Mon. Not. R. Astron. Soc. **347,** 307–315 (2004)

Long-term photometric study of the W UMa binary star V523 Cas

X. B. Zhang★ and R. X. Zhang
National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012, China

Accepted 2003 September 10. Received 2003 September 10; in original form 2003 July 23

ABSTRACT

We present a long-term photoelectric and charge-coupled device (CCD) photometric study of the short-period W UMa star V523 Cas made from 1986 to 2000. The orbital-period changes and light-curve variations of the binary system are studied. 47 new times of minima are obtained from our data. A period study covering more than 43 000 cycles based on the photoelectric and CCD photometric times of minima confirms the long-term, secular period changes of the system. It is found that the orbital period has been continuously increasing in the past three decades at a rate of $\mathrm{d}P/\mathrm{d}t = 8.84 \times 10^{-8}$ d yr^{-1}. No cyclic period variations are found from our result. Eight V and five B completely covered light curves are formed from the observations made in eight epochs. The light curves are of W UMa type and show marked asymmetries with unequal maxima. The differences between the two maxima in each light curve appear to be cyclic over a time-scale of about 8 yr. Based on a one-spot model, the light curves are analysed with the Wilson–Devinney code. The photometric solutions reveal a W-subtype, contact configuration for V523 Cas. The photometric mass ratio is found to be 0.51, and the masses and radii for the components are deduced as 0.75 ± 0.03 M$_\odot$, 0.74 ± 0.04 R$_\odot$ for the primary and 0.38 ± 0.02 M$_\odot$, 0.55 ± 0.02 R$_\odot$ for the secondary, respectively. We discuss the evolutionary status of the system as well as the possible spot activity along with the mass transfer among the components.

Key words: binaries: eclipsing – stars: individual: V523 Cas – stars: late-type.

1 INTRODUCTION

V523 Cas (Wr 16, GSV 5867, GSC 03257−00167) is an overcontact, W-type W UMa binary system with a very short orbital period. Its variability was discovered by Weber (1957). Haussler (1974a,b) provided the first light curve and period, and he classified it as a W UMa star through photographic observations. At about 0.23 d, the orbital period of V523 Cas is one of the really shortest among late-type W UMa stars. It has been studied frequently in the past decades. A series of photometric studies have been made on the system by several groups (Lavrov & Zhukov 1976; Bradstreet 1981; Hoffman 1981; Giurincin, Mardirossian & Mezzetti 1982; Zhukov 1985; Maceroni 1986; Samec & Bookmyer 1987; Samec, van Hamme & Bookmyer 1989; Lister, McDermid & Hilditch 2000; Elias & Koch 2000). The first radial velocity measurements were made by Milone, Hrivnak & Fisher (1985). The results of most of the photometric studies mentioned revealed a W-type, overcontact configuration for the system. The values of the mass ratio derived from photometric solutions, which range from 0.5 to 0.6, however, are quite discrepant with the mass ratio of 0.42 determined from the spectroscopic study. This result was found by Maceroni (1986) and reviewed in detail by Samec et al. (1989) and Lister et al. (2000). Very recently, Rucinski et al. (2003) contributed a new spectroscopic study of V523 Cas. Based on a much improved radial velocity curve, they provided a mass ratio of 0.516 ± 0.008, which is close to the photometric result of Lister et al. (2000). It would seem that the long dispute about the discrepancy between the photometric and spectroscopic mass ratio of V523 Cas is over.

V523 Cas is also noted for its light-curve variations and large period changes. The light-curve variations of V523 Cas were first studied by Zhukov (1985). With all available light curves published previously, he found both long-term and short-term cyclic variations, which were interpreted as the existence of a 10–12 yr sunspot cycle on the primary component of the system. Such cