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Four-colour photometry of eclipsing binaries. XLI.

uvby light curves for AD Bootis, HW Canis Majoris, SW Canis Majoris, V636 Centauri, VZ Hydrae, and WZ Ophiuchi⋆,⋆⋆,⋆⋆⋆

J. V. Clausen[1], L. P. R. Vaz[2], J. M. García[3], A. Giménez[4,5], B. E. Helt[1], E. H. Olsen[1], and J. Andersen[1,6]

[1] Niels Bohr Institute, Copenhagen University, Juliane Maries Vej 30, 2100 Copenhagen Ø, Denmark
e-mail: `jvc@astro.ku.dk`
[2] Depto. de Física, ICEx, UFMG, CP 702 – 30.123-970 – Belo Horizonte, MG, Brazil
[3] Departamento de Física, E.U.I.T. Industriales, UPM, Ronda de Valencia 3, 28012 Madrid, Spain
[4] Laboratorio de Astrofísica Espacial y Física Fundamental, INTA, Apartado 50727, 28080 Madrid, Spain
[5] Research and Scientific Support Department, ESA, ESTEC, 2200 AG Nordwijk, The Netherlands
[6] Nordic Optical Telescope Scientific Association, Apartado 474, 38 700 Santa Cruz de La Palma, Spain

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ABSTRACT

Context. Accurate mass, radius, and abundance determinations from binaries provide important information on stellar evolution, fundamental to central fields in modern astrophysics and cosmology.
Aims. Within the long-term Copenhagen Binary Project, we aim to obtain high-quality light curves and standard photometry for double-lined detached eclipsing binaries with late A, F, and G type main-sequence components, needed for the determination of accurate absolute dimensions and abundances, and for detailed comparisons with results from recent stellar evolutionary models.
Methods. Between March 1985 and July 2007, we carried out photometric observations of AD Boo, HW CMa, SW CMa, V636 Cen, VZ Hya, and WZ Oph at the Strömgren Automatic Telescope at ESO, La Silla.
Results. We obtained complete *uvby* light curves, ephemerides, and standard *uvbyβ* indices for all six systems. For V636 Cen and HW CMa, we present the first modern light curves, whereas for AD Boo, SW CMa, VZ Hya, and WZ Oph, they are both more accurate and more complete than earlier data. Due to a high orbital eccentricity ($e = 0.50$), combined with a low orbital inclination ($i = 84\overset{\circ}{.}7$), only one eclipse, close to periastron, occurs for HW CMa. For the two other eccentric systems, V636 Cen ($e = 0.134$) and SW CMa ($e = 0.316$), apsidal motion has been detected with periods of 5270 ± 335 and 14 900 ± 3600 years, respectively.

Key words. stars: evolution – stars: fundamental parameters – stars: binaries: close – stars: binaries: eclipsing – techniques: photometric

1. Introduction

Detached, double-lined eclipsing binaries are well-known as the main source of accurate (1–2% or even better) data on stellar masses and radii. During the last two-three decades, such results have been published for about 50 systems within the main-sequence band (e.g. Andersen 1991; Ribas et al. 2000a; Southworth, private communication[1]), but some mass intervals, especially around and below 1 $M_\odot$, still need better coverage, as do parts of the main-sequence band at higher masses. A rich sample of accurate binary results is mandatory for detailed tests of stellar models in general, as well as for many specific astrophysical investigations (Ribas 2004, 2006b). Remarkable recent examples are the determination of the helium-to-metal enrichment ratio (Ribas et al. 2000a) and investigations of the mass dependence of convective core overshooting (Ribas et al. 2000b; Claret 2007).

In this paper, we present new accurate and complete *uvby* light curves for six detached double-lined eclipsing binaries having late A, F, and G-type main-sequence components. In addition, new spectroscopic observations for radial velocities and abundance analyses have been obtained, and detailed analyses for all the systems will be published separately (Clausen et al. 2008; Clausen et al., in prep.; Torres et al. in prep.).

When we decided to observe AD Boo (F6+G0) and SW CMa (A8), they were lacking modern photometric and spectroscopic observations. This was independently noticed by Lacy (1997a,b) who studied both systems, and by Popper (1998a) who obtained spectroscopic orbits for AD Boo, leading to masses for the components which differ somewhat from those by Lacy. For both systems, a new analysis based on new light curve and radial velocity observations, supplemented with a spectroscopic abundance analysis, is desirable.

HW CMa (A8) is only about 2′ distant from SW CMa and was discovered to be a double-lined spectroscopic binary during the radial velocity observations of SW CMa. It was later found to be eclipsing (Liu et al. 1992), and we decided to obtain complete light curves and spectroscopic orbits.

⋆ Based on observations carried out with the Strömgren Automatic Telescope (SAT) at ESO, La Silla, Chile.

⋆⋆ Appendix A is only available in electronic form at http://www.aanda.org

⋆⋆⋆ Tables 6–13 are only available in electronic form at the CDS via anonymous ftp to `cdsarc.u-strasbg.fr (130.79.128.5)` or via `http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/487/1081`

[1] http://www.astro.keele.ac.uk/~jkt/

V636 Cen (F8/G0V) was selected as part of a large-scale study of new systems with solar-type components (Clausen et al. 2001). We want e.g. to investigate a serious dilemma that appears to be present in the comparison of predictions from current stellar models with fundamental properties of known 0.7−1.1 $M_{\odot}$ eclipsing binaries (Popper 1997; Clausen et al. 1999b). Our results for V636 Cen support the presence of a real discrepancy – current models, adopting a fixed mixing length parameter calibrated on the Sun for envelope convection, do not predict identical ages for the two components (Larsen 1998; Clausen et al., in prep.). A similar case, V1061 Cyg, was presented by Torres et al. (2006). See also Ribas (2006a) for eclipsing binaries with K and M type components and Morales et al. (2007) for single active late-K and M stars.

VZ Hya (F5) and WZ Oph (F8) are well known systems included by Popper (1980) in his critical review of stellar masses, but excluded by Andersen (1991), since the available results did not fulfill his 2% criteria for masses and radii. We therefore decided to provide the new observations needed for the determination of more accurate dimensions.

In the following, we first give a general description of the observations, the basic photometric reduction, and the light curve formation (Sect. 2), and we then present the results for the individual systems (Sects. 3–8). Throughout the paper, the component eclipsed at the deeper eclipse at phase 0.0 is referred to as the primary, and the other as the secondary component.

2. Observations and photometric reduction

The differential *uvby* light curve observations were obtained with the Strömgren Automatic Telescope (SAT) at ESO, La Silla and its 6-channel *uvbyβ* photometer during several campaigns between March 1985 and March 2002. For SW CMa and V 636 Cen, more eclipse observations were carried out between January 2001 and July 2007 to follow the apsidal motion of their orbits. In addition, on many nights we observed the binaries and the comparison stars together with a large sample of *uvby* and *β* standard stars in order to obtain homogeneous standard *uvbyβ* indices, primarily for the determination of effective temperatures and interstellar reddening. Details on the photometer and the (semi)automatic mode of the telescope are given by Olsen (1993, 1994b).

2.1. Light curve observations

The differential *uvby* observations were, depending on the orbital phase of the binary, carried out either continuously over several hours or as shorter series. Automatic centering within a circular diaphragm of 13″ (HW CMa, part of light curves; SW CMa, light curves; V636 Cen, light curves) or 17″ (AD Boo, light curves; HW CMa, part of light curves; SW CMa, additional eclipse observations; V636 Cen, additional eclipse observations; VZ Hya, light curves; WZ Oph, light curves) diameter was used throughout. Nearly all observations were performed at an airmass less than 2.1, and the few at higher airmass passed additional quality checks.

Two or three comparison (C) stars, preferably matching the spectral type of the binary and positioned on the sky within a few degrees from it, were adopted for each candidate. They were in general selected from systematic searches in the extensive *uvbyβ* catalogues published by Olsen (1983, 1988, 1993, 1994a,b), and unpublished *β* photometry (cf. Olsen 1994b), avoiding known and suspected variables, as well as most visual binaries.

Table 1. rms errors of the magnitude differences (instrumental system) between the comparison stars in units of 0.1 mmag. *N* is the total number of magnitude differences.

Objects	*N*	*y*	*b*	*v*	*u*
AD Boo					
HD 128369, HD 129430 (C1, C2)	196	47	45	46	68
HD 128369, HD 128185 (C1, C3)	164	58	57	62	85
HD 129430, HD 128185 (C2, C3)	141	67	59	66	81
HW CMa & SW CMa					
HD 56341, HD 53123 (C1, C2)	536	54	45	48	54
V636 Cen					
HD 124829, HD 125444 (C1, C2)	388	51	52	54	65
VZ Hya					
HD 72528, HD 71615 (C1, C2)	328	37	35	37	59
HD 72528, HD 72782 (C1, C3)	333	43	36	41	61
HD 71615, HD 72782 (C2, C3)	335	43	33	36	57
WZ Oph					
HD 155193, HD 154931 (C1, C2)	288	40	38	39	61

The observations were carried out in C1-binary-C2-binary-C3-binary-C1-etc. or C1-binary-C2-binary-C1-etc. sequences, allowing accurate magnitude differences to be formed, even if one of the comparisons were later found to be variable. In the case of HW CMa and SW CMa, which are close on the sky and of similar spectral types, we often used C1-SW CMa-C2-HW CMa-C1-etc. An observation consisted in general of three individual integrations, each with an integration time of 10−60 s, and sky measurements were taken at least once per sequence, normally at a fixed position close to the binary. The resulting rms contributions from photon statistics, including the sky contributions, were in general kept at 5 mmag or lower. The Heliocentric Julian Date (HJD) given for an observation refers to the midpoint of the time interval covered by the integrations.

2.2. Photometric reduction and formation of light curves

Linear extinction coefficients were determined individually for each night from the observations of comparison stars and other constant stars. Whenever appropriate, linear or quadratic corrections for drift during the night, caused by changes in the sky transparency and/or the influence of temperature variations on the uncooled photomultipliers, were also applied.

The *uvby* instrumental system of the SAT, where the same spectrometer, including its filters, most of the photomultipliers, and the photon counting system have been used since 1985, has proved to be very stable (e.g. Olsen et al., in prep.). Therefore, transformation of the light curve observations, e.g. to the standard *uvby* system, is not needed, and the light curves are generated in the instrumental system.

Differential magnitudes were formed for each binary observation from the two comparison star observations closest in time. All comparison star observations were used with C2 and C3, if observed, first shifted to the level of C1. A careful check of the constancy of all two/three stars was performed. For each binary, typical rms errors per light curve point are close to those listed in Table 1 for the magnitude differences between the corresponding comparison stars.

Ephemerides were calculated from published and new times of minima, listed in Tables A.1–A.8. For most of the systems, our literature searches were significantly supplemented by the compilations by Kreiner (private communication); see

Table 2. New photometric data for the eclipsing binaries and the comparison stars. For the eclipsing binaries, the *uvby*β information is the mean values outside eclipses, see also Fig 1. N is the total number of observations used to form the mean values, and σ is the rms error (per observation) in mmag. See also Table 3.

