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Four-colour photometry of eclipsing binaries

XL. *uvby* light curves for the B-type systems DW Carinae, BF Centauri, AC Velorum, and NSV 5783⋆,⋆⋆

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ABSTRACT

Aims. In order to increase the limited number of B-stars with accurately known dimensions, and also the number of well studied eclipsing binaries in open clusters, we have undertaken observations and studies of four southern double-lined eclipsing B-type binaries; DW Car, BF Cen, AC Vel, and NSV 5783.

Methods. Complete *uvby* light curves were observed between January 1982 and April 1991 at the Danish 0.5 m telescope at ESO La Silla, since 1985 known as the Strömgren Automatic Telescope (SAT). Standard indices for the systems and the comparison stars, as well as additional minima observations for AC Vel, have been obtained later at SAT. For DW Car and AC Vel, high-resolution spectra for definitive spectroscopic orbits have also been obtained; they are presented as part of the detailed analyses of these systems. A few spectra of NSV 5783 are included in the present paper.

Results. For all four systems, the first modern accurate light curves have been established. DW Car is a detached system consisting of two nearly identical components. It is member of the young open cluster Cr228. A detailed analysis, based on the new light curves and 29 high-resolution spectra, is published separately. BF Cen is semidetached and is member of NGC 3766. Modern spectra are needed for a detailed study. AC Vel is a detached system with at least one more star. A full analysis, based on the new light curves and 18 high-resolution spectra, is published separately. NSV 5783 is discovered to be an eclipsing binary consisting of two well-detached components in an 11-day period eccentric ($e = 0.18$) orbit. Secondary eclipse is practically total. From the light curves and a few high-resolution spectra, accurate photometric elements and preliminary absolute dimensions have been determined. The quite similar components have masses of about 5 $M_{\odot}$ and radii of about 3.5 $R_{\odot}$, and they seem to have evolved just slightly off the ZAMS. The measured rotational velocities ($\approx$150 km s^{-1}) are about 6 times those corresponding to pseudosynchronization.

Key words. stars: fundamental parameters – stars: binaries: eclipsing – stars: evolution – galaxy: open clusters and associations: general – techniques: photometric – techniques: spectroscopic

1. Introduction

Our main motivations to observe and study DW Car, BF Cen, AC Vel, and NSV 5783 were firstly to increase the limited number of B-stars with accurately known dimensions (see e.g. Hilditch & Bell 1987; Andersen 1991; Gies 2003; Hilditch 2004), and secondly to extend research on eclipsing binaries in open clusters and associations (see e.g. Clausen & Giménez 1987; Giménez & Clausen 1996; Clausen et al. 1996; Clausen & Giménez 1991; Giménez & Clausen 1994). A recent example of the potential of studying eclipsing binaries in open clusters is given by Southworth et al. (2004a).

DW Car was chosen as a young, massive member of Cr228, whereas BF Cen, which is member of NGC 3766, and AC Vel were selected from a survey of spectra of southern eclipsing binaries by Popper (1966), from which EM Car (Andersen & Clausen 1989), GV Car (Clausen et al., in prep.), TU Mus (Andersen & Grønbech 1975), V346 Cen (Giménez et al. 1986), LZ Cen (Vaz et al. 1995), SZ Cen (Andersen 1975), and V636 Cen (Clausen et al., in prep.) have also been included in the Copenhagen binary project. NSV 5783 was taken from a list of new bright southern variables by Strohmeier (1972).

In Sect. 2, we describe the photometric observations, the reduction methods, the formation of the *uvby* light curves, and the determination of standard *uvbyβ* indices for the binaries and the comparison stars. The individual systems, their *uvby* light curves and ephemerides are presented in Sects. 3–6. Section 6 also

⋆ Based on observations carried out with the Strömgren Automatic Telescope (SAT) and the FEROS spectrograph at ESO, La Silla, Chile (62.L-0284, 63.H-0080).

⋆⋆ Tables 11–14 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/461/1065 contains photometric elements and preliminary absolute dimensions for NSV 5783.

2. Observations and photometric reduction

All the photoelectric light curves were obtained in the Strömgren *uvby* system at the Copenhagen 50 cm reflecting telescope at ESO, La Silla, since 1985 known as the Strömgren Automatic Telescope (SAT). The light curves of AC Vel and BF Cen were observed before 1985, where the telescope was operated manually and equipped with a four-channel *uvby* photometer and photon counting system (Grønbech et al. 1976); a circular diaphragm of 30″ was used. The light curves of DW Car and NSV 5783, and additional eclipse observations for AC Vel, were observed after 1985, where the telescope became computer controlled and since then operated in a (semi)-automatic mode with e.g. automatic centering of the stars, and was equipped with a new 6-channel *uvbyβ* photometer and a new photon counting system (Florentin Nielsen 1983; Olsen 1993, 1994a). For DW Car, a circular diaphragm of 13″ was selected, whereas 17″ was used for NSV 5783. Most of the standard photometry was obtained during a dedicated campaign 1999–2000, see Sect. 2.3.

2.1. Light curve observations

The differential *uvby* observations were, depending on the orbital phase of the binary, done either continuously during several hours or as shorter series at an airmass generally less than 2.0. 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. The observations were done 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 should later be found to be variable. 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, if possible, kept at 5 mmag or lower in all four bands. 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. On a few nights with few observations, mean extinction coefficients had to be used. 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 two *uvby* instrumental systems of the SAT, before and after 1985, where the given spectrometer, including its filters and most of the photomultipliers, and the photon counting systems have been unchanged, have both proved to be very stable (Olsen 1977; Olsen et al. in prep.). Therefore, transformations of the light curve observations, e.g. to the standard *uvby* system, are not needed and the light curves, and the additional minima data for AC Vel, are generated in one of the two instrumental systems of the equipment.

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*
DW Car					
HD 93191, HD 92072 (C1,C2)	141	50	47	44	62
HD 93191, HD 92288 (C1,C3)	279	59	56	56	79
HD 92072, HD 92288 (C2,C3)	115	69	58	63	88
BF Cen					
HD 100942, HD 101466 (C1,C2)	989	40	37	35	53
AC Vel					
HD 93943, HD 92757 (C1,C2)	1678	37	35	58	66
NSV5783					
HD 108925, HD 109808 (C1,C2)	413	49	41	43	59

Differential magnitudes were formed using for each candidate observation 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.

Linear ephemerides for DW Car, BF Cen and NSV 5783 were calculated from published and new times of minima, listed in Tables 4–6. For AC Vel, which has at least one more component than the eclipsing pair, we refer to Helt et al. (in prep.). 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 fits to the (few) observations.

The individual light curves are shown in Figs. 1–4 and presented in Tables 11–14, which will only be made available in electronic form.

2.3. Standard uvbyβ photometry

New standard *uvbyβ* indices for the four eclipsing binaries outside eclipses, and for all comparison stars, are listed in Table 2. Most of the photometry was obtained at SAT on several nights 1999–2000, where the binaries and the comparison stars were observed together with a large sample of *uvby* and β standard stars. For the comparison stars of BF Cen, the observations were obtained in 1982. The basic reduction and transformation to the standard system was done as described by Olsen (e.g. 1993, 1994b), Kaltcheva & Olsen (1999), and Kaltcheva et al. (1999). For comparison, published *uvbyβ* indices have been collected in Table 3. Individual differences at the 0.02 mag level between the published indices and the new results, which appear to be systematic, are noticed. Similar trends were reported by Kaltcheva et al. (2000).

