Leiden Southern Station in South Africa. The four-band Walraven *VBLU* observations of the eclipsing binaries AQ Tuc and AY Vel were obtained in 1965 and 1969 as a part of the program mentioned above. They were published by van Houten et al. (2001). The aim of our paper is to analyze these multicolour light curves employing the revised version (Wilson, 1992) of Wilson-Devinney's (1971,1973) code (W&D).

2. Basic informations about AQ Tuc and AY Vel

2.1. AQ Tucanae

The eclipsing binary AQ Tuc (HD 1372, sp. type F3/5 (Houk & Cowley, 1975); $m_{\rm pg}^{\rm max} = 9.91$ mag; $m_{\rm pg}^{\rm min\ I} \approx m_{\rm pg}^{\rm min\ II} = 10.48$ mag; $P = 0.59484$ days) was first reported to be a variable by Strohmeier (1964). Köhler & Schöffel (1965) suggested it is an eclipsing binary, which was later confirmed by Collins (1971) who determined from his B and V light curves its orbital period quoted above. The same light curves were employed by Williamon et al. (1978) and Maceroni et al. (1981) for determining the photometric elements using Russell-Merrill and W&D methods, respectively. Although the latter authors already suggested that the binary is an A-type W UMa system, the final proof was given by Hilditch & King (1986) on the basis of their spectroscopy that provided the reliable mass ratio $q = 0.354 \pm 0.012$. Their orbital solution leads to $V_0 = 20.6 \pm 1.9$ km s^{-1}, $K_1 = 88.5 \pm 2.2$ km s^{-1} and $a \sin i = 3.98 \pm 0.21\ R_\odot$. They also computed photometric elements from B and V light curves of Collins (1971), found $i = 76.2°$ and calculated absolute parameters of the components $M_1 = 1.93 \pm 0.21\ M_\odot$, $M_2 = 0.69 \pm 0.08\ M_\odot$, $R_1 = 2.05 \pm 0.11\ R_\odot$, $R_2 = 1.32 \pm 0.07\ R_\odot$.

We derived a new ephemeris of AQ Tuc from the compilation of minima times covering the interval of 28 years. The weight 1 was assigned to photographic minima published by Köhler & Schöffel (1965). The weight 10 was given to photoelectric minima published by Collins (1971) and two minima determined from our observations using Kwee & van Woerden's (1956) method. We added the normal minimum, which we derived from spectroscopic data published by Hilditch & King (1986) and minimum derived from the HIPPARCOS (ESA, 1997) data. All minima are listed in Table 1. The least-squares solution resulted in the light elements:

$$\begin{array}{llll} \mathrm{Min\ I} = \mathrm{HJD} & 2\,438257.231 & + 0.5948421 & \times E \\ & \pm 9 & \pm 13 & \end{array} \quad (1)$$

The last two (O-C) deviations from the fit are very large and suggest an apparent period change on a time scale comparable to the interval of observations.

2.2. AY Velorum

Eclipsing binary AY Vel (HD 70448, sp. type B9 (Popper, 1966); $m_{\rm pg}^{\rm max} = 9.46$ mag; $m_{\rm pg}^{\rm min\ I} = 9.9$ mag; $m_{\rm pg}^{\rm min\ II} = 9.7$ mag; $P = 1.6177$ days) was discovered as a β Lyrae variable by Hertzsprung (1937). He published photographic light curves from estimates of Johannesburg and Harvard plates and found the light elements: Min I = 26308.903 + 1.6176531$\times E$. Eggen (1978) obtained (unpublished) photoelectric observations of the object in 1976-77 remarking: "The light elements need correction as the minima are now occurring 0.15 of the period late". We determined one minimum using our photoelectric observations of AY Vel in 1969. The minimum was shifted by +0.129 of the period as regards the ephemeris of Hertzsprung (1937), in accordance with the change of the period found by Eggen. Thus, a new quadratic ephemeris was derived using the photographic minima times (weight 1) of Hertzsprung (1937) and photoelectric minimum (weight 10), determined from our observations using the Kwee & van

Woerden's (1956) method. All minima are listed in Table 2. The least-squares solution resulted in the light elements:

$$\text{Min I} = \text{HJD}\ \underset{\pm 2}{2\,415\,842.66} + \underset{\pm 5}{1.617640} \times E + \underset{\pm 30}{1.89\ 10^{-9}} \times E^2 \tag{2}$$