Object	Sp. type	V	σ	$b-y$	σ	m_1	σ	c_1	σ	N (*uvby*)	β	σ	N (β)
AD Boo	F6+G0	9.379	7	0.322	4	0.186	10	0.431	14	14	2.647	8	16
HD 128369	F5	7.959	8	0.281	3	0.149	8	0.455	11	17	2.640	8	15
HD 129430	G8III-IV	6.402	5	0.581	2	0.311	6	0.385	9	5	2.573	3	3
HD 128185	F8V	7.925	11	0.373	5	0.183	10	0.402	12	13	2.606	8	14
HW CMa	A8	9.190	6	0.128	3	0.228	10	0.839	14	6	2.853	10	95
SW CMa	A8	9.149	9	0.094	8	0.210	9	1.013	7	12	2.865	10	104
HD 56341	A0V	6.358	8	–0.001	2	0.127	5	1.098	7	17	2.861	6	53
HD 53123	B9V	7.156	13	–0.020	5	0.112	7	0.878	9	10	2.805	8	51
HD 55271	B5V	6.950	14	0.005	2	0.060	8	0.290	6	2	2.520	10	9
V636 Cen	F8/G0V	8.704	11	0.410	4	0.205	7	0.285	18	16	2.594	12	57
HD 124829	F2	8.466	6	0.266	4	0.143	6	0.516	6	16	2.682	6	16
HD 125444	A6V	7.557	12	0.111	4	0.176	7	0.918	5	10	2.814	9	34
VZ Hya	F5+F6	8.953	4	0.300	4	0.166	7	0.389	9	9	2.640	9	83
HD 72528	F7V	7.330	3	0.337	2	0.177	3	0.388	6	8	2.628	8	33
HD 71615	F0	7.946	3	0.233	4	0.176	7	0.516	8	9	2.692	8	34
HD 72782	A2	7.641	10	0.109	2	0.183	3	0.947	11	5	2.831	7	61
WZ Oph	F8	9.096	7	0.366	5	0.145	7	0.375	5	11	2.627	8	11
HD 155193	F8IV	7.007	7	0.338	4	0.185	5	0.405	6	12	2.623	7	12
HD 154931	G0	7.258	7	0.384	4	0.189	6	0.361	4	12	2.600	8	13

Table 3. Published photometric data for the eclipsing binaries and the comparison stars. N is the total number of observations used to form the mean values, and σ is the rms error (per observation) in mmag.

Object	Reference	V	σ	$b-y$	σ	m_1	σ	c_1	σ	N(*uvby*)	β	σ	$N(\beta)$
AD Boo	HH75	9.370		0.348		0.153		0.419		1			
	L02	9.399		0.335		0.161		0.446		1	2.645		1
HD 128369	O83	7.965	3	0.298	3	0.122	5	0.453	5	5	2.643	2	3
HD 129430	O93	6.401	4	0.590	2	0.293	2	0.413	3	1			
HD 128185	O83	7.925	4	0.387	6	0.163	2	0.420	3	4	2.604	8	3
SW CMa	L02	9.121		0.108		0.221		1.026		1	2.860		1
	WK83	9.15		0.095		0.209		1.036		1	2.863		1
V636 Cen	O83, OP84	8.713	6	0.407	5	0.220	9	0.259	7	1	2.601	7	1
	O85	8.706	7	0.426	3	0.197	5	0.276	8	3			
	O93	8.720	2	0.414	3	0.205	6	0.284	8	3			
VZ Hya	WK83	9.660	30	0.333	1	0.146	1	0.368	4	2	2.624	7	2
HD 72528	O83, OP84	7.335	6	0.328	4	0.181	6	0.381	6	1	2.617	7	1
HD 71615	O83, OP84	7.949	5	0.249	4	0.141	6	0.520	7	1	2.685	7	1
HD 72782	O83	7.648	6	0.103	5	0.193	9	0.947	15	2			
	J96										2.840	9	2
WZ Oph	HH75	9.095	7	0.377	32	0.119	42	0.367	10	2			
HD 155193	O83	7.010	5	0.352	3	0.168	4	0.419	4	1			
	O94	7.020	4	0.350	3	0.163	4	0.429	4	1			
	P69	7.020		0.348		0.168		0.418		2			
HD 154931	O83	7.263	9	0.385	7	0.192	0	0.372	7	2			
	O94	7.251	4	0.396	3	0.167	4	0.378	5	1			
	P69	7.250		0.392		0.179		0.365		2			

References are: HH75 = Hilditch & Hill (1975); J96 = Jordi et al. (1996); O83 = Olsen (1983); O93 = Olsen (1993); O94 = Olsen (1994b); OP83 = Olsen & Perry (1984); P69 = Perry (1969); WK83 = Wolf & Kern (1983); L02 = Lacy (2002). The two WK83 observations of VZ Hya are done near phase 0.00. Two WK83 observations of SW CMa inside eclipses have not been included. Two HH75 observations of WZ Oph inside eclipses have not been included.

Kreiner et al. (2001)[2] for further details. The new times of minima have been calculated using the method of Kwee & van Woerden (1956), except for a few cases which could only be determined by 2nd order polynomial fits to the (few) observations.

The individual light curves are shown in Figs. 2–4, 6, 8, and 9, and are presented in Tables 6–11. The additional eclipse observations of SW CMa and V636 Cen are presented in Tables 12 and 13. These eight tables will only be made available in electronic form.

2.3. Standard *uvby*β photometry

New standard *uvby*β indices for the six eclipsing binaries outside eclipses and for all comparison stars are listed in Table 2, and the phase distributions of the β observations are shown in Fig. 1.

Part of the standard photometry was obtained at SAT on several nights in 1987–1993, where the binaries and the comparison stars were observed together with a large sample of *uvby*

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[2] `http://www.as.ap.krakow.pl/ephem`

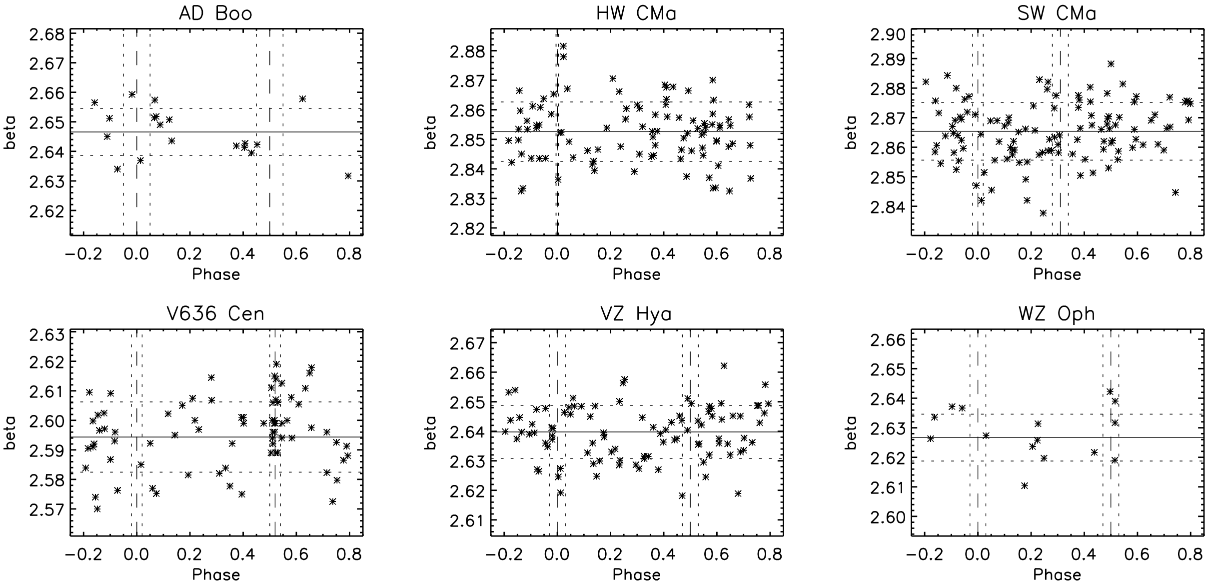

Fig. 1. Phase distribution of the β observations, see Table 2. The horizontal lines represent the mean value of β outside eclipses (*solid*) and the rms error of one observation (*dotted*). The vertical lines show the phase intervals of the eclipses (*dashed*, central eclipses) and their duration (*dotted*).

and β standard stars. The basic reduction and transformation to the standard system was done as described by Olsen (e.g. 1993, 1994b). Furthermore, some of the binaries and their comparisons were also included in the long term search for new solar-type binaries, carried out at SAT since 1994, and additional standard photometry from many nights has been obtained from this project; see Olsen et al. (in prep.) for details.

For comparison, we have listed published *uvbyβ* indices for some of the binaries and their comparison stars in Table 3. Individual differences larger than the quoted errors occur; we have used the new homogeneous results in Table 2 for the binary analyses.

3. AD Boo

AD Boo = BD +25°2800 = BV 135 was discovered by Strohmeier et al. (1956) to be an eclipsing binary, and times of minima, a linear ephemeris, and a photographic light curve were published by Strohmeier et al. (1963; orbital period half the correct value). A large number of times of minima of AD Boo has later been observed (see Tables A.1 and A.2), and an improved ephemeris and a visual light curve was published by van Buren (1974; orbital period half the correct value). Koch (1974) presented blue CN-absorption measurements, and Zhai et al. (1982, 1983) obtained photoelectric B, V light curves and derived the true orbital period of about $2\overset{\mathrm{d}}{.}07$.

Lacy (1985) discovered AD Boo to be a double-lined spectroscopic binary, and later (Lacy 1997a) he presented absolute dimensions based on spectroscopic elements from 23 KPNO CCD spectra and photometric elements derived from EBOP (Popper & Etzel 1981) re-analyses of the light curves (normal points) by Zhai et al. (1982). AD Boo was included by Popper in his extensive study of F−K binaries (e.g. Popper 1993; Popper & Jeong 1994; Popper 1996), and he obtained a very accurate spectroscopic orbit based on 31 Lick CCD echelle spectra (Popper 1998a). He also pointed out that the components of AD Boo have the largest differences in mass and radius among well-studied systems in its mass range (1.4 and 1.2 $M_\odot$, 1.6 and 1.2 $R_\odot$). Hence, it may provide stringent tests of stellar models.

3.1. *uvby* light curves

Complete *uvby* light curves containing 652 points in each colour were observed on 42 nights during five periods between March 1988 and March 1992 (JD 2 447 234–JD 2 448 695). HD 128185, HD 128369, and HD 129430 = HR 5483 were selected as comparison stars; see Tables 1–3 for further information. The last two stars were found to be constant within the observational accuracy of a few mmag during our observations, whereas signs of a slight long term variability at the level of about ±5 mmag were noticed for HD 128185, and it was consequently decided to reject it for the calculations of the final light curves. We have not studied the possible variations of HD 128185 further; our photometric data for it are available on request.

The light curves of AD Boo are shown in Fig. 2. The eclipses have been covered several times and most out-of-eclipse phases at least twice. The accuracy per point is about 0.005 mag (*vby*) and 0.007 mag (*u*), but comparison of the data from the five periods reveals that at some phases, systematic differences in the light level exist, of the order of 0.01–0.03 mag, and increasing from y to u. Especially the observations during eclipses from 1989 are systematically fainter. The scatter is probably caused by slight activity of the cooler secondary component, since a weak emission feature in the Ca II H and K lines is seen at the position of the secondary component on high-resolution spectra of AD Boo (Clausen et al. 2008). Zhai et al. (1982) also noticed scatter in their B and V light curves, which were obtained from April to June 1981, but at a much higher level of about 0.075 mag, compared to their observing error of about 0.02 mag.

The new *uvby* light curves confirm that AD Boo consists of two well-detached and rather different stars in a circular orbit, and our photometric analysis reveals that the secondary eclipse is in fact total.

3.2. Ephemeris

Four times of primary minimum and two of secondary, derived from the *uvby* observations, are listed in Tables A.1 and A.2 together with 130 published times.

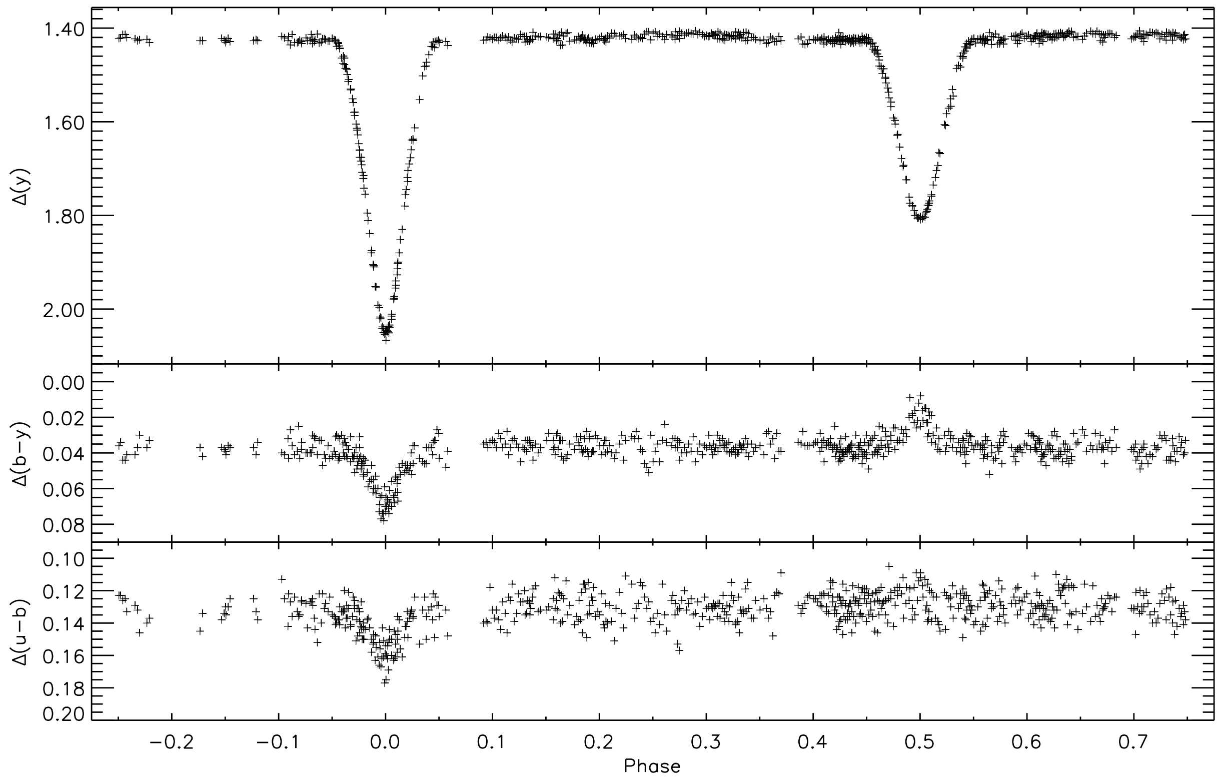

Fig. 2. y light curve and $b-y$ and $u-b$ colour curves (instrumental system) for AD Boo.

The linear ephemeris given in Eq. (1) was computed by least squares based on all available visual, photographic, and photoelectric/CCD times of eclipses, assuming a circular orbit.

$$\text{Min I} = \begin{array}{c} 2\,449\,311.43169 \\ \pm 22 \end{array} + \begin{array}{c} 2\overset{\mathrm{d}}{.}06880704 \\ \pm 17 \end{array} \times E \qquad (1)$$

Weights were assigned to the observations based on the individual uncertainties, when available. Typically the visual and photographic minima have no published uncertainties, so those were determined iteratively based on the residuals from the fit, in such a way as to achieve a reduced χ^2 of unity for each type of observation. Similarly, scale factors were determined for the photoelectric/CCD measurements so as to yield a reduced χ^2 of unity, separately for the primary and secondary minima, since they can have different precisions due to the different depth of the eclipses.

Separate least squares fits to all primary and secondary times yield identical periods within errors, and again within errors the same ephemeris is obtained from the subset of photoelectric and CCD data. The method of Lafler & Kinman (1965) applied to the *uvby* eclipse observations also confirms the period.

Zhai et al. (1983) derived a slightly longer period of $2\overset{\mathrm{d}}{.}0688112 \pm 0.0000002$ from their times of minima and those listed by van Buren (1974), and their ephemeris was used by Lacy (1997a) and Popper (1998a). We see, however, no clear signs of period changes from the data listed in Tables A.1 and A.2.

4. HW CMa

HW CMa = HD 54549 was discovered by Liu et al. (1992) to be a double-lined eclipsing binary in a highly eccentric orbit ($P = 21\overset{\mathrm{d}}{.}1$, $e = 0.5$). Minimum masses of 1.74 and 1.80 $M_\odot$ were determined, and a shallow eclipse (about 0.13 mag deep) lasting for about 5 h (0.010 in phase) was detected at conjunction, which occurs close to periastron. The star eclipsed is the less massive one. At apastron, the separation between the components is about three times larger, and no eclipse is seen around the predicted phase (0.517). This is due to the high orbital eccentricity, combined with a low orbital inclination ($i = 84\overset{\circ}{.}7$). Houk & Smith-Moore (1988) classify HW CMa as A1 III, but CfA spectra and *uvby* photometry reveal that the components are almost identical unevolved main-sequence stars near A8.

4.1. *uvby* light curves

The *uvby* light curves, which contain 414 points in each colour, were observed on 53 nights between February 1989 and March 2002 (JD 2 447 576–JD 2 452 335). The observations by Liu et al. (1992), with the same system, have been included. HW CMa is only about 2′ distant from SW CMa and of similar spectral type. Therefore, we have used the same comparison stars, HD 56341 = HR 2755 and HD 53123, and as mentioned in Sect. 2.1 HW CMa was often observed in series which also included SW CMa. For the October 2001−March 2002 period, a third star HD55344 was added as a further check of the comparison stars, which were found to be constant within the observational accuracy; see Tables 1−3 for further information.

The light curves are shown in Fig. 3. The eclipse at phase 0.0 was observed on three nights, and the expected interval near phase 0.517 for the other eclipse, which should last significantly longer, was covered closely on one night with a few additional observations from other nights. As mentioned above, no sign of an eclipse is, however, seen. As expected, the light curves are essentially constant outside eclipse, and no significant colour changes are seen during the eclipse, where ~20% of the light of the primary component is blocked.

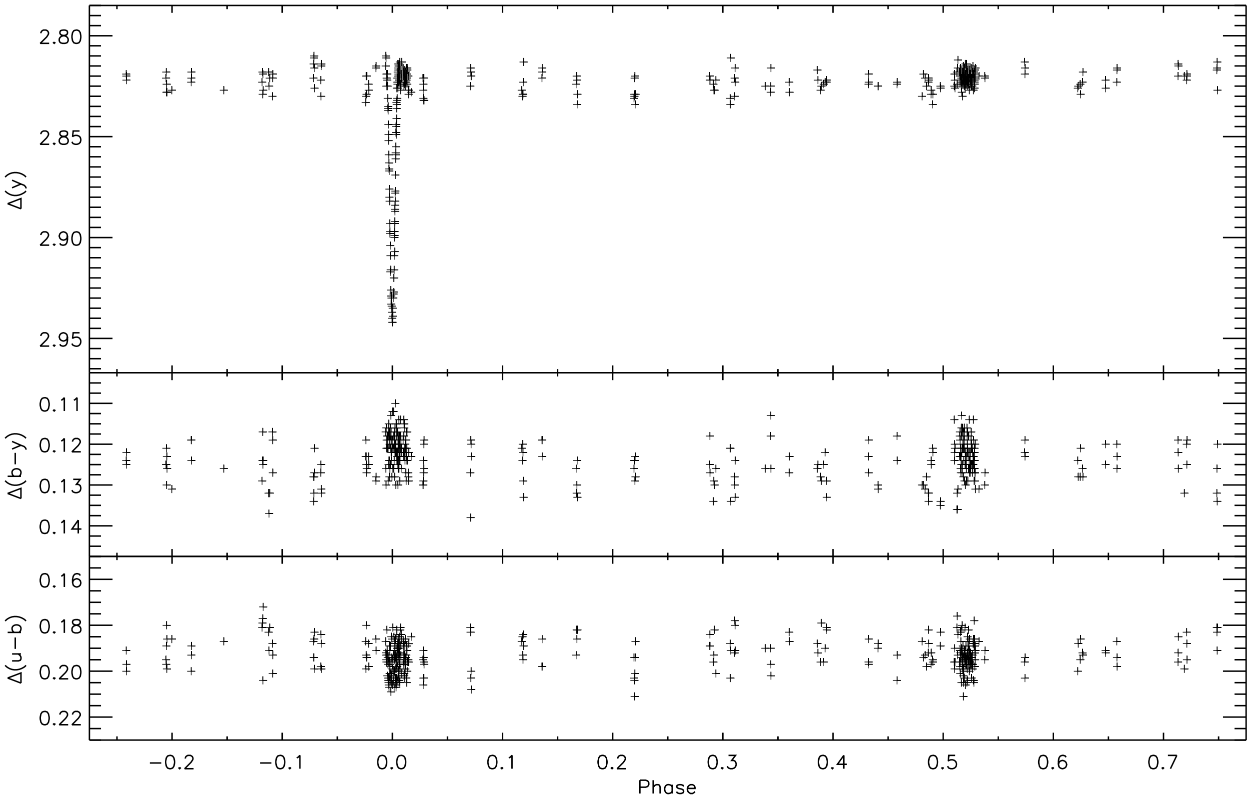

Fig. 3. y light curve and $b-y$ and $u-b$ colour curves (instrumental system) for HW CMa.

4.2. Ephemeris

Two minimum times, separated by 170 epochs, have been determined from the *uvby* observations; see Table A.3. This limited material yields the following linear ephemeris for HW CMa:

$$\text{Min I} = \underset{\pm 4}{2\,452\,279.6787} + \underset{\pm 33}{21\overset{\text{d}}{.}1178329} \times E \tag{2}$$

For comparison, Liu et al. (1992) derived a period of $21\overset{\text{d}}{.}1178 \pm 0\overset{\text{d}}{.}0005$, and the spectroscopic orbit based on the CfA velocities, which cover 178 cycles, gives $21\overset{\text{d}}{.}11790 \pm 0\overset{\text{d}}{.}00025$. Since the orbit is highly eccentric, apsidal motion is expected to be present, although with a long period due to the large separation between the components and the correspondingly small relative radii. The orbital parameters and estimated stellar dimensions yield a theoretically predicted period of about 90 000 yr.

5. SW CMa

SW CMa = HD 54520 = HIP 34431 was discovered by Hoffmeister (1932) to be an eclipsing binary, and Florja (1937) observed it visually and determined its ephemeris (Min = 2 426 709.324 + $10\overset{\text{d}}{.}092 \times E$). The period is close to the correct value, but today we know that the epoch corresponds to secondary eclipse. Floja's visual light curve shows only one eclipse, and he therefore speculates whether one of the only two times where Hoffmeister found a minimum, which does not fit the ephemeris, is wrong. Again, today we know that this observation is correct and corresponds to the primary minimum.

Struve (1945) found SW CMa to be a double-lined spectroscopic binary with ≈2 $M_\odot$ components in a very eccentric orbit ($e = 0.5$; significantly higher than the correct value of about 0.3). Later, a photographic light curve and times of minima, based on the old Sonneberg plates used by Hoffmeister, were presented by Wenzel (1952), and several additional times of minima are available in the literature (see Table A.4).

Popper (1965) mentioned SW CMa as one of several southern late B to early A systems that should be studied, and, using modern detectors, Lacy (1984) found narrow, deep lines of nearly equal strength for the components, and encouraged photoelectric observers to obtain accurate light curves. *uvbyβ* indices have been published by Wolf & Kern (1983), and *UBV* indices by Lacy (1992). SW CMa was included by Giménez (1994) in his list of eccentric binaries that should be monitored photometrically in order to study apsidal motion, and finally Lacy (1997b) determined absolute dimensions from analyses of *UBV* light curves observed at CTIO 1993−95 and coudé spectra observed at McDonald and KPNO 1982−89. His analysis reveals that SW CMa consists of two somewhat different components (2.2 and 2.0 $M_\odot$, 3.0 and 2.5 $R_\odot$) which have evolved to the upper part of the main-sequence band.

5.1. uvby light curves

Complete *uvby* light curves containing 820 points in each colour were observed on 89 nights during five periods between February 1987 and March 1992 (JD 2 446 825–JD 2 448 689). As mentioned in Sect. 2.1, SW CMa was often observed in series which also included HW CMa. For the 1987 observations, we selected HD 55271 and HD 56341 = HR 2755 as comparison stars, and in addition HD 53123 was observed frequently on each night. None of the stars shows any sign of variability within the observational accuracy of a few mmag; see Tables 1 and 2. However, HD 55271 = ADS 5863A = WDS 07113-2148A (A-BC: $\rho = 13\overset{''}{.}6$, $\Delta m = 1.3$, Worley & Douglass 1997) is a member of a double star, and automatic centering of it proved to

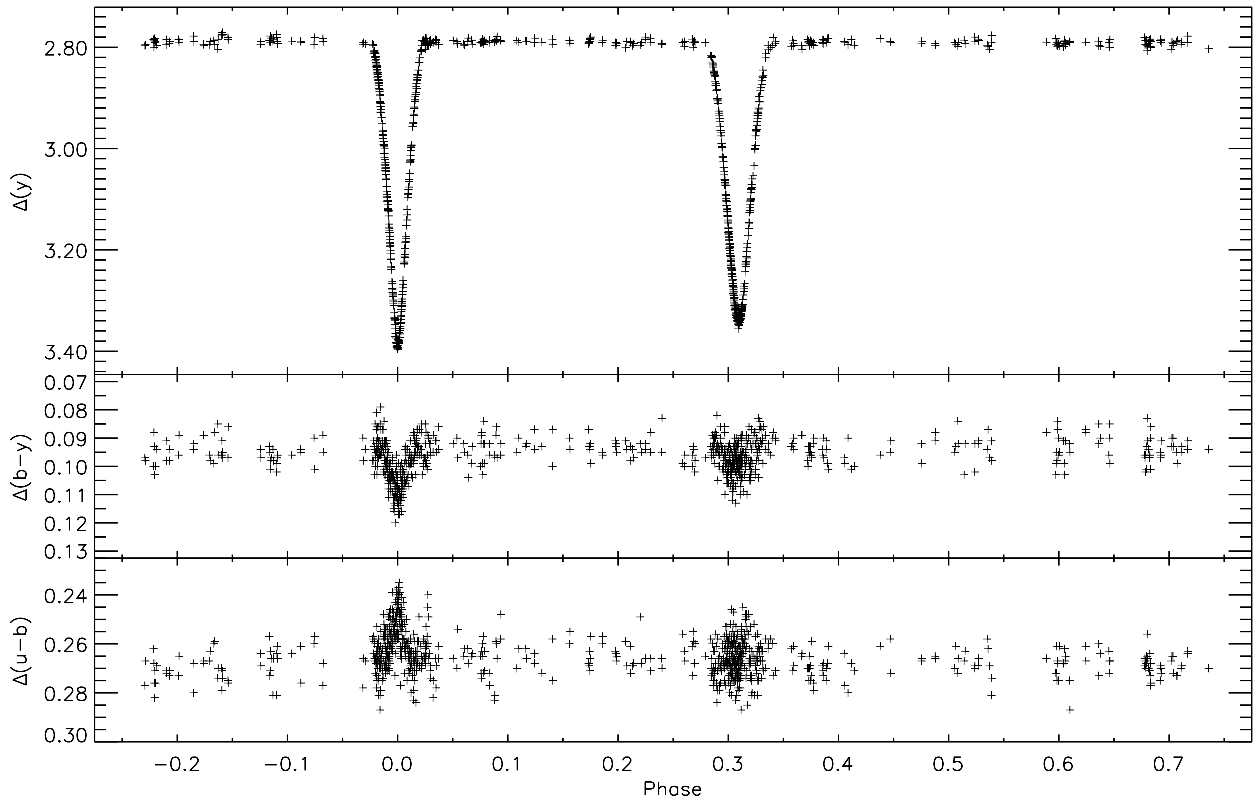

Fig. 4. y light curve and $b-y$ and $u-b$ colour curves (instrumental system) for SW CMa.

be less precise than desirable due to the companion. HD 55271 was therefore rejected as comparison for the 1988−92 observations and replaced by HD 53123. We have used the HD 56341 and HD53123 observations for calculation of the light curves.

The new *uvby* light curves, which are shown in Fig. 4, contain about twice the number of points per band as the *UBV* light curves by Lacy (1997b), and they are of at least the same photometric quality. Furthermore, they cover the orbit better, especially with respect to the shoulders of the minima, and this allows more accurate photometric elements to be determined. The eclipses have been covered several times and most out-of-eclipse phases at least twice. In addition, eclipse observations were made January−February 2002, October 2005, and December 2006 in order to establish more times of minima and investigate whether apsidal motion could be detected; see below.

5.2. Ephemeris and apsidal motion

Five times of primary minimum and six of secondary minimum, derived from the *uvby* observations, are given in Table A.4 together with 26 published times. Weighted (weight proportional to the square of the inverse rms) least squares fits to all times of primary and secondary minima yield nearly identical periods of $10\overset{\mathrm{d}}{.}091985 \pm 0\overset{\mathrm{d}}{.}000002$ and $10\overset{\mathrm{d}}{.}091981 \pm 0\overset{\mathrm{d}}{.}000003$, respectively, whereas adopting equal weights leads to slightly larger values of $10\overset{\mathrm{d}}{.}092003 \pm 0\overset{\mathrm{d}}{.}000008$ and $10\overset{\mathrm{d}}{.}091999 \pm 0\overset{\mathrm{d}}{.}000005$. However, the derived linear ephemerides do not represent the observed times very well. Ziegler (1965) derived $10\overset{\mathrm{d}}{.}091948$, which was adopted by Lacy (1997b). If only the photoelectric times of minima are fitted, periods of $10\overset{\mathrm{d}}{.}091983 \pm 0\overset{\mathrm{d}}{.}000001$ and $10\overset{\mathrm{d}}{.}091977 \pm 0\overset{\mathrm{d}}{.}000002$ are obtained from primary and secondary eclipses, respectively.

Table 4. Apsidal motion parameters for SW CMa derived from the photoelectric times of minima.

Parameter	Value and rms error
i (°)	88.6 (assumed)
e	0.316 (assumed)
T_0	2 446 828.7512 ± 0.0006
$P_{\mathrm{anomalistic}}$ (d)	10.091997 ± 0.000005
P_{sidereal} (d)	10.091978
ω_0 (°)	163.52 ± 0.10
ω_1 (°/cycle)	0.00067 ± 0.00021
U (yr)	14 900 ± 3600

Since the orbit of SW CMA is eccentric ($e \approx 0.3$), apsidal motion should be present, as also discussed by Lacy (1997b), who found a poorly determined apsidal motion period of several thousand years. We now have more precise times of minima available and derive the apsidal motion parameters presented in Table 4 from a weighted least squares method, following the formalism by Giménez & Garcia-Pelayo (1983) and Giménez & Bastero (1995). The orbital inclination i and eccentricity e were fixed to the values derived from the photometric analysis (Torres et al., in prep.). As seen, also in Fig. 5, a slow but significant motion has been detected, but the apsidal motion period is still very uncertain, although the value obtained is in good agreement with predictions from stellar models. For more precise apsidal motion information, SW CMa should be monitored regularly in the coming decades.

The detected apsidal motion leads to an insignificant phase shift of the secondary eclipse compared to the primary eclipse of only −0.00012 during the 1987−92 *uvby* light curve

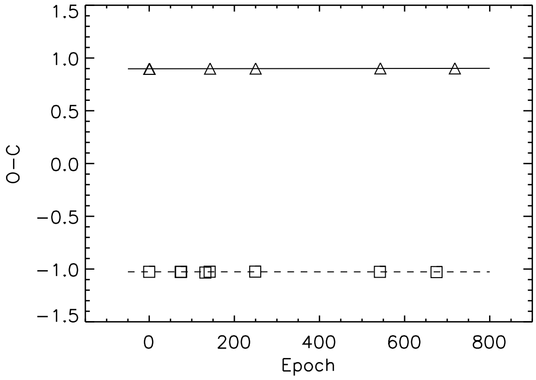

Fig. 5. Apsidal motion for SW CMa. O−C are the residuals (days) from the linear part of the apsidal motion ephemeris defined by the parameters given in Table 4. The full and dashed curves represent predictions from the apsidal motion parameters for primary (triangles) and secondary (squares) eclipses, respectively. Only the photoelectric observations are shown.

observations. Therefore, a linear ephemeris can safely be used for the light curve analysis, and we adopt

$$\text{Min I} = \underset{\pm 1}{2\,446\,829.6482} + \underset{\pm 5}{10\overset{\mathrm{d}}{.}091988} \times E \tag{3}$$

which has been derived from the 1982−87 times of minima. Secondary eclipses occur at phase 0.309. For comparison, the method of Lafler & Kinman (1965) applied to the 1987−92 *uvby* eclipse observations gives a period of $10\overset{\mathrm{d}}{.}091982$.

The 2002–2006 *uvby* eclipse observations have not been included in the light curve analyses, since their phase shifts are larger.

6. V636 Cen

From 276 visual (1952−53) and 282 photographic (1935−38, 1952−53) observations, Hoffmeister (1958) reported V636 Cen = HD 124784 = HIP 69781 to be a $4\overset{\mathrm{d}}{.}3$ period G0 eclipsing binary, and he gave a linear ephemeris and seven times of minima. Later, Popper (1966) obtained two 22 Å/mm spectra and found sharp but single lines. Today V636 Cen is known to be double-lined, but the lines of the secondary component are much fainter than those from the primary. Dworak (1973) pointed out that V636 Cen is within 100 pc of the Sun, and it was included in the list by Dworak & Oblak (1989) of 95 such eclipsing binaries selected for Hipparcos observations. The parallax determined by Hipparcos (ESA 1997) is 15.36 ± 1.12 mas, corresponding to a distance of only 65 pc. With accurate absolute dimensions becoming available, V636 Cen can therefore be added to the (short) list of eclipsing binaries useful for the definition of the radiative flux scale (Popper 1998b).

A preliminary analysis of V636 Cen, based on the *uvby* light curves presented here and complete spectroscopic orbits from CORAVEL radial velocity measurements has been done by Larsen (1998). She finds that V636 Cen is one of the few well studied systems with components in the 0.7−1.1 $M_\odot$ range; preliminary masses are 1.04 and 0.85 $M_\odot$, respectively. Furthermore, V636 Cen is well detached, and such systems are important for detailed tests of stellar models around and especially below 1 $M_\odot$.

6.1. uvby light curves

uvby light curves, containing in total 853 points in each colour, were observed on 76 nights during six periods between March 1985 and April 1991 (JD 2 446 144–JD 2 448 377). HD 124829 and HD 125444 were selected as comparison stars, see Tables 1–3 for further information, and they were both found to be constant within the observational accuracy of a few mmag during our observations.

The light curves of V636 Cen are shown in Fig. 6, and variations due to surface activity (from spots) are clearly seen from the *uvby* observations. However, the large number of observations obtained during some of the seasons allows a detailed study of the activity and its influence on the accuracy of the photometric elements (Larsen 1998). As seen, V636 Cen consists of two well detached components of very different surface fluxes in an eccentric orbit ($e \approx 0.13$).

Further eclipse observation were made January 2002–July 2007. They have been used in the apsidal motion analysis presented below, but not in the light curve analyses.

6.2. Ephemeris and apsidal motion

Nine times of primary and nine of secondary minimum, derived from the *uvby* observations, are given in Table A.5 together with eight published times of primary minimum (none available for the secondary minimum). Weighted (weight proportional to square of inverse rms) least squares fits to all times of primary and secondary minima yield significantly different periods of $4\overset{\mathrm{d}}{.}28394311 \pm 0\overset{\mathrm{d}}{.}00000013$ and $4\overset{\mathrm{d}}{.}28394845 \pm 0\overset{\mathrm{d}}{.}00000019$, respectively. Fitting only the *uvby* times of primary minima leads to the same period.

As mentioned in Sect. 6.1, the orbit of V636 Cen is eccentric ($e = 0.13$), and the secondary eclipse occurs near phase 0.52. Apsidal motion must therefore exist, although at a slow rate, since the relative radii of the components are small. From theoretical density concentration coefficients, the absolute dimensions, the eccentricity and inclination of the orbit, and assuming the rotation of the components to be pseudosynchronized, Larsen (1998) derived an expected apsidal motion period of $U \approx$ 6000 yr. The relativistic contribution and the classical contribution from tidal effects are of almost the same size ($P/U \approx 10^{-6}$), making V636 Cen particularly interesting among apsidal motion systems.

With additional *uvby* times of minima available, we have repeated the apsidal motion analysis and obtain the parameters listed in Table 5; see also Fig. 7. Well defined apsidal motion parameters have now been determined for meaningful comparison with theoretical density concentrations of stellar models.

The apsidal motion does not lead to significant phase shifts of secondary eclipse compared to primary eclipse during the 1985−1991 *uvby* light curve observations. We have adopted the following linear ephemeris, derived from the corresponding times of primary minima for the light curve analyses:

$$\text{Min I} = \underset{\pm 14}{2\,446\,873.80124} + \underset{\pm 7}{4\overset{\mathrm{d}}{.}2839423} \times E \tag{4}$$

7. VZ Hya

VZ Hya = HD 72257 = HIP 41834 was discovered by O’Connell (1932) to be an eclipsing binary, and spectroscopic elements were obtained from 75 Å/mm spectra by Struve (1945), who

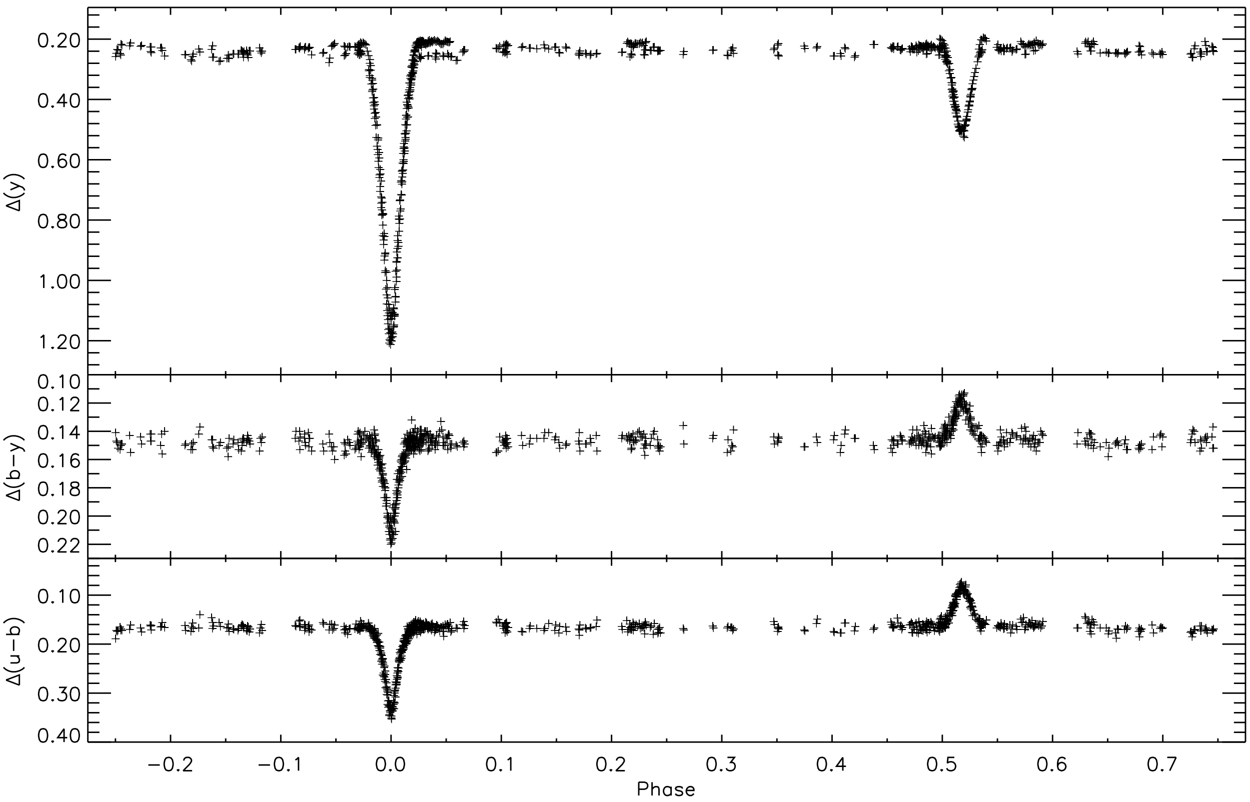

Fig. 6. y light curve and $b-y$ and $u-b$ colour curves (instrumental system) for V636 Cen.

Table 5. Apsidal motion parameters for V636 Cen derived from the photoelectric times of minima.

Parameter	Value and rms error
i (°)	89.65 (assumed)
e	0.134 (assumed)
T_0	2 447 220.8424 ± 0.0002
$P_{\rm anomalistic}$ (d)	4.283956 ± 0.0000008
$P_{\rm sidereal}$ (d)	4.283946
ω_0 (°)	281.95 ± 0.06
ω_1 (°/ cycle)	0.00080 ± 0.00005
U (yr)	5270 ± 335

showed that the period is twice the value given by O'Connell. Early light curves and absolute dimensions were published by Wood (1946, visual data) as part of his thesis, and by Gaposchkin (1953, photographic data). From 20 and 40 Å/mm spectra, Popper (1965) later determined improved elements, leading to masses accurate to about 2.5%.

The first photoelectric (*UBV*) light curves were presented by Walker (1970) together with a preliminary photometric solution, whereas Wood (1971) performed a complete analysis as part of the introduction of his then new binary model and the corresponding WINK code. A photometric analysis, also based on WINK, was published by Cester et al. (1978).

Another set of photoelectric *UBV* light curves were published by Padalia & Srivastava (1975). In contrast to Walker, Wood, and Cester et al. they found primary eclipse to be an occultation (larger star in front) rather than a transit (smaller star in front). This picture of VZ Hya was soon shown by Popper (1976) to be wrong, but it was nevertheless defended once more by Padalia (1986).

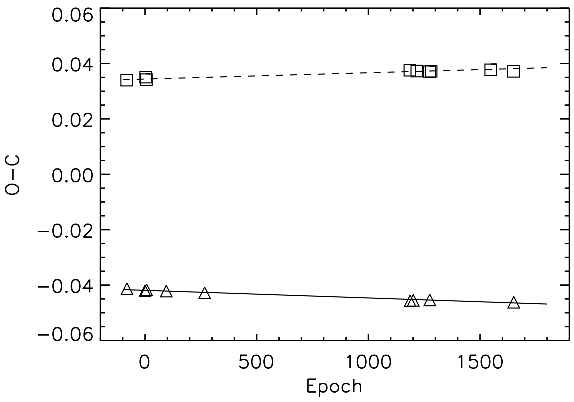

Fig. 7. Apsidal motion for V636 Cen. O−C are the residuals (days) from the linear part of the apsidal motion ephemeris defined by the parameters given in Table 5. The full and dashed curves represent predictions from the apsidal motion parameters for primary (triangles) and secondary (squares) eclipses, respectively. Only the *uvby* observations are shown.

Because its dimensions were relatively well known, VZ Hya has often been included in binary samples used in various astrophysical investigations, e.g. He abundance in Population I stars (Popper et al. 1970), stellar radii (Lacy 1977; Shallis & Blackwell 1980; Pastori et al. 1985), and mass-radius relations (Zhai & Zhang 1989). The currently most reliable absolute dimensions are those given by Popper (1980) in his critical review of stellar masses. There is, however, still ample space for improvement, provided more accurate light curves and radial velocities are obtained. Since VZ Hya is an important F-type system, we decided to obtain the observations needed for this purpose.

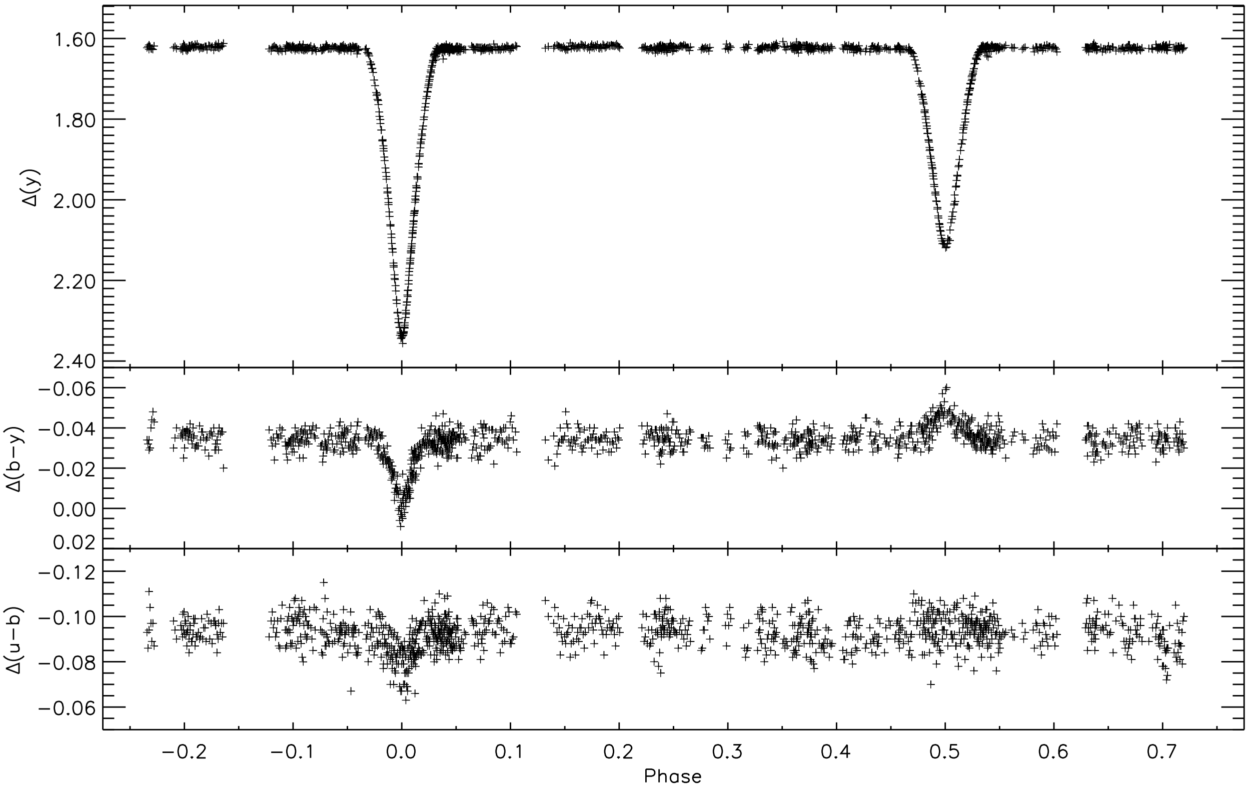

Fig. 8. y light curve and $b-y$ and $u-b$ colour curves (instrumental system) for VZ Hya.

7.1. *uvby* light curves

Complete *uvby* light curves containing 1180 points in each colour were observed on 44 nights during four periods between February 1989 and April 1992 (JD 2 447 575–JD 2 448 684). HD 72528, HD 71615, and HD 72782 were used as comparison stars and were found to be constant within the observational accuracy of a few mmag during our observations; see Tables 1–3 for further information.

The light curves of VZ Hya are shown in Fig. 8. As seen, VZ Hya consists of two well-detached components of different surface fluxes in a circular orbit. Both eclipses have been covered several times and most out-of-eclipse phases at least twice. The accuracy per point is about 0.004 mag (*vby*) and 0.006 mag (u), meaning that the new light curves are of significantly higher quality than those by Walker (1970) and Padalia & Srivastava (1975). We see no signs of intrinsic variability. Photometric analyses reveal that the secondary eclipse is very close to being total (Clausen et al. 2008).

7.2. Ephemeris

Three times of primary minimum and one of secondary minimum, derived from the *uvby* observations, are given in Table A.6 together with 26 published times and times redetermined from the photometry by Walker (1970).

We adopt the following linear ephemeris, which is based on all available times assuming a circular orbit and derived as described in Sect. 3.2:

$$\mathrm{Min\ I} = \underset{\pm 9}{2\,448\,273.63450} + \underset{\pm 11}{2\overset{\mathrm{d}}{.}90430023} \times E \qquad (5)$$

Within the errors, separate least squares fits to all primary and secondary times yield identical periods. The period is close to the most recent published determination (Srivastava 1987); see also Kreiner[3]. Srivastava found evidence for a slowly increasing period and sinusoidal variations of the O–C residuals, indicating a possible third body in the system. The data in Table A.6 provide no clear evidence for such variations, however.

8. WZ Oph

WZ Oph = HD 154676 = HIP 83719 was discovered by Metcalf to be an eclipsing binary (Pickering 1917). Visual light curves and times of minima were published by Leiner (1921, 1926), who derived an orbital period of about $2\overset{\mathrm{d}}{.}09$, whereas the correct value of about $4\overset{\mathrm{d}}{.}18$ was proposed by McLaughlin (1929). Lause (1936) presented further visual minima. Sanford (1937) obtained the first radial velocities, and Gaposchkin (1938) established visual (from Leiner's observations) and photographic (from Harvard patrol plates) light curves, and he derived the first absolute dimensions of the two nearly identical components of WZ Oph.

The first modern analysis of WZ Oph, leading to masses and radii accurate to 3–4%, was done by Popper (1965) from photoelectric light curves and 20 Å/mm spectra. WZ Oph is included in his comprehensive review on stellar masses (Popper 1980), but not in the later review on accurate masses of radii of normal stars by Andersen (1991), where a more strict limit of 2% was applied. Very accurate light curves and radial velocities are needed in order to reach such accuracies (e.g. Andersen et al. 1980), and besides standard *uvby* indices (Hilditch & Hill 1975) and additional times of minima (see Tables A.7, A.8), practically no new observational data for WZ Oph have been published since those by Popper. We now remedy this lack.

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[3] `http://www.as.ap.krakow.pl/ephem`

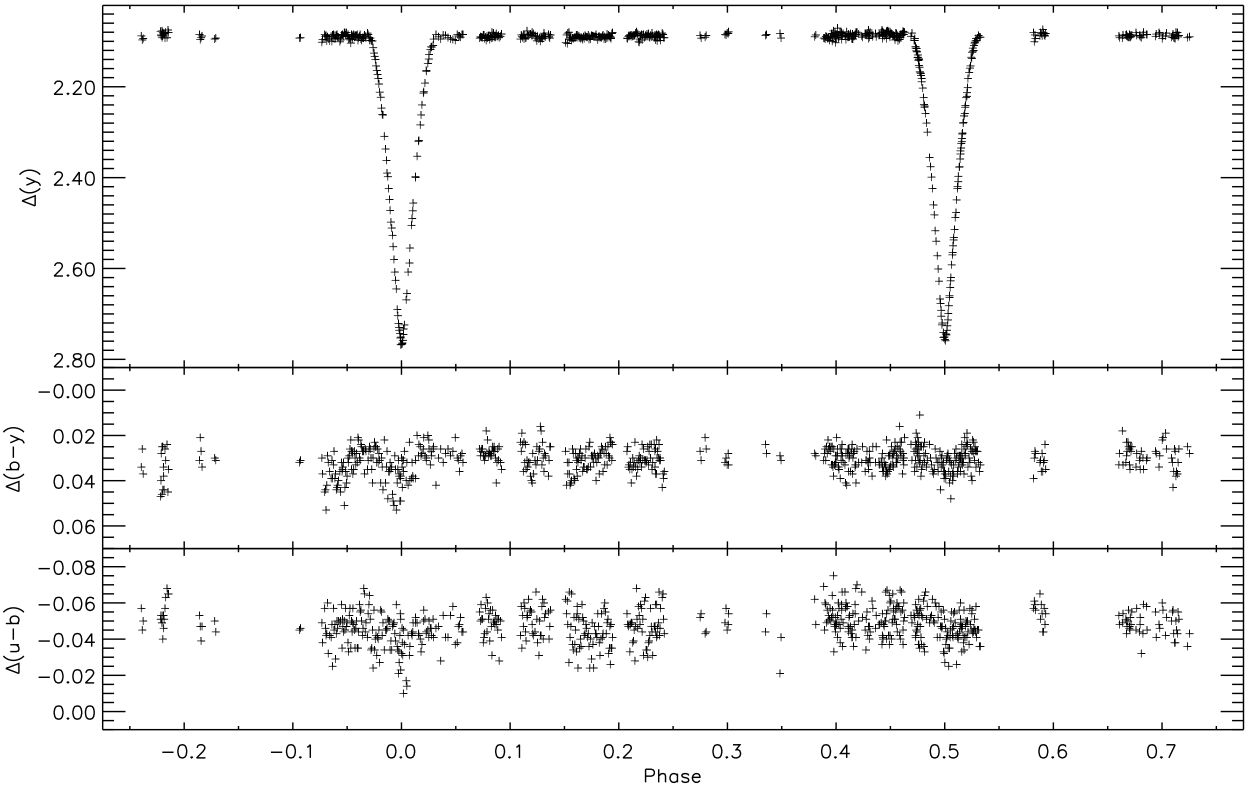

Fig. 9. y light curve and $b-y$ and $u-b$ colour curves (instrumental system) for WZ Oph.

8.1. uvby light curves

Complete *uvby* light curves containing 697 points in each colour were observed on 41 nights during six periods between May 1991 and March 1997 (JD 2 448 370–JD 2 450 535). HD 155193 and HD 154931 were selected as comparison stars, and they were found to be constant within the observational accuracy of a few mmag during our observations; see Tables 1–3 for further information. The eclipses have been covered on several nights and out-of-eclipse phases, except for a few gaps, at least twice.

As seen in Fig. 9, WZ Oph consists of two well-detached components of almost identical surface fluxes in a circular orbit, and from the analysis by Popper (1965) they are also known to be very similar with respect to masses and radii. The accuracy per point is about 0.004 mag (*vby*) and 0.006 mag (u), meaning that they are of significantly higher quality than those by Popper (1965). However, our photometric analyses (Clausen et al. 2008) reveal that throughout all phases the points scatter by 1−4 mmag more than this, highest in u. At a given phase, the observations from different seasons do not differ systematically. The extra scatter may be due to low-level surface activity, since weak emission features in the Ca II H and K lines are seen at the position of both components on high-resolution spectra of WZ Oph.

For the ephemeris adopted by Popper, the component eclipsed at phase 0.0 (his component 1) was found to be (formally) slightly more massive, slightly smaller, and appeared to have slightly weaker lines and to be less luminous than the other. The new accurate *uvby* light curves reveal that, adopting Popper's ephemeris, the eclipse at phase 0.5 is in fact slightly deeper in all four colours, meaning that the component eclipsed here has a slightly higher surface flux than the other. Since analyses of new CfA radial velocities (Clausen et al. 2008) show that this component is also marginally the more massive, we have decided to interchange the minima compared to Popper's notation, so for the linear ephemeris presented below, the deeper (primary) eclipse occurs at phase 0.0.

8.2. Ephemeris

From the *uvby* observations, two times of primary and two times of secondary minimum are available, see Tables A.7 and A.8, where the 104 times of minima we have been able to locate in the literature are also included. We note that those by Gaposchkin (1938) are based on Harvard patrol plates with usual exposure times of one hour.

We adopt the following linear ephemeris, which is based on all available times, assuming a circular orbit, and derived as described in Sect. 3.2:

$$\text{Min I} = \underset{\pm 24}{2\,450\,535.78331} + \underset{\pm 24}{4\overset{\text{d}}{.}18350681} \times E \tag{6}$$

It represents a significant improvement compared to previous determinations. Excluding the rather inaccurate times by Gaposchkin (1938), which also show large O−C residuals in Tables A.7 and A.8, does not change the result significantly. The Lafler & Kinman (1965) method applied to the *uvby* observations yields $4\overset{\text{d}}{.}1835070$. Finally, separate least squares fits to all primary and secondary times yield identical periods within errors.

Note that, as mentioned above, the new epoch is shifted by half a period compared to (most) previous ephemerides given for WZ Oph, including that by Kreiner[4].

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[4] `http://www.as.ap.krakow.pl/ephem`

9. Summary and conclusions

Complete *uvby* light cuves and $uvby\beta$ standard indices have been obtained for the six main-sequence eclipsing binaries AD Boo, HW CMa, SW CMa, V636 Cen, VZ Hya, and WZ Oph. For V636 Cen and HW CMa, the light curves are the first modern ones obtained, and for the other systems they are both more complete and more accurate than earlier data. Ephemerides have been determined from all available times of minima, and apsidal motion has been detected and quantified for SW CMa and V636 Cen.

For AD Boo, the new photometry indicates low-level surface activity, and spectroscopy supports that the cooler secondary component is the most likely candidate (Clausen et al. 2008). The new photometry and spectroscopy also suggests that WZ Oph is mildly active. The *uvby* light curves of V636 Cen clearly show variations due to activity at a moderate level, also confirmed by spectroscopy (Clausen et al., in prep.).

In parallel, new spectroscopic observations for accurate radial velocities and abundance determinations were obtained. The combined data yield accurate absolute dimensions and heavy-element abundances for all six systems and allow detailed tests of current stellar evolutionary models. Our analyses will be published in three separate papers (Clausen et al. 2008; the F-type systems AD Boo, VZ Hya, and WZ Oph), (Clausen et al., in prep.; the G-type system V636 Cen); (Torres et al., in prep.; the late A-type systems HW CMa and SW CMa).

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Appendix A: Times of minima tables

Table A.1. Times of *primary* minima for AD Boo. O−C values are calculated for the ephemeris given in Eq. (1) assuming a circular orbit. Observing methods are: PG photographic; V visual; PE photoelectric or CCD. Times marked with an asterisk were published after we completed the ephemeris calculations; including them makes no significant changes.

HJD − 2 400 000	rms publ.	rms adopt.	O−C days	Observing method	Reference
15 552.681		0.0320	0.0426	PG	S68
16 576.720		0.0320	0.0221	PG	–
16 605.709		0.0320	0.0478	PG	–
16 880.830		0.0320	0.0175	PG	–
17 329.796		0.0320	0.0524	PG	–
17 660.792		0.0320	0.0393	PG	–
19 439.923		0.0320	−0.0038	PG	–
20 244.712		0.0320	0.0193	PG	–
23 612.695		0.0320	−0.0156	PG	–
23 612.706		0.0320	−0.0046	PG	–
26 190.436		0.0320	−0.0082	PG	S63
26 767.648		0.0320	0.0067	PG	–
27 183.483		0.0320	0.0114	PG	–
27 212.436		0.0320	0.0011	PG	–
27 609.605		0.0320	−0.0408	PG	S68
28 219.931		0.0320	−0.0129	PG	–
28 962.610		0.0320	−0.0356	PG	S63
29 014.430		0.0320	0.0642	PG	–
30 439.803		0.0320	0.0292	PG	S68
32 659.663		0.0320	0.0592	PG	–
33 023.667		0.0320	−0.0468	PG	–
37 016.535		0.0320	0.0236	PG	S63
37 018.539		0.0320	−0.0412	PG	–
37 018.585		0.0320	0.0048	PG	–
37 351.647		0.0320	−0.0112	PG	–
40 711.396		0.0150	−0.0048	V	O119 (1970), VB74
41 042.409		0.0150	−0.0009	V	O124 (1971)
41 042.411		0.0150	0.0011	V	–
41 048.614		0.0150	−0.0024	V	–
41 071.381		0.0150	0.0078	V	O125 (1971), VB74
41 104.453		0.0150	−0.0211	V	–
41 135.498		0.0150	−0.0083	V	O126 (1971)
41 135.503		0.0150	−0.0033	V	–
41 162.412		0.0150	0.0113	V	–
41 402.385		0.0150	0.0026	V	B3 (1972), VB74
41 402.393		0.0150	0.0106	V	B4 (1972), VB74
41 433.423		0.0150	0.0085	V	B3 (1972), VB74
41 764.378		0.0150	−0.0456	V	B8 (1973), VB74
41 764.413		0.0150	−0.0106	V	–
41 795.459		0.0150	0.0033	V	B9 (1973), VB74
41 824.387		0.0150	−0.0320	V	–
41 853.381		0.0150	−0.0013	V	B10 (1973), VB74
42 186.454		0.0150	−0.0062	V	B15 (1974)
42 275.417		0.0150	−0.0019	V	B17 (1974)
42 614.686		0.0150	−0.0173	V	BA78
42 860.8760		0.0150	−0.0153	V	BS97
42 937.427		0.0150	−0.0102	V	B28 (1976)
42 997.442		0.0150	0.0094	V	B29 (1976)
44 079.417		0.0150	−0.0017	V	B44 (1979)
44 704.1985	0.0005	0.0007	0.0001	PE	Z83
44 731.0935	0.0005	0.0007	0.0006	PE	–
44 766.2627	0.0003	0.0004	0.0001	PE	–
45 074.5133	0.0005	0.0035	−0.0016	PE	B60 (1982)
45 082.781		0.0150	−0.0091	V	BS97
45 101.407		0.0150	−0.0024	V	B60 (1982)
45 442.761		0.0150	−0.0015	V	BS97
46 216.495		0.0150	−0.0014	V	I86
46 216.508		0.0150	0.0117	V	–
46 907.472		0.0150	−0.0059	V	–

Table A.1. continued.

HJD − 2 400 000	rms publ.	rms adopt.	O–C days	Observing method	Reference
46 963.339		0.0150	0.0033	V	B84 (1987)
47 161.910		0.0150	−0.0312	V	BS97
47 219.865		0.0150	−0.0028	V	–
47 246.7620	0.0010	0.0014	−0.0003	PE	This paper
47 248.8312	0.0002	0.0003	0.0001	PE	–
47 383.313		0.0150	0.0095	V	B89 (1988)
47 579.8410	0.0010	0.0014	0.0008	PE	This paper
48 026.7022	0.0002	0.0003	−0.0003	PE	–
48 357.704		0.0150	−0.0076	V	BS97
48 407.372	0.001	0.0043	0.0090	PE	B98 (1991)
48 438.3944	0.0006	0.0009	−0.0007	PE	–
49 501.7627	0.0003	0.0004	0.0008	PE	BS97
52 745.6521	0.0012	0.0017	0.0007	PE	MK04
52 758.0641		0.0035	−0.0001	PE	N04
53 006.3222		0.0035	0.0011	PE	N05
53 124.2389		0.0035	−0.0042	PE	–
53 461.4575*	0.0004		−0.0011	PE	H06
53 463.5256*	0.0013		−0.0018	PE	D05

References are: B = BBSAG Bulletin, followed by volume number and year of publication; BA78 = Baldwin (1978); BS97 = Baldwin & Samolyk (1997); D05 = Diethelm (2005); H06 = Hübscher et al. (2006); I86 = Isles (1986); MK04 = Maciejewski & Karska (2004); N04 = Nagai (2004); N05 = Nagai (2005); O = Orion (Diethelm & Locker 1970a, 1971a–c), followed by volume number and year of publication; S63 = Strohmeier et al. (1963); S68 = Strohmeier et al. (1968); VB74 = van Buren (1974); his data are taken from B and O; Z83 = Zhai et al. (1983).

Table A.2. Times of *secondary* minima for AD Boo. See Table A.1 for details.

HJD – 2 400 000	rms publ.	rms adopt.	O–C days	Type	Reference
15 437.897		0.0320	0.0774	PG	S68
18 439.694		0.0320	0.0354	PG	–
18 799.671		0.0320	0.0400	PG	–
19 883.703		0.0320	0.0171	PG	–
20 636.749		0.0320	0.0173	PG	–
20 940.860		0.0320	0.0137	PG	–
20 967.771		0.0320	0.0302	PG	–
21 716.692		0.0320	0.0430	PG	–
24 995.683		0.0320	−0.0251	PG	–
25 738.438		0.0320	0.0282	PG	S63
25 827.366		0.0320	−0.0025	PG	S63
26 830.727		0.0320	−0.0130	PG	S68
27 182.494		0.0320	0.0568	PG	S63
27 213.451		0.0320	−0.0183	PG	–
27 573.458		0.0320	0.0163	PG	–
27 602.416		0.0320	0.0110	PG	–
28 996.735		0.0320	−0.0459	PG	S68
29 495.393		0.0320	0.0296	PG	S63
37 017.537		0.0320	−0.0088	PG	–
40 745.534		0.0150	−0.0021	V	O119 (1970), VB74
41 041.378		0.0150	0.0025	V	O124 (1971)
41 041.382		0.0150	0.0065	V	–
41 134.446		0.0150	−0.0259	V	VB74
41 405.466		0.0150	−0.0196	V	B2 (1972), VB74
41 434.442		0.0150	−0.0069	V	B3 (1972), VB74
41 434.446		0.0150	−0.0029	V	B3 (1972)
41 436.516		0.0150	−0.0017	V	B4 (1972)
41 494.440		0.0150	−0.0043	V	B3 (1972), VB74
41 763.339		0.0150	−0.0502	V	B8 (1973), VB74
41 763.381		0.0150	−0.0082	V	–
41 794.399		0.0150	−0.0223	V	B9 (1973), VB74
41 794.411		0.0150	−0.0103	V	–
41 912.365		0.0150	0.0217	V	B11 (1973)
42 156.453		0.0150	−0.0095	V	B15 (1974)
42 158.525		0.0150	−0.0063	V	–
42 183.344		0.0150	−0.0130	V	–
42 183.369		0.0150	0.0120	V	–
42 214.380		0.0150	−0.0091	V	B16 (1974)
42 303.335		0.0150	−0.0128	V	B17 (1974)
42 404.709		0.0150	−0.0104	V	B19 (1974)
42 917.765		0.0150	−0.0185	V	BS97
43 190.826		0.0150	−0.0401	V	–
43 219.825		0.0150	−0.0043	V	–
43 689.457		0.0150	0.0085	V	B37 (1978)
44 334.900		0.0150	−0.0163	V	BS97
44 701.0941	0.0003	0.0010	−0.0011	PE	Z83
44 730.0570	0.0005	0.0017	−0.0015	PE	–
44 736.2642	0.0004	0.0014	−0.0007	PE	–
44 779.686		0.0150	−0.0239	V	BS97
45 100.390		0.0150	0.0150	V	B60 (1982)
45 162.420		0.0150	−0.0192	V	B61 (1982)
46 169.922		0.0150	−0.0262	V	BS97
46 217.514		0.0150	−0.0168	V	I86
47 580.8765	0.0005	0.0017	0.0019	PE	This paper
48 360.8148	0.0002	0.0007	−0.0001	PE	–
49 829.661		0.0035	−0.0069	PE	BS97
50 189.636		0.0035	−0.0043	PE	–
52 322.5851	0.0003	0.0031	0.0048	PE	B127 (2002)
53 522.4864*	0.0020		−0.0020	PE	H06

Table A.3. Times of primary (P) minima of HW CMa. O−C values are calculated for the ephemeris given in Eq. (2).

HJD − 2 400 000	rms	Type	O–C	Reference
48 689.6471	0.0004	P	0.0000	This paper
52 279.6787	0.0004	P	0.0000	–

Table A.4. Times of primary (P) and secondary (S) minima of SW CMa. O−C values are calculated for the apsidal motion ephemeris given in Table 4. Times given in brackets have not been used for the ephemeris determination.

HJD − 2 400 000	rms	Type	O–C	Reference
25 646.489	0.010	P	−0.087	W52
25 969.426	0.010	P	−0.094	–
25 969.469	0.010	P	−0.051	–
26 393.319	0.010	P	−0.064	–
26 393.404	0.010	P	0.021	–
27 160.327	0.010	P	−0.047	–
28 250.320	0.010	P	0.012	–
37 696.372	0.010	P	−0.032	Z65
38 372.541	0.010	P	−0.026	–
38 463.330	0.010	P	−0.065	–
46 829.6482	0.0003	P	−0.0008	This paper
46 839.7405	0.0008	P	−0.0005	–
48 272.8031	0.0003	P	0.0005	–
49 352.6453	0.0004	P	0.0005	LF94
52 309.5963	0.0002	P	0.0005	This paper
54 075.6924	0.0002	P	−0.0005	–
25 619.400	0.010	S	−0.035	W52
26 628.566	0.010	S	−0.067	F37
26 709.324	0.010	S	−0.044	F37
27 123.080	0.010	S	−0.060	F37
(27 133.308)	0.010	S	0.077	W52
(27 780.015)	0.010	?	0.897	F37
27 890.090	0.010	S	−0.040	–
28 162.530	0.010	S	−0.083	W52
28 495.601	0.010	S	−0.047	–
30 433.316	0.010	S	0.008	–
34 066.378	0.010	S	−0.042	–
36 599.438	0.010	S	−0.068	Z65
(37 366.328)	0.010	S	−0.168	–
46 832.7710	0.0010	S	0.0001	This paper
47 579.5765	0.0004	S	−0.0007	–
47 589.6690	0.0004	S	−0.0002	–
48 164.905	0.003	S	−0.007	H00
48 265.8327	0.0010	S	0.0011	This paper
49 345.6754	0.0006	S	0.0022	LF94
52 302.6227	0.0002	S	0.0001	This paper
53 644.8536	0.0007	S	−0.0020	–

References are: F37 = Florja (1937). H00 = Hipparcos 2000, unpublished. LF94 = Lacy & Fox (1994). W52 = Wenzel (1952); photographic observations (rms of $0\overset{d}{.}01$ has been estimated). Z65 = Ziegler (1965); photographic observations (rms of $0\overset{d}{.}01$ has been estimated).

Table A.5. Times of primary (P) and secondary (S) minima for V636 Cen. O-C values are calculated from the apsidal motion parameters given in Table 5.