3. DW Car

DW Car (HD 305543, m_V = 9.68, Sp. type B1 V, $P = 1\overset{\mathrm{d}}{.}38$) is a southern double-lined eclipsing binary consisting of two almost identical main sequence stars (11.2 and 10.5 $M_{\odot}$). It is a known member of the young open cluster Cr228 situated in the η Carinae complex (Feinstein et al. 1976; Turner & Moffat 1980). DW Car has a circular orbit, and although the relative radii of its components are quite large (about 0.3), the system is clearly detached.

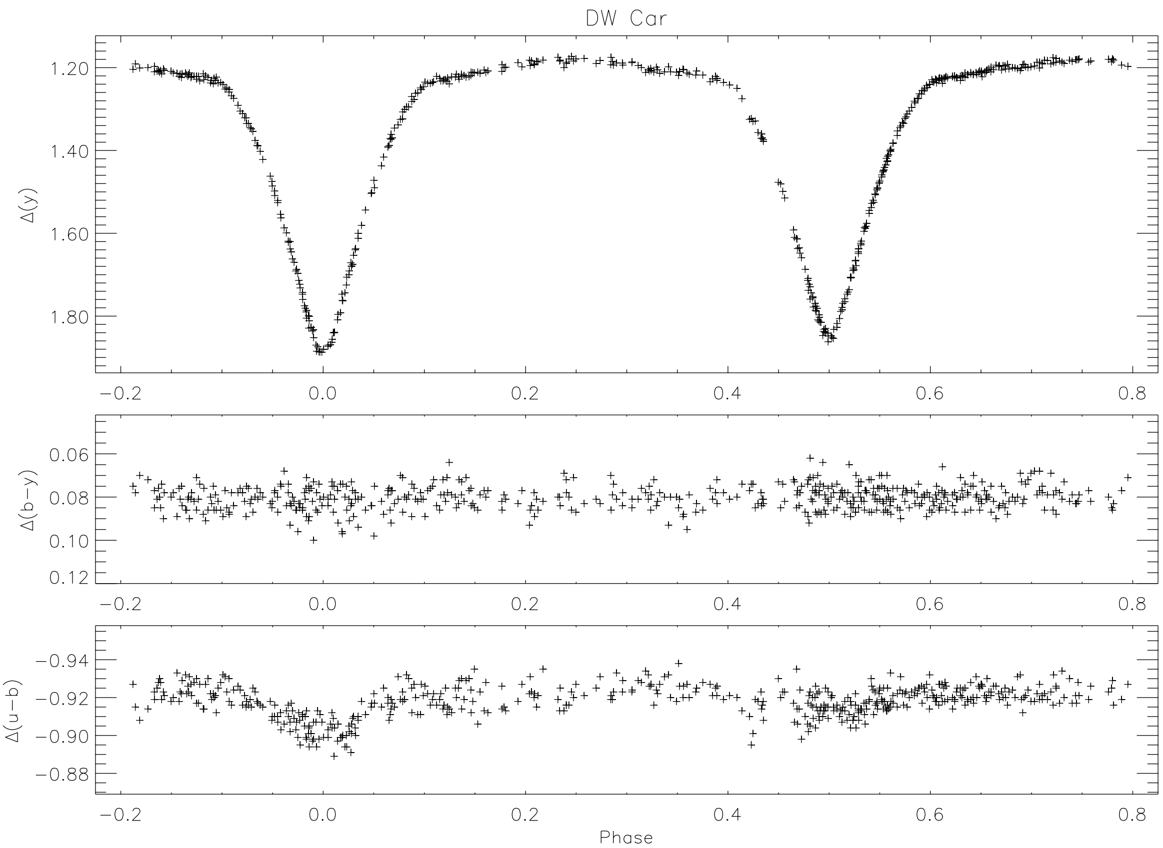

Fig. 1. y light curve and $b-y$ and $u-b$ colour curves (instrumental system) for DW Car.

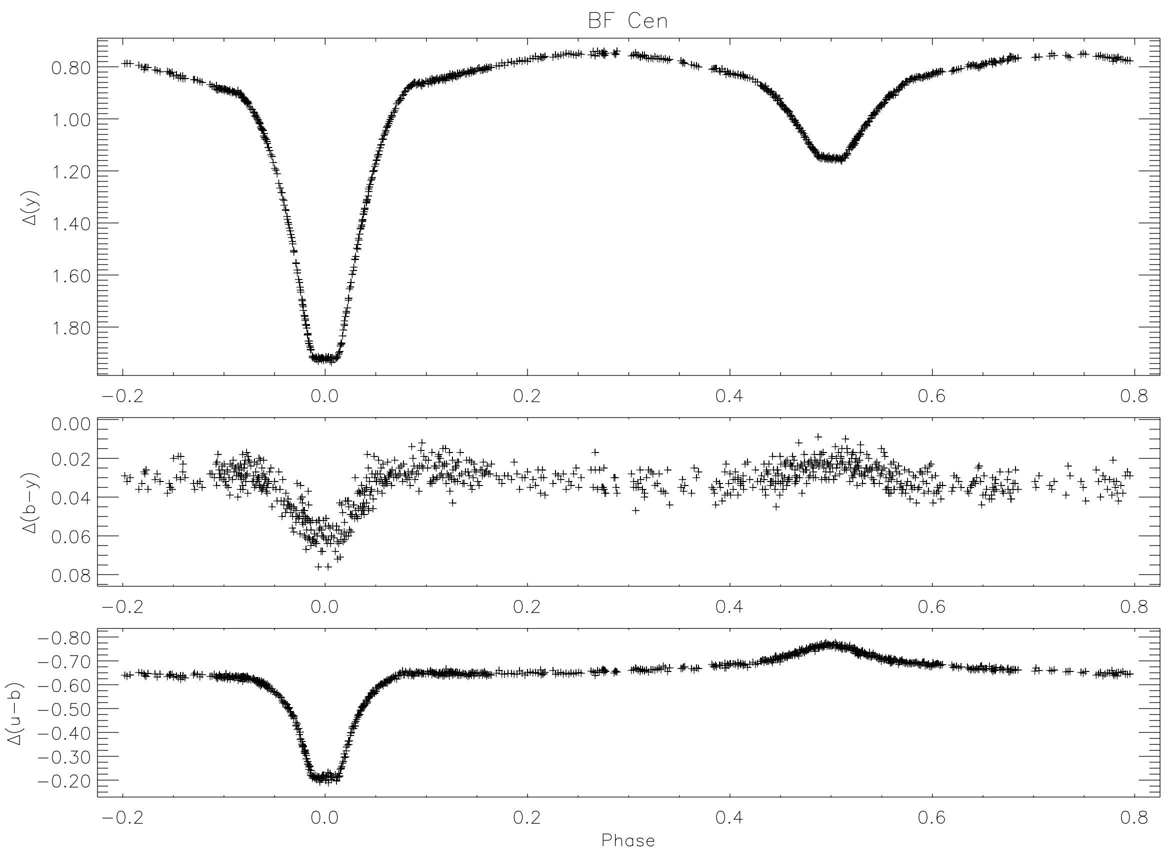

Fig. 2. y light curve and $b-y$ and $u-b$ colour curves (instrumental system) for BF Cen.

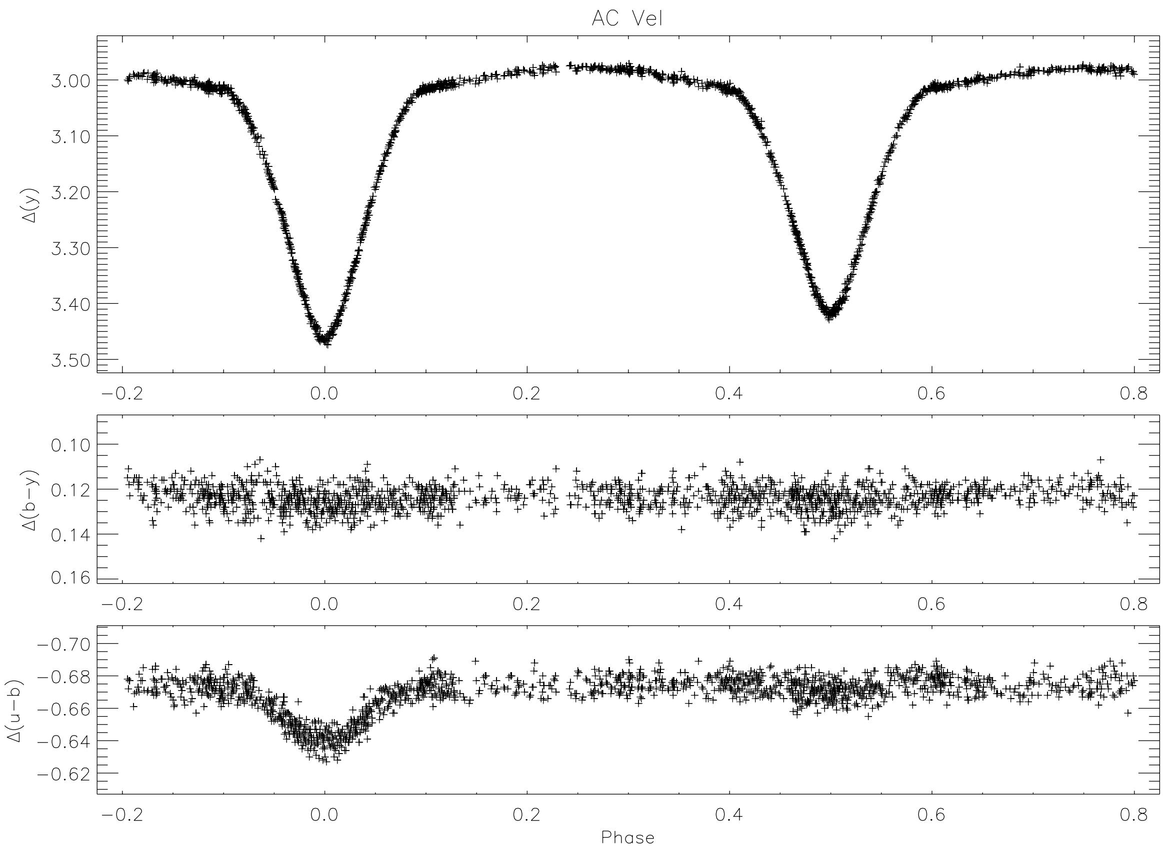

Fig. 3. y light curve and $b-y$ and $u-b$ colour curves (instrumental system) for AC Vel.

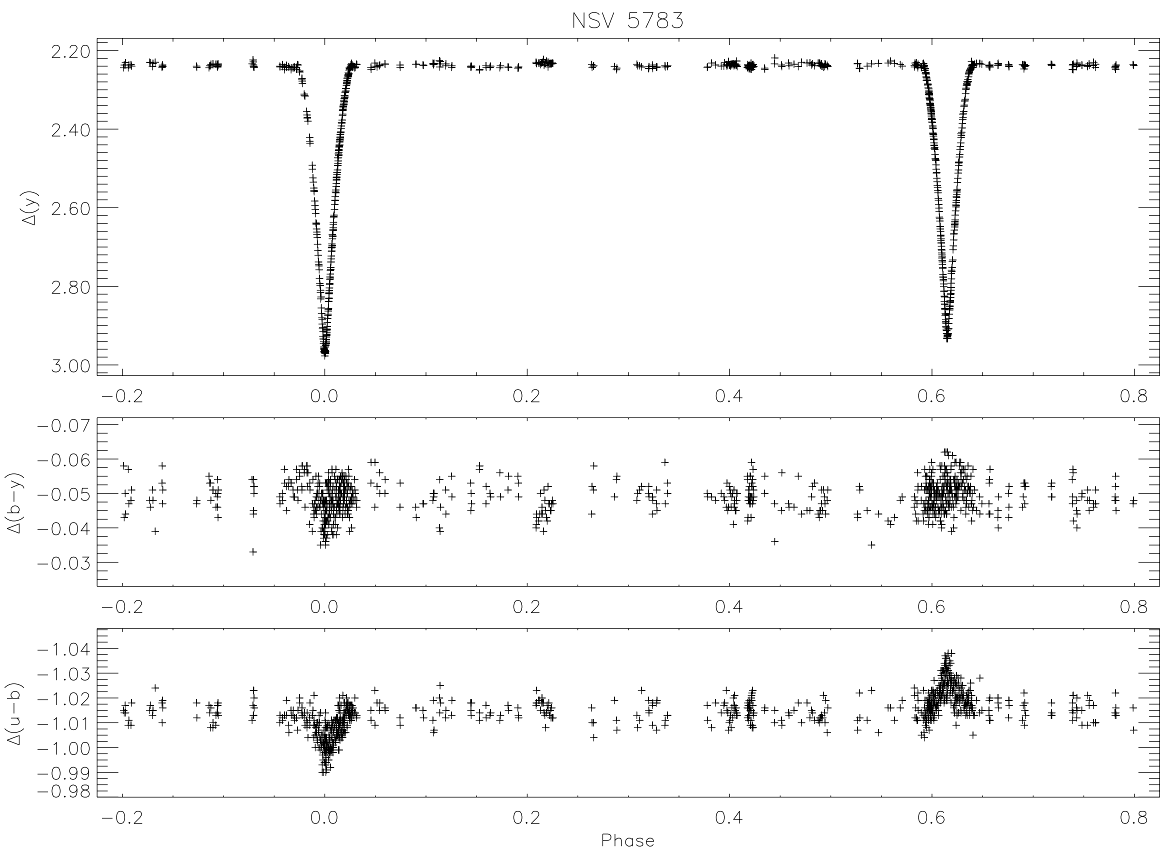

Fig. 4. y light curve and $b-y$ and $u-b$ colour curves (instrumental system) for NSV 5783.

Table 2. Photometric data for the eclipsing binaries and the comparison stars in the *uvby* and β standard systems. For the eclipsing binaries, the *uvby* information is given at maximum light level outside eclipses. The β information is the mean values outside eclipses. N is the total number of observations used to form the mean values, and σ is the rms error (per observation) in mmag.

Object	Sp. type	V	σ	$b-y$	σ	m_1	σ	c_1	σ	$N(uvby)$	β	σ	$N(\beta)$
DW Car	B1V+B1V	9.675	5	0.067	5	0.046	8	−0.017	8	7	2.528	7	7
HD 93191	A0	8.488	5	−0.011	3	0.157	4	0.824	4	2	2.804	5	2
HD 92072	B5V	7.044	4	−0.052	5	0.131	8	0.394	5	3	2.720	5	2
HD 92288	B6V	7.902	4	−0.033	1	0.130	2	0.482	4	3	2.705	2	2
BF Cen	B8	8.513	10	0.046	8	0.063	15	0.136	11	4	2.616	6	2
HD 100942	B8/B9V	7.770	16	0.026	5	0.114	8	0.708	7	16	2.797	6	7
HD 101466	A0IV	7.322	26	0.045	4	0.123	8	1.062	5	19	2.851	9	6
AC Vel	B3IV	8.869	8	0.118	3	0.044	4	0.309	1	4	2.637	5	4
HD 93943	B9.5IV-V	5.863	27	0.016	5	0.129	8	1.016	4	11	2.843	8	3
HD 92757	B9.5V	6.820	3	−0.029	2	0.180	1	0.945	2	3	2.891	4	2
HD 92155	B3V	6.430	1	−0.079	1	0.121	0	0.328	1	2	2.653	6	2
NSV 5783	B5V	8.679	8	0.011	4	0.107	9	0.391	6	8	2.695	2	4
HD 108925	A3V	6.477		0.068		0.183		1.141		1	2.842	7	2
HD 109808	A1/A2V	6.948	4	0.073	3	0.193	6	0.905	4	2	2.853	1	2

Table 3. Published *uvbyβ* photometry 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. References are: GO76 = Grønbech & Olsen (1976), GO77 = Grønbech & Olsen (1977), HM80 = Heck & Manfroid (1980), K98 = Kaltcheva (1998), KOC00 = Kaltcheva et al. (2000), K78 = Kilkenny (1978), K81 = Kilkenny (1981), K92 = Knude (1992), LPLM90 = Landolt et al. (1990), S85 = Shobbrook (1985), SHL92 = Slawson et al. (1992), TAT95 = Twarog & Anthony-Twarog (1995), WK83 = Wolf & Kern (1983).

Object	Ref.	Sp. type	V	σ	$b-y$	σ	m_1	σ	c_1	σ	$N(uvby)$	β	σ	$N(\beta)$
DW Car	–	B1V+B1V												
HD 93191	–	A0												
HD 92072	K98	B5V	7.119		−0.030		0.085		0.433			2.715		
	LPLM90		7.068	12	−0.046	4	0.115	8	0.423	8	17	2.702	8	15
HD92288	KOC00	B6V	7.893	17	−0.012	3	0.102	1	0.500	4	2	2.705	1	2
	LPLM90		7.904	5	−0.022	2	0.099	7	0.525	12	3	2.708	4	3
BF Cen	WK83	B8	8.54		0.054		0.029		0.172		1	2.609		1
	S85		8.62		0.058		0.010		0.150		4	2.619		3
HD 100942	KOC00	B8/B9V	7.762	2	0.011	3	0.138	5	0.698	11	3	2.800	7	1
HD 101466	KOC00	A0IV	7.318	3	0.034	8	0.143	8	1.052	0	2	2.858	7	1
	SHL92		7.35								2			
AC Vel	WK83	B3IV	8.88		0.155		–0.013		0.331		1	2.629		1
HD 93943	GO76,77	B9.5IV-V	5.865	8	0.018	7	0.122	10	1.029	1	2	2.848	5	3
HD 92757	–	B9.5V												
HD 92155	HM80	B3V	6.432	4	−0.069	2	0.096	6	0.356	6	6	2.654	4	5
NSV5783	K92	B5V	8.674		0.029		0.060		0.428			2.714		
	K81											2.696		2
	K78		8.69		0.023		0.075		0.410		3			
HD 108925	GO76, 77	A3V	6.448	8	0.087	8	0.153	4	1.172	3	2	2.853	9	3
	TAT95		6.452	2	0.081	4	–		–		4			
	SHL92		6.44								1			
HD 109808	SHL92	A1/A2V	6.934											

Hertzsprung (1924) discovered the eclipsing nature of DW Car, and photographic light curves have been published by him, by van den Hoven van Genderen (1941), and by Gaposchkin (1952, 1953), who also noted that the previously published value for the orbital period had to be doubled. Radial velocities and spectroscopic elements, based on 39–86 Å/mm photographic spectra, were published by Ferrer et al. (1985).

In this paper, we present the first accurate and complete photoelectric light curves of DW Car.

3.1. uvby light curves

Complete *uvby* light curves containing 518 points in each colour were observed on 28 nights during two periods between February 1987 and March 1988 (JD 2 446 825–JD 2 447 244). HD 93191, HD 92072, and HD 92288 were selected as comparison stars, and the two first stars were found to be constant within the observational accuracy of a few mmag during our observations; see Tables 1–3 for further information. Signs of very slight variations at the 5 mmag level were, however, noted for HD 92288, and it was consequently not used for the light curve calculations.

As seen in Fig. 1, DW Car consists of two detached components of nearly identical surface fluxes in a circular orbit. The eclipses have been covered several times and most out-of-eclipse phases at least twice.

3.2. Ephemeris

Three times of primary minimum (P) and four of secondary minimum (S), derived from the *uvby* observations, are given in Table 4. Sixty four additional times of minima, based on

Table 4. Times of minima determined from the new *uvby* photometry for DW Car. O–C values are calculated from the ephemeris given in Eq. (1) adopting a circular orbit. See van den Hoven van Genderen (1941) for additional times of minima.

HJD - 2 400 000	rms	Type	O–C
46 828.6692	0.0001	P	0.0000
46 852.5690	0.0010	P	0.0003
46 869.8296	0.0005	P	0.0002
46 826.6776	0.0001	S	0.0000
46 854.5600	0.0010	S	−0.0003
47 239.6060	0.0010	S	−0.0016
47 243.5913	0.0005	S	0.0004

photographic observations, were published by van den Hoven van Genderen (1941) and have been included in the ephemerides calculations.

Weighted (weight proportional to square of inverse rms.; we have assumed rms errors of 0.01 for the photographic data) least squares fits to all the times of primary and secondary minima yield periods of $1\overset{\mathrm{d}}{.}32774937 \pm 0.00000044$ and $1\overset{\mathrm{d}}{.}32774932 \pm 0.00000031$. respectively. Applying the method of Lafler & Kinman (1965) to the *uvby* light curves leads to a nearly identical period, and we adopt the ephemeris

$$\mathrm{Min\ I} = \underset{\pm 4}{2446828.6692} + \underset{\pm 44}{1\overset{\mathrm{d}}{.}32774934} \times E. \qquad (1)$$

3.3. Discussion

A detailed analysis of DW Car, based on the new *uvby* light curves and 29 high-resolution spectra obtained with the FEROS spectrograph at the ESO 1.52 m telescope (Kaufer et al. 1999, 2000) is published separately (Southworth & Clausen 2007). This is part of a study of selected eclipsing binaries in open clusters and associations (Clausen & Giménez 1987; Giménez & Clausen 1996; Clausen et al. 1996). DW Car is found to have evolved only slightly off the zero-age main-sequence (ZAMS) and hence is one of the youngest known candidates for accurate masses and radii in the 10 $M_{\odot}$ region (Hilditch & Bell 1987; Andersen 1991; Gies 2003; Hilditch 2004)

4. BF Cen

BF Cen (HD 100915, m_V = 8.51, Sp. type B8, $P = 3\overset{\mathrm{d}}{.}69$) is a southern double-lined eclipsing binary located near the edge of the young open cluster NGC 3766. Its variability was discovered by Oosterhoff (1928, 1930), who also determined an ephemeris. From two spectrograms, Popper (1966) found that BF Cen has broad, shallow, double lines.

Gaposchkin (1953) published a photographic light curve and Buckley (1982) part of a photoelectric light curve. CCD light curves in the V and I bands have been observed at the Las Campanas Observatory as part of the All Sky Automated Survey[1] (ASAS, Pojmański 1998). However, the photometric accuracy is only around 0.05 mag, so although the phase coverage is very good, the light curves are probably not suited for detailed light curve analyses.

Kraft & Landolt (1959) pointed out that BF Cen lies near NGC 3766, and Sahade & Dávila (1963) distinguished it as a certain member in their discussion of eclipsing binaries in galactic clusters. Its systemic velocity and colour excess agree precisely with the cluster means.

[1] `http://archive.princeton.edu/~asas/`

Table 5. Times of minima for BF Cen. O–C values are calculated from the ephemeris given in Eq. (2) adopting a circular orbit. References are: O28 = Oosterhoff (1928), O30 = Oosterhoff (1930), WR94 = Wolf & Ratzlaff (1994), OZ04 = Ogloza & Zakrzewski (2004).

HJD - 2 400 000	rms	Type	O–C	Ref.
19 878.270	0.01	P	−0.009	O30
23 974.257	0.01	P	+0.072	O28
23 985.231	0.01	P	−0.034	O28
24 262.292	0.01	P	+0.027	O28
24 288.200	0.01	P	+0.082	O28
25 381.313	0.01	P	−0.032	O30
25 418.272	0.01	P	−0.006	O30
45 055.7275	0.0003	P	+0.0002	This study
45 064.953	0.008	S	−0.008	WR94
45 087.100	0.009	S	−0.020	WR94
45 380.7405	0.0001	P	−0.0001	This study
47 628.128	0.005	S	−0.005	WR94
47 665.064	0.002	S	−0.003	WR94
50 556.9475	0.0031	S	+0.0012	OZ04
50 558.7950	0.0014	P	+0.0021	OZ04
51 238.3685	0.0010	P	+0.0024	OZ04
51 236.5238	0.0011	S	+0.0044	OZ04
51 531.9907	0.0065	S	+0.0047	OZ04
51 533.8332	0.0011	P	+0.0005	OZ04

4.1. uvby light curves

Complete *uvby* light curves containing 876 points in each colour were observed on 38 nights between January 1982 and April 1983 (JD 2 444 989–JD 2 445 449). HD 100942 and HD 101466 were selected 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 eclipses have been covered several times and most out-of-eclipse phases at least twice.

As seen in Fig. 2, BF Cen consists of two components of quite different surface fluxes, and as mentioned below the system is semi-detached. Primary eclipse is total, and some asymmetries, e.g. during central secondary eclipse, are present in the light curves. The orbit is circular.

4.2. Ephemeris

Two times of primary minimum (P), but none of secondary minimum (S), could be derived from the *uvby* observations and are given in Table 5 together with earlier and later published results.

Weighted (weight proportional to square of inverse rms; we have assumed rms errors of 0.01 for the photographic data) least squares fits to all the times of primary minima yield a period of $3\overset{\mathrm{d}}{.}6933326 \pm 0.0000014$, whereas the photoelectric/CCD results lead to $3\overset{\mathrm{d}}{.}6933336 \pm 0.0000004$, and the times of secondary minima to a slightly higher value of $3\overset{\mathrm{d}}{.}6933410 \pm 0.0000013$. Applying the method of Lafler & Kinman (1965) to the *uvby* light curves gives $3\overset{\mathrm{d}}{.}6933310$.

We adopt

$$\mathrm{Min\ I} = \underset{\pm 4}{2445055.7273} + \underset{\pm 14}{3\overset{\mathrm{d}}{.}6933326} \times E. \qquad (2)$$

It reproduces the epochs given by Gaposchkin (1952, 1953) to within 1–2 h.

4.3. Discussion

A preliminary analysis of BF Cen, based on the *uvby* light curves included here and 11 photographic ESO coudé spectra, has been presented by Helt et al. (1989). They find BF Cen to be a semi-detached Algol type system with component masses and radii of about 8.7 $M_{\odot}$ and 5.1 $R_{\odot}$ (primary), and 3.8 $M_{\odot}$ and 7.1 $R_{\odot}$ (secondary). Modern spectra are needed for a more detailed study; we do not intend to undertake such a project.

5. AC Vel

AC Vel (HD 93468, $m_V = 8.87$, Sp. type B3 IV, $P = 4\fd56$) is a southern double-lined eclipsing binary consisting of two stars, which have evolved to the TAMS region (6.6 and 6.8 $M_{\odot}$), plus at least one more star. Hertzsprung (1926) discovered its eclipsing nature, and an ephemeris and photographic light curves have been published by Gaposchkin (1952, 1953). We refer to Johansen et al. (1997) and Ilijić et al. (2004) for more recent information.

5.1. uvby light curves and times of minima

Complete *uvby* light curves containing 1525 points in each colour were observed on 69 nights between January 1982 and April 1984 (JD 2 444 989–JD 2 445 799). HD 93943, which is a close visual binary (IDS 10454-5848), and HD 92757 were selected 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 eclipses have been covered several times and out-of-eclipse phases at least twice. The y light curve is shown in in Fig. 3. Phases were calculated as described by Helt et al. (in prep.).

In order to establish a reliable ephemeris for AC Vel, additional eclipse observations were done, and it gradually became evident that a linear ephemeris was inadequate, meaning – since the orbit is circular – that the system contains more than two stars. Initial light curve analyses also pointed at the presence of third light. Between April 1984 and March 2003, six times of primary and eight times of secondary minimum were therefore established. In order to facilitate the automatic centering of SAT, one of the comparison stars, HD 93943, was replaced by HD 92155 after 1987. The times of minima will be presented as part of the full analysis of AC Vel.

5.2. Discussion

A detailed analysis of AC Vel, based on the new *uvby* light curves and 18 high-resolution spectra ($R = 48\,000$, 3800–8600 Å) obtained with the FEROS spectrograph at the ESO 1.52 m telescope (Kaufer et al. 1999, 2000) is published separately (Helt et al., in prep.). As mentioned above, the two eclipsing components of this multiple system have evolved to the TAMS region and are therefore important for e.g. studies of convective overshooting as a function of mass (e.g. Ribas et al. 2000).

6. NSV 5783

NSV 5783 (HD 109724, BV 1493, $m_V = 8.68$, Sp. type B5 V) was discovered by Strohmeier (1972) to be a bright southern variable. In March 1985, we included it in our program at the SAT and gradually discovered that it is an eclipsing binary with an eccentric ($e \sim 0.19$) 11-day period orbit. The literature on NSV 5783 is scarce; we have only been able to trace a few *uvbyβ* measurements included in Table 3.

Besides complete *uvby* light curves, we have obtained 5 high-resolution spectra with the FEROS spectrograph at the ESO 1.52 m telescope (Kaufer et al. 1999, 2000), allowing us to estimate absolute dimensions for the components in addition to determining accurate photometric elements.

6.1. uvby light curves

Complete *uvby* light curves containing 877 points in each colour were observed on 68 nights between March 1985 and April 1991 (JD 2 446 136–JD 2 448 370) using HD 108925 and HD 109808 as comparison stars. As seen from Table 1, the rms errors of their magnitude differences do not directly indicate any variability, but on a few nights, e.g. JD 2 446 819 (ingress of secondary eclipse) with about 40 observations of each star, the nightly mean differences are systematically off by about 5 mmag in all four bands. This indicates that at least one of the stars is variable, but from the available data it is not possible to identify safely which one it might be. Photometric solutions based on two sets of light curves generated by using either HD 108925 or HD 109808 as comparison agree well, and the O–C residuals between the observed and theoretical light curves on the deviating nights do not show any systematic offsets. Both sets of light curves, however, reveal that NSV 5783 itself might be variable at the 5–10 mmag level, since eclipse observations from different nights/seasons differ systematically by that amount in both sets of light curves. With masses of about 5 $M_{\odot}$ the components, or one of them, could potentially belong to the group of slowly pulsating B-stars (SPB). Analyses of the residuals of the *uvby* observations from the theoretical light curves however, do not reveal any significant frequences. On the other hand, as the observations were not sampled with the purpose of studying intrinsic variability we cannot exclude that they exist.

For the final light curves, we have chosen to use both comparisons and thereby minimize the effect of possible variability of one of them. We have also kept all nights, since photometric solutions from different subsets with eclipse observations from individual nights excluded agree well. The eclipses have been covered 2–3 times and out-of-eclipse phases at least twice. The y light curve is shown in Fig. 4. As seen, NSV 5783 consists of two well-separated components of comparable surface flux in an eccentric orbit; secondary eclipse occurs at phase 0.651. Both eclipses are about 0.7 mag deep, and the out-of-eclipse parts are practically flat.

6.2. Ephemeris

Three times of primary minimum and one of secondary minimum, derived from the *uvby* observations, are given in Table 6. A least squares fit to the three times of primary minima yield a period of $11\fd0774701 \pm 0.0000042$. Applying the method of Lafler & Kinman (1965) to the *uvby* light curves leads to $11\fd0774772$. We have adopted

$$\mathrm{Min\ I} = \underset{\pm 3}{2446181.7061} + \underset{\pm 42}{11\fd0774701} \times E \tag{3}$$

for the light curve analyses.

As already suggested by Giménez (1995), further times of minima for NSV 5783 should be obtained in order to improve

Table 6. Times of minima for NSV5783. O–C values (primary eclipse, P) and phase (secondary eclipse, S) are calculated from the ephemeris given in Eq. (3).

HJD - 2 400 000	rms	Type	O–C / Phase
46 170.6283	0.0001	P	−0.0003
46 181.7064	0.0001	P	0.0003
47 621.7772	0.0001	P	0.0000
47 628.5912	0.0001	S	0.6151

Table 7. Photometric solutions for NSV5783 from the EBOP code. Phase shift and magnitude normalization were included as free parameters. A mass ratio of 0.95 was assumed. The errors quoted for the free parameters are the *formal* errors determined from the iterative least squares solution procedure.

	y	b	v	u
i (°)	89.64 ±2	89.69 ±2	89.70 ±2	89.64 ±2
$e\cos\omega$	0.18170 ±3	0.18162 ±2	0.18162 ±2	0.18154 ±3
$e\sin\omega$	−0.0467 ±13	−0.0471 ±8	−0.0479 ±8	−0.0483 ±12
e	0.1876	0.1876	0.1878	0.1879
ω (°)	345.60	345.46	345.23	345.10
r_p	0.0808 ±5	0.0811 ±3	0.0813 ±3	0.0806 ±5
r_s	0.0789	0.0779	0.0775	0.0785
k	0.977 ±13	0.960 ±7	0.954 ±6	0.973 ±11
$r_p + r_s$	0.1596	0.1590	0.1588	0.1591
$u_p = u_s$	0.37 ±1	0.39 ±1	0.41 ±1	0.41 ±1
y_p	0.52	0.57	0.63	0.72
y_s	0.53	0.59	0.65	0.74
J_s/J_p	0.9632 ±29	0.9609 ±20	0.9581 ±18	0.9291 ±27
L_s/L_p	0.9193	0.8864	0.8722	0.8805
σ (mag)	0.0049	0.0034	0.0036	0.0048

the ephemeris and to establish if apsidal motion is present. The apsidal motion period predicted from our analysis and density concentration coefficients from theoretical models is, however, of the order of several thousand years.

6.3. Photometric elements

NSV 5783 is a well detached eclipsing binary with relative radii of the components of around 0.08. Deformation of the stars is very small (oblateness about 0.0008), and models based on two axial ellipsoids are therefore sufficient for the light curve analyses. Among the existing models, that by Nelson-Davis-Etzel (Nelson & Davis 1972; Etzel 1981; Martynov 1973) was selected. The corresponding EBOP code is described by Popper & Etzel (1981).

For the analysis, effective temperatures of T_p = 15 500 K and T_s = 15 000 K for the primary and secondary components, respectively, were assumed as estimated from the combined intrinsic *uvby* indices given in Table 2 and the $[u - b]$ and $(b - y)$ calibrations by Napiwotzki et al. (1993). Gravity darkening coefficients y corresponding to radiative atmospheres were adopted, and the simple built-in bolometric reflection model of EBOP was used. Linear limb darkening coefficients u, identical for the two components in each band, were included as free parameters. Adopting instead theoretical coefficients by Claret (2000),

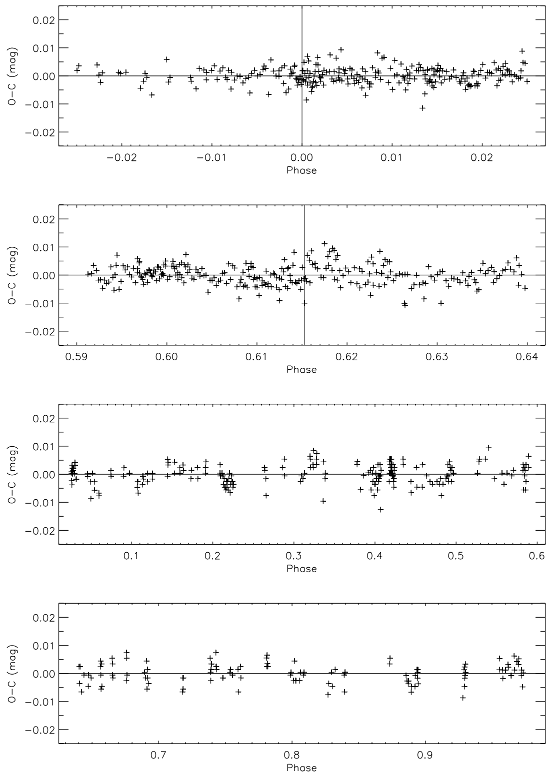

Fig. 5. Residuals (O–C) of the b observations of NSV 5783 from the theoretical light curve computed for the photometric elements given in Table 7. The slightly systematic residuals near central secondary eclipse are due to deviating observations from one night; see Sect. 6.1 for details.

which are 0.02–0.07 higher than those of the light curve analyses, does not change other photometric elements significantly. For the model calculations of the small stellar deformations, a mass ratio of q = 0.95 was assumed. An integration ring size of 5° was selected, and identical weights were assigned to all observations.

Solutions based on the *uvby* light curves are presented in Table 7, and (O−C) residuals in the b band are shown in Fig. 5. As seen, the elements obtained from the individual y, b, v, and u light curves agree well. Furthermore, practically identical elements are obtained from the extended WINK code (Wood 1971, 1972; Vaz 1984, 1986; Vaz & Nordlund 1985; Nordlund & Vaz 1990). About 93% of the light of the primary component is eclipsed at phase 0.0, and about 99% of the light of the secondary component at phase 0.615, i.e. secondary eclipse is almost total.

In Fig. 6, results from solutions for fixed $k = r_s/r_p$ values between 0.95 and 1.00 are shown. The preferred k range differ slightly between the four bands, and therefore the realistic error of k is somewhat larger than the formal errors given in Table 7. Also, for a given k, the y light curve is seen to give slightly larger (about 0.3%) relative radii for the components than the three other bands, and in u the orbital eccentricity e is slightly larger and the longitude of periastron ω slightly smaller.

Based on the solutions mentioned above, we have adopted the photometric elements for NSV 5783 listed in Table 8. Realistic errors are derived from comparison of the solutions for the four bands, as well as from Monte Carlo simulations; see e.g. Southworth et al. (2004b). We note that relative radii of a precision better than 1%, as well as solid orbital parameters, have been obtained.

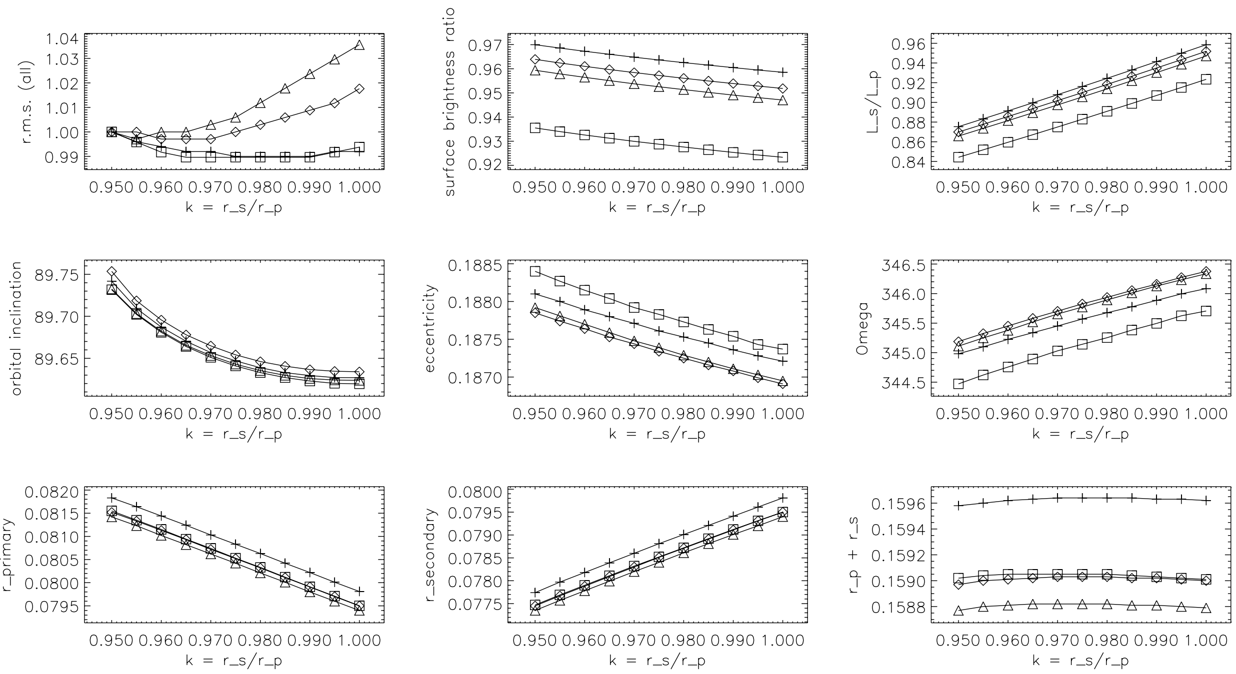

Fig. 6. EBOP solutions for NSV 5783 for a range of adopted $k = r_s/r_p$ values. The upper left figure shows the rms of the fit to the observations normalized to the value for $k = 0.95$. Symbols are: y cross, b diamond, v triangle, u square.

Table 8. Adopted photometric elements for NSV 5783. The individual flux and luminosity ratios are based on the mean stellar and orbital parameters.

i	$86\overset{\circ}{.}67 \pm 0\overset{\circ}{.}09$
$e\cos\omega$	0.18162 ± 0.00007
$e\sin\omega$	-0.0475 ± 0.0020
e	0.1877 ± 0.0005
ω	$345\overset{\circ}{.}4 \pm 0\overset{\circ}{.}6$
r_p	0.0810 ± 0.0006
r_s	0.0782 ± 0.0006
$r_p + r_s$	0.1592 ± 0.0003
k	0.966 ± 0.019

	y	b	v	u
J_s/J_p	0.968	0.963	0.956	0.929
	±12	±11	±11	±11
L_s/L_p	0.9019	0.8972	0.8938	0.8690
	±31	±20	±16	±24

6.4. Spectroscopic elements

5 high-resolution spectra have been obtained January-February and July 1999 with the FEROS fiber echelle spectrograph at the ESO 1.52 m telescope at La Silla, Chile (Kaufer et al. 1999, 2000); see Table 9. The spectrograph, which resides in a temperature controlled room, cover without gaps the spectral region from the Balmer jump to 8700 Å, at a constant velocity resolution of 2.7 km s^{-1} per pixel ($\lambda/\Delta\lambda = 48\,000$).

A modified version of the MIDAS FEROS[2,3] package, prepared by H. Hensberge, was used for the basic reductions. Compared to the standard package, background removal, definition and extraction of the individual orders, and wavelength calibration are significantly improved. The observations were reduced night by night using calibration exposures (ThAr and flat field) obtained during the afternoon/morning. Standard extraction (i.e. no optimization) was applied, and no order merging was attempted. Typically, a standard error of the wavelength calibration of 0.002–0.003 Å was obtained.

[2] http://www.ls.eso.org/lasilla/sciops/2p2/E2p2M/FEROS/DRS

[3] http://www.ls.eso.org/lasilla/sciops/2p2/E1p5M/FEROS/Reports

Table 9. FEROS spectra of NSV5783. S/N is the signal to noise ratio at approximately 5000 Å. The exposure time is 30 min for all spectra, and the Heliocentric Julian Dates correspond to mid-exposure. The radial velocities given in brackets are strongly affected by blending and have not been used to estimate the spectroscopic elements. See text for details.

HJD −2 400 000	ID	S/N	Phase	RV$_p$ (km s^{-1})	RV$_s$ (km s^{-1})
51 208.76908	s1	190	0.8097	86.2	−152.5
51 209.83220	s2	190	0.9056	(58.5)	(−88.7)
51 211.79340	s3	160	0.0827	(−61.1)	(36.0)
51 212.87435	s4	125	0.1803	(−124.7)	(4.9)
51 374.59662	s5	75	0.7795	83.2	−160.6

As seen on Fig. 7, the lines are heavily broadened to at least 150 km s^{-1}, which is about 6 times the pseudosynchronous value at periastron. Double-Gaussian fits to the HeI line at 5875 Å, which is the best one available, yield the radial velocities listed in Table 9. Unfortunately, two components of the line are only clearly visible on two of the five spectra (s1 and s5), and we have discarded the measurements from the three other spectra.

In order to estimate the spectroscopic elements from this very limited material, we have measured the system velocity on spectrum s3, taken quite close to phase 0.0, and then adopted this value (–33 km s^{-1}) plus e and ω from the photometric solution (Table 8). The resulting semiamplitudes are $K_p = 100.9 \pm 1.3$

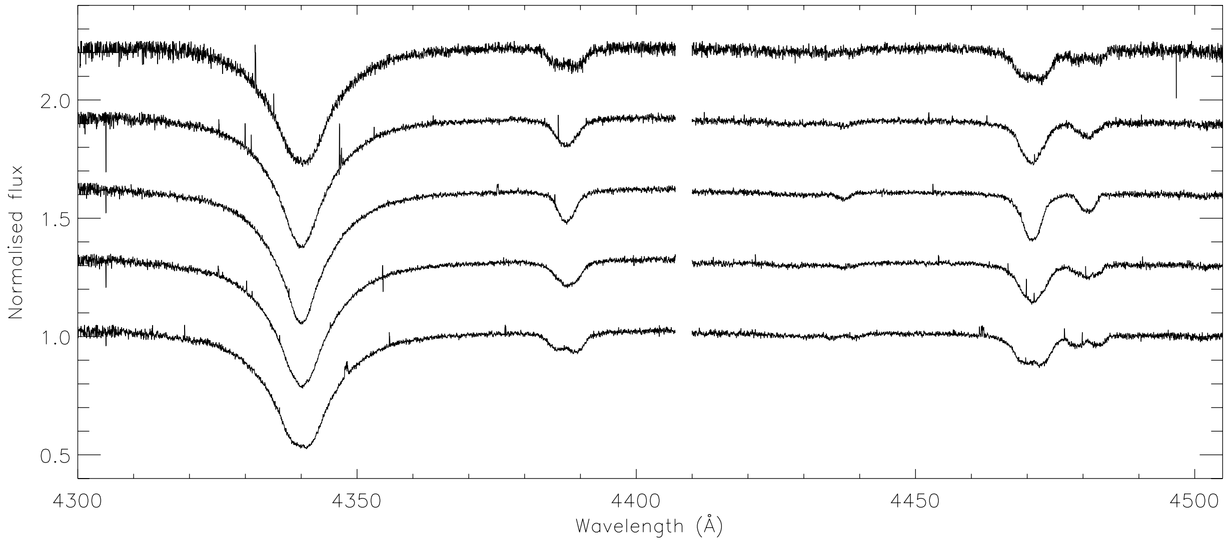

Fig. 7. The 4300–4500 Å region of normalized FEROS spectra of NSV 5783. The four strongest (double) lines shown in the two orders (51 and 50) are H_γ 4340 Å, HeI 4388 Å, HeI 4472 Å, and MgII 4481 Å. Spectrum s1 (see Table 9) is displayed at the bottom and s5 at the top; a horizontal shift of 0.3 has been added between the spectra.

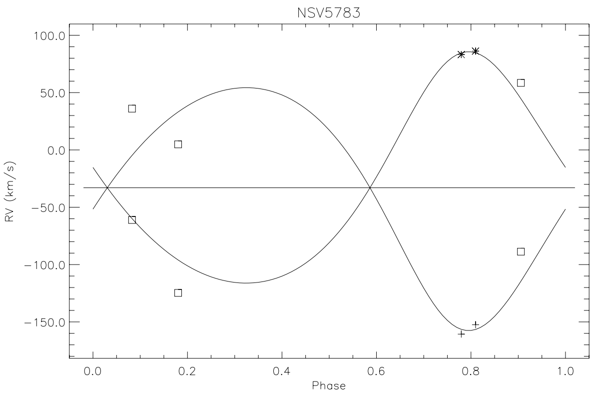

Fig. 8. Radial velocities and adopted spectroscopic orbit for NSV 5783. Symbols are: *primary* asterisk, *secondary* plus, *not used* square.

and $K_s = 105.9 \pm 3.5$ km s^{-1}. Realistic errors of the semiamplitudes will be significantly larger, and for calculation of masses and radii, we have used 10 km s^{-1} for both components. The measured radial velocities, including the rejected ones, and the spectroscopic orbit are shown in Fig. 8.

Due to the quite large semi-major axis of the orbit of $A = 44.6 \pm 4.2\ R_\odot$ and an orbital period of 11.1 days, the velocity amplitudes are small compared to the large rotational broadening of the spectral lines. However, applying disentangling on a sufficient number of spectra, it should be possible to obtain accurate spectroscopic elements and good individual component spectra for abundance analyses. Furthermore NSV 5783 has the advantage that the spectrum of the primary component can be obtained during central secondary eclipse, which is practically total. We plan to secure these observations in the future.

6.5. Discussion

Preliminary absolute dimensions for the components of NSV 5783 have been calculated from the photometric elements given in Table 8 and the spectroscopic elements obtained from the few FEROS spectra, assuming conservatively an accuracy of 10 km s^{-1} of the semiamplitudes. Individual *uvby* indices are calculated from the combined indices outside eclipses (Table 2) and the luminosity ratios (Table 8). The $(b-y)_0 - c_0$ relation by Crawford (1978) yields a reddening of $E_{b-y} = 0.087$ corresponding to $A_V = 0.37$. The effective temperatures given in Table 10 are average values derived from the empirical calibrations by Napiwotzki et al. (1993) and Davis & Shobbrook (1977). Errors include the uncertainty of the photometric indices and calibration differences. The $[u-b]$ calibrations agree perfectly well giving temperatures of 15 200 K and 14 900 K for the primary and secondary, respectively, whereas the c_0 calibration by Davis & Shobbrook and a similar c_0 calibration established

Table 10. Astrophysical data for NSV 5783. $T_{\mathrm{eff}\odot} = 5780$ K, $B.C._\odot = -0.08$, and $M_{\mathrm{bol}\odot} = 4.74$ has been assumed, and bolometric corrections by Flower (1996) have been adopted.

	Primary	Secondary
Absolute dimensions:		
$M/M_\odot$	4.95 ± 1.06	4.72 ± 1.03
$R/R_\odot$	3.61 ± 0.25	3.48 ± 0.24
$\log g$ (cgs)	4.02 ± 0.11	4.03 ± 0.11
Photometric data:		
V	9.414	9.449
$(b-y)$	0.009	0.013
m_1	0.105	0.109
c_1	0.380	0.402
$E(b-y)$	0.086	0.088
$(b-y)_0$	−0.077	−0.075
c_0	0.363	0.384
$[u-b]$	0.594	0.625
$\log T_{\mathrm{eff}}$	4.196 ± 0.014	4.188 ± 0.014
M_{bol}	−2.39 ± 0.21	−2.23 ± 0.21
$\log L/L_\odot$	2.85 ± 0.08	2.79 ± 0.08
$B.C.$	−1.37	−1.32
M_V	−1.02 ± 0.21	−0.91 ± 0.21
$V_0 - M_V$	10.02 ± 0.15	
Distance (kpc)	1.0± 0.1	

from the temperatures and indices used by Napiwotzki et al. yield 16 200 K and 15 900 K. Both indices are good temperature indicators; $[u-b]$ is preferred by Napiwotzki et al. because it is slightly more sensitive than c_0, whereas Davis & Shobbrook argue in favour of c_0 due to its smaller reddening correction. The $(b-y)$ calibration by Napiwotzki et al. give intermediate results of 15 800 K and 15 400 K.

From comparison between the preliminary absolute dimensions and theoretical stellar models (e.g. Claret 1995; hydrogen abundance $X = 0.70$, metal abundance $Z = 0.02$), the components of NSV 5783 appear to have evolved just slightly off the ZAMS, supporting our finding that their rotation is far from having yet been synchronized. An age of about 5×10^7 yr is estimated.

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