Table 1. Times of minimum light of AQ Tuc used for the least squares solutions

Epoch	HJD	O-C	Ref.	Epoch	HJD	O-C	Ref.
	2 400 000+				2 400 000+		
0.5	38257.502	-0.0253	1	746.5	38701.258	-0.0232	1
10.5	38263.49	0.0134	1	1279.5	39018.3303	-0.0017	2
67.5	38297.364	-0.0188	1	1288	39023.3827	-0.0040	2
87.5	38309.322	0.0447	1	3733	40477.7743	-0.0030	3
96	38314.322	-0.0139	1	3734.5	40478.6667	-0.0013	3
96	38314.367	0.0311	1	3738	40480.7482	-0.0018	3
138	38339.293	-0.0273	1	3743	40483.7227	-0.0039	3
646	38641.497	-0.0030	1	3746.5	40485.8046	-0.0040	3
736.5	38695.294	-0.0380	1	11800	45276.439	0.0718	2
736.5	38695.34	0.0080	1	17220	48500.3690	-0.0451	4

References: 1 - Köhler & Schöffel (1965), 2 - present work, 3 - Collins (1971), 4 - ESA (1997)

Table 2. Times of minimum light of AY Vel used for the least squares solutions. All minima except our last one were published by Hertzsprung (1937)

Epoch	HJD	Epoch	HJD	Epoch	HJD
	2 400 000+		2 400 000+		2 400 000+
0	15842.629	3392.5	21330.536	6468.5	26306.395
114.5	16027.866	3416	21368.523	6471	26310.368
251.5	16249.521	3493.5	21493.880	6471	26310.434
254	16253.537	3633	21719.546	6471	26310.500
269.5	16278.501	3641	21732.498	6479	26323.451
350	16408.851	4655	23372.858	6479	26323.472
471	16604.522	6113	25731.330	6524	26396.309
675	16934.557	6259.5	25968.374	6537	26417.270
675	16934.601	6262	25972.360	6537	26417.293
847	17212.792	6285	26009.555	6539.5	26421.281
876	17259.767	6296.5	26028.285	6539.5	26421.300
913	17319.590	6304	26040.311	6560.5	26455.216
1268	17893.862	6333	26087.272	6589	26501.188
1376	18068.552	6354	26121.217	6597.5	26515.219
2945.5	20607.563	6450	26276.502	7397.5	27809.299
3196.5	21013.501	6450	26276.524	15105.5	40278.35519
3284.5	21155.870	6450	26276.550		

3. Multicolour light-curves analysis

Table 3. Photometric elements and their probable errors σ (i - inclination; $q = m_2/m_1$ - mass ratio; Ω - surface potential; T_1, T_2 - polar temperatures; L_1, L_2 - luminosities of the components, u_1, u_2 - limb darkening coefficients, g - gravity darkening coefficient). $\sum w$(O-C)^2 is weighted sum of squares of residuals for all four light curves. Parameters not adjusted in the solution are denoted by a superscript "a".

Element		AQ Tuc	σ	AY Vel	σ
i [°]		75.89	0.18	72.16	0.08
q		0.354^a	–	3.0^a	–
Ω		2.5028	0.0034	6.6572	0.0042
r_1		0.494	0.001	0.4740	0.0004
r_2		0.316	0.001	0.2835	0.0004
Fill-out		0.366	0.015	-0.066	0.007
T_1 [K]		6900^a	–	10350^a	–
T_2 [K]		7048	13	9256	12
g		1.00^a	–	1.00^a	–
A		0.50^a	–	1.00^a	–
$u_1 = u_2$	V	0.61^a	–	0.40^a	–
	B	0.76^a	–	0.48^a	–
	L	0.68^a	–	0.52^a	–
	U	0.57^a	–	0.42^a	–
L_1	V	0.6967	0.0006	0.3629	0.0004
	B	0.6921	0.0007	0.3374	0.0003
	L	0.6891	0.0008	0.3289	0.0003
	U	0.6994	0.0005	0.3156	0.0002
$\sum w$(O-C)^2		0.017823	–	0.002449	–

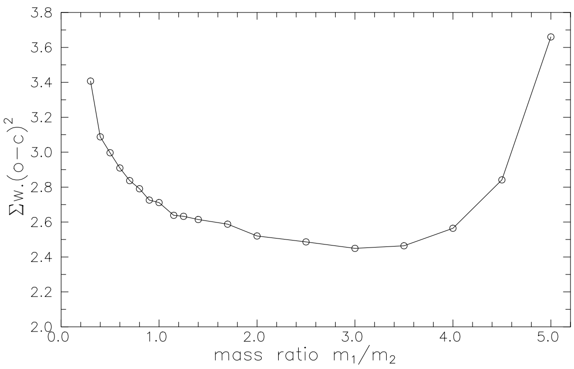

Figure 1. The χ^2 dependence on the mass ratio for AY Vel

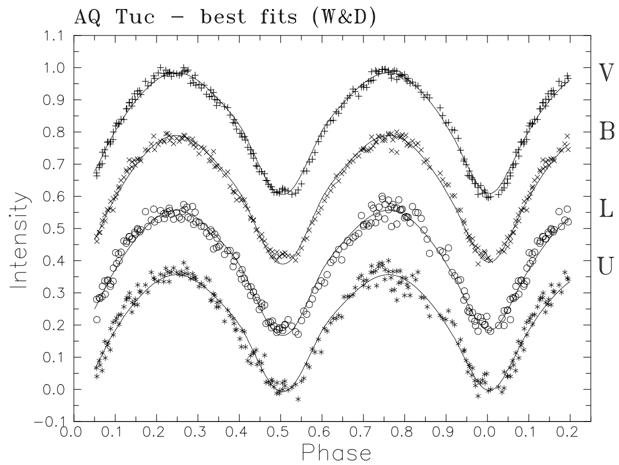

Figure 2. *VBLU* observations (in intensities) of AQ Tuc and their best fits. The light curves and fits are shifted by 0.2 in intensities for clarity

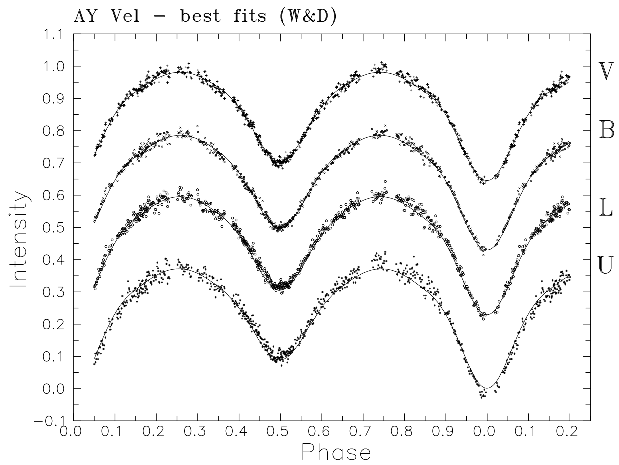

Figure 3. *VBLU* observations (in intensities) of AY Vel and their best fits. The light curves and fits are shifted by 0.2 in intensities for clarity

The photometric elements of AQ Tuc and AY Vel were determined using the W&D method and observations published by the authors (van Houten et al., 2001). At first the mode 3 for contact systems was employed. Synchronous rotation, zero eccentricity and approximate atmosphere model option were applied. Temperature of the primary components corresponding to their spectral type was accepted. For AY Vel, the hotter, but less massive component is denoted as the primary one. In order to decrease the number of free parameters, we assumed theoretically predicted values of limb darkening given by Al-Naimiy (1978), gravitational darkening and bolometric albedo given by Rucinski (1973). With these

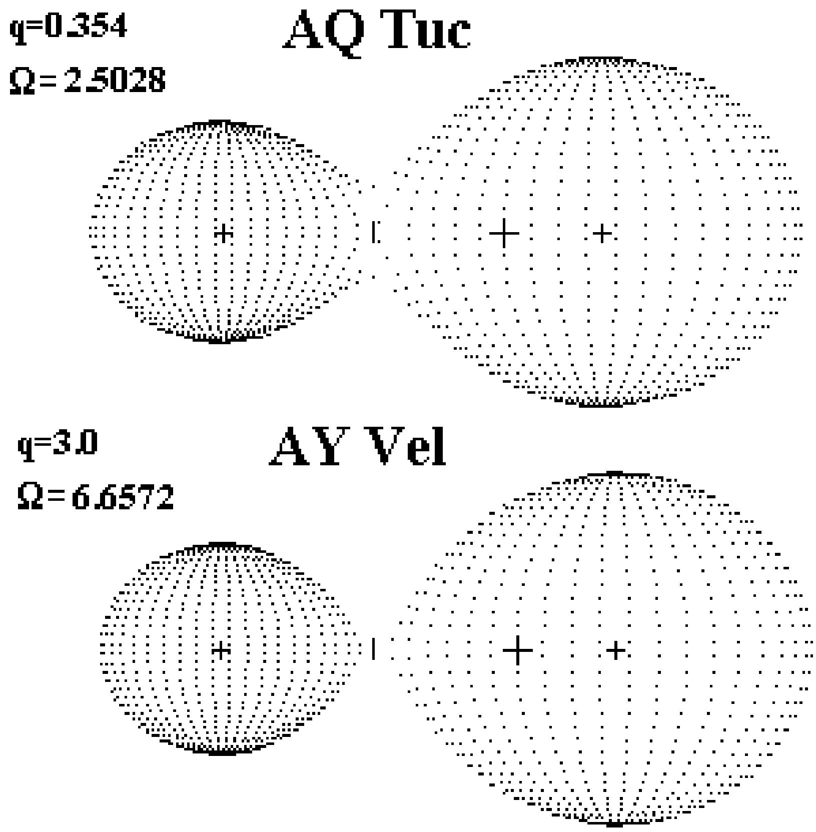

Figure 4. The 3D surfaces of AQ Tuc (top) and AY Vel (bottom)

assumptions, all four light curves in the $VBLU$ passbands were solved simultaneously. The differential corrections code was run until the output corrections were smaller than the probable errors σ of the elements. The differential corrections converged rather slowly. We had to perform more than 10 steps. While for AQ Tuc we accepted the mass ratio $q = 0.354$ from spectroscopy, for AY Vel we have solved the $VBLU$ light curves for several fixed values of mass ratio q in the interval 0.15 - 5.0. As shown in Fig. 1, the χ^2 reached the minimum around $q = 3$.

The temperature of the primary component of AY Vel $T_{eff} = 10350$ K (Popper, 1980) corresponding to its B9 spectral type indicates the presence of the radiative envelope. The accuracy of elements determination for AY Vel is adversely influenced by low inclination of the orbit, resulting in partial eclipses, while the system AQ Tuc probably exhibits short totality during the secondary minimum.

The resulting photometric elements of AQ Tuc and AY Vel with their probable errors are given in Table 3. The fits corresponding to these elements are shown in Figs. 2 and 3. The discrepancy between the fit and observations of AY Vel in the U passband (phases 0.75-0.9) is most probably caused by chromospheric activity or a hot spot in the system. The 3D surfaces for AQ Tuc and AY Vel, plotted using the Binary Maker 2.0 (Bradstreet, 1993), are depicted in Fig. 4.

4. Conclusions

It is obvious that our multicolour photoelectric light curves for both systems presented here are superior to all previously published photometric data. The photoelectric light curves of AY Vel are unique until today. The derived photometric elements for the contact system AQ Tuc supersede the elements found in the current literature. The spectroscopic elements published by Hilditch & King (1986) combined with our photometric elements (see Table 3) lead to the absolute radii of the components of AQ Tuc: $R_1 = 2.03{\pm}0.11\ R_{\odot}$ and $R_2 = 1.30{\pm}0.07\ R_{\odot}$. Our photometric elements of AY Vel for the optimal value of the mass ratio $q = 3.0$ leads to an "almost contact" configuration. Nevertheless, good spectroscopy of AY Vel is necessary to prove this conclusion.

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References

Al-Naimiy, H.M.: 1978, *Astrophys. Space Sci.* **53**, 181

Bradstreet, D.H.: 1993, *Binary Maker 2.0* , Dept. Phys. Sci., Eastern College, St. Davids, PA, U.S.A.

Collins, T.F.: 1971, *Inf. Bull. Var. Stars* , 575

Eggen, O.J.: 1978, *Astron. J.* **83**, 288

ESA: 1997, in*: The Hipparcos Catalogue* , ESA SP-1200

Hertzsprung, E.: 1937, *Bull. Astron. Inst. Nether.* **8**, 157

Hilditch, R.W., King, D.J.: 1986, *Mon. Not. R. Astron. Soc.* **223**, 581

Houk, N., Cowley, A.P.: 1975, *Michigan Spectral Catalogue* **1**, Dept. Astron., U. Michigan, Ann Arbor, U.S.A.

Köhler, U., Schöffel, E.: 1965, *Inf. Bull. Var. Stars* , 91

Kwee, K.K., van Woerden, H.: 1956, *Bull. Astron. Inst. Nether.* **12**, 237

Maceroni, C., Milano, L., Russo, G., Sollazzo: 1981, *Astron. Astrophys. Suppl. Ser.* **45**, 187

Popper, D.M.: 1966, *Astron. J.* **71**, 175

Popper, D.M.: 1980, *Ann. Rev. Astron. Astrophys.* **18**, 115
Rucinski, S.: 1973, *Acta Astron.* **23**, 79
Strohmeier, W.: 1964, *Inf. Bull. Var. Stars* , 51
van Houten, C.J., Chochol, D., Pribulla, T., Grygar, J.: 2001, *Contrib. Astron. Obs. Skalnaté Pleso* **31**, 61
Williamon, R.M., Collins, T.F., Chen, K.: 1978, *Astron. Astrophys. Suppl. Ser.* **34**, 207
Wilson, R.E.: 1992, *private comm.* ,
Wilson, R.E., Devinney, E.J.: 1971, *Astrophys. J.* **166**, 605
Wilson, R.E., Devinney, E.J.: 1973, *Astrophys. J.* **182**, 539