HJD − 2 400 000	rms	Type	O–C	Reference
27 977.317	0.030	P	−0.010	H58
28 658.405	0.030	P	−0.069	–
28 688.414	0.030	P	−0.048	–
34 480.390	0.030	P	0.037	–
34 510.323	0.030	P	−0.018	–
34 540.340	0.030	P	0.012	–
34 570.300	0.030	P	−0.016	–
46 873.8014	0.0001	P	0.0003	This paper
47 220.8003	0.0001	P	−0.0002	–
47 250.7883	0.0002	P	0.0002	–
47 627.7751	0.0001	P	0.0000	–
48 167.538	0.014	P	−0.014	H00
48 364.6132	0.0001	P	−0.0002	This paper
52 305.84068	0.00020	P	−0.00056	–
52 365.81615	0.00015	P	−0.00030	–
52 682.82827	0.00015	P	0.00001	–
54 293.59119	0.00010	P	0.00023	–
46 871.7348	0.0003	S	−0.0002	–
47 235.8713	0.0005	S	0.0007	–
47 248.7222	0.0003	S	−0.0003	–
52 303.78204	0.00030	S	0.00051	–
52 436.58404	0.00015	S	0.00011	–
52 680.76871	0.00040	S	−0.00028	–
52 710.75656	0.00030	S	−0.00007	–
53 854.57063	0.00030	S	−0.00021	–
54 291.53262	0.00050	S	−0.00096	–

References are: H58 = Hoffmeister (1958); rms of $0\overset{d}{.}03$ has been estimated. H00 = Hipparcos 2000, unpublished.

Table A.6. Times of primary (P) and secondary (S) minima for VZ Hya. O−C values are calculated for the ephemeris given in Eq. (5) adopting a circular orbit. Observing methods are: PG photographic; V visual; PE photoelectric or CCD. Times marked with an asterisk were published after we completed the ephemeris calculations; including them makes no significant changes.

HJD – 2 400 000	rms publ.	rms adopt.	O−C days	Type	Observing method	Reference
21 925.8246	0.0008	0.0011	0.0018	P	PG	O32 (T_0)
26 674.3410	0.0010	0.0120	−0.0127	P	PG	G53 (T_0)
27 856.412		0.0063	0.0081	P	V	L49
29 604.794		0.0063	0.0014	P	V	W46
29 700.634		0.0063	−0.0006	P	V	–
30 034.626		0.0063	−0.0031	P	V	–
39 926.673		0.0063	−0.0027	P	V	BA74
40 254.8602	0.0005	0.0007	−0.0014	P	PE	W70
40 998.362		0.0028	−0.0004	P	PE	PS75
41 033.212		0.0028	−0.0020	P	PE	–
42 354.668		0.0063	−0.0026	P	V	B18(1974)
42 848.401		0.0063	−0.0007	P	V	B27(1976)
43 577.372		0.0063	−0.0090	P	V	B37(1978)
44 236.6532		0.0028	−0.0040	P	PE	W82
47 971.5876*	0.0003		0.0003	P	PE	SC07
48 267.8259	0.0001	0.0001	−0.0001	P	PE	This paper
48 270.7303	0.0001	0.0001	0.0000	P	PE	–
48 273.6346	0.0001	0.0001	0.0001	P	PE	–
51 253.4340		0.0063	−0.0125	P	V	BAV122(1999)
51 256.3520		0.0063	0.0012	P	V	–
52 702.6936*	0.0001		0.0012	P	PE	SC07
27 840.437		0.0063	0.0067	S	V	L49
29 681.751		0.0063	−0.0056	S	V	W46
29 748.556		0.0063	0.0005	S	V	–
30 015.742		0.0063	−0.0091	S	V	–
40 305.6848	0.0005	0.0015	−0.0020	S	PE	W70
40 654.201		0.0028	−0.0019	S	PE	PS75
40 686.154		0.0028	0.0038	S	PE	–
41 743.305		0.0063	−0.0104	S	V	B8(1973)
48 684.5934	0.0002	0.0006	0.0004	S	PE	This paper

References are: B = BBSAG Bulletin, followed by volume number and year of publication; BA74 = Baldwin (1974); BAV = B.A.V. Mitt., followed by volume number and year of publication; G53 = epoch given by Gaposchkin (1953); L49 = Lause (1949); O32 = epoch given by O'Connell (1932); PS75 = Padalia & Srivastava (1975); SC07 = Smith & Caton (2007); W46 = Wood (1946); W70 = redetermined from B and V data by Walker (1970); W82 = Wolf et al. (1982).

Table A.7. Times of *primary* minima for WZ Oph. O−C values are calculated for the ephemeris given in Eq. (6) assuming a circular orbit. Observing methods are: PG photographic; V visual; PE photoelectric or CCD. Times marked with an asterisk were published after we completed the ephemeris calculations; including them makes no significant changes.

HJD − 2 400 000	rms publ.	rms adopt.	O−C days	Observing method	Reference
14 766.779		0.0340	−0.0211	PG	G38
16 402.534		0.0340	−0.0172	PG	–
16 678.62		0.0340	−0.0427	PG	–
16 975.67		0.0340	−0.0217	PG	–
17 707.813		0.0340	0.0076	PG	–
17 728.754		0.0340	0.0311	PG	–
18 523.56		0.0340	−0.0292	PG	–
19 531.77		0.0340	−0.0443	PG	–
20 778.51		0.0340	0.0106	PG	–
22 531.385		0.0110	−0.0037	V	L21
22 836.74		0.0340	−0.0447	PG	G38
22 941.379		0.0110	0.0066	V	L21
22 962.303		0.0110	0.0131	V	–
23 284.431		0.0110	0.0111	V	L26
23 535.440		0.0110	0.0097	V	–
23 581.451		0.0110	0.0021	V	–
23 648.393		0.0110	0.0080	V	–
24 355.405		0.0110	0.0073	V	–
24 702.626		0.0340	−0.0027	PG	G38
24 744.520		0.0340	0.0562	PG	–
25 363.601		0.0340	−0.0218	PG	–
25 384.477		0.0340	−0.0634	PG	–
25 384.563		0.0340	0.0226	PG	–
25 388.729		0.0110	0.0051	V	M29
27 250.410	0.004	0.0180	0.0256	V	D77
27 639.444		0.0110	−0.0065	V	L36
27 660.376		0.0110	0.0079	V	–
27 890.448		0.0110	−0.0129	V	–
27 961.570		0.0110	−0.0106	V	–
28 003.411		0.0110	−0.0046	V	–
28 455.228		0.0110	−0.0064	V	L38
28 555.627		0.0110	−0.0115	V	–
28 664.418		0.0110	0.0083	V	–
28 689.498		0.0110	−0.0127	V	–
28 819.172		0.0110	−0.0274	V	–
28 844.310		0.0110	0.0095	V	–
35 650.8670	0.0010	0.0028	0.0009	PE	P65
40 859.331		0.0110	−0.0011	V	O121 (1970)
41 135.427		0.0110	−0.0165	V	O126 (1971)
46 243.508		0.0110	0.0027	V	B77 (1985)
47 381.420		0.0110	0.0008	V	BR30 (1992)
47 724.471		0.0110	0.0043	V	BAV56 (1989)
48 004.7536*	0.0002		−0.0081	PE	SC07
48 042.420		0.0110	0.0068	V	B95 (1990)
48 088.453		0.0110	0.0212	V	B96 (1990)
48 372.9097	0.0004	0.0011	−0.0006	PE	This paper
48 452.3967		0.0003	−0.0002	PE	BAA91 (1997)
48 795.445	0.010	0.0280	0.0005	PE	B102 (1992)
48 883.3011	0.0008	0.0022	0.0030	PE	B103 (1993)
50 535.7849	0.0003	0.0008	0.0016	PE	This paper
52 054.396		0.0110	−0.0003	V	BAV143 (2001)
52 100.411		0.0110	−0.0039	V	BAV154 (2002)
53 476.7886*	0.0001		0.0000	PE	SC07

References are: B = BBSAG Bulletin, followed by volume number and year of publication; BAA = BAA VSS Circ., followed by volume number and year of publication; BAV = B.A.V. Mitt., followed by volume number and year of publication; BR = Brno Contr., followed by volume number and year of publication; G38 = Gaposchkin (1938); D77 = Dworak (1977); H01 = Hipparcos 2001, unpublished; H06 = Hübscher et al. (2006); L21 = Leiner (1921); L26 = Leiner (1926); L36 = Lause (1936); L38 = Lause (1938); M29 = McLaughlin (1929; N05 = Nagai (2005); O = Orion (Diethelm & Locker 1970b,1971c), followed by volume number and year of publication; P36 = Prager (1936); P65 = Popper (1965); determined by the present authors; SC07 = Smith & Caton (2007).

Table A.8. Times of *secondary* minima for WZ Oph. See Table A.7 for details.

HJD − 2 400 000	rms publ.	rms adopt.	O−C days	Observing method	Reference
16 379.51		0.0340	−0.0319	PG	G38
16 634.72		0.0340	−0.0159	PG	–
17 107.531		0.0340	0.0589	PG	–
17 341.73		0.0340	−0.0185	PG	–
18 027.80		0.0340	−0.0436	PG	–
19 596.592		0.0340	−0.0667	PG	–
19 596.634		0.0340	−0.0247	PG	–
20 604.847		0.0340	−0.0368	PG	–
21 675.81		0.0340	−0.0516	PG	–
22 215.56		0.0340	0.0261	PG	–
22 487.458		0.0110	−0.0039	V	L21
22 897.4557		0.0340	0.0101	PG	P36
22 897.458		0.0110	0.0124	V	L21
22 918.374		0.0110	0.0109	V	–
23 516.615		0.0110	0.0104	V	L26
23 692.315		0.0110	0.0031	V	–
23 859.662		0.0110	0.0099	V	–
24 273.807		0.0340	−0.0123	PG	G38
24 286.376		0.0110	0.0062	V	L26
25 127.259	0.005	0.0225	0.0043	V	D77
25 361.511		0.0340	−0.0201	PG	G38
26 482.74		0.0340	0.0291	PG	G38
26 545.487	0.006	0.0270	0.0235	V	D77
27 570.425		0.0110	0.0023	V	L36
27 637.360		0.0110	0.0012	V	–
27 980.411		0.0110	0.0047	V	–
27 984.593		0.0110	0.0032	V	–
28 026.418		0.0340	−0.0069	PG	–
28 068.266		0.0110	0.0060	V	–
28 072.420		0.0110	−0.0235	V	–
28 298.356		0.0110	0.0031	V	L38
28 390.384		0.0110	−0.0060	V	–
28 457.325		0.0110	−0.0011	V	–
28 687.434		0.0110	0.0150	V	–
28 754.337		0.0110	−0.0181	V	–
28 779.454		0.0110	−0.0021	V	–
33 063.382	0.002	0.0090	0.0149	V	D77
35 648.7748	0.0007	0.0014	0.0005	PE	P65
40 836.327		0.0110	0.0042	V	O121 (1970)
41 522.387		0.0110	−0.0309	V	B4 (1972)
41 522.403		0.0110	−0.0149	V	–
41 522.408		0.0110	−0.0099	V	–
41 819.460		0.0110	0.0131	V	B9 (1973)
42 183.416		0.0110	0.0040	V	B15 (1974)
43 689.479		0.0110	0.0046	V	B37 (1978)
46 241.431		0.0110	0.0174	V	B77 (1985)
48 370.8180	0.0003	0.0006	−0.0005	PE	This paper
48 408.468	0.006	0.0120	−0.0021	PE	B98 (1991)
48 521.431	0.008	0.0160	0.0062	PE	H01
49 115.4800	0.0007	0.0014	−0.0027	PE	BAV62 (1993)
49 115.4824	0.0007	0.0014	−0.0003	PE	–
49 504.5461	0.0012	0.0024	−0.0028	PE	B107 (1994)
49 529.6504	0.0002	0.0004	0.0005	PE	This paper
53 098.180		0.0110	−0.0012	V	N05
53 901.4151*	0.0002		0.0006	PE	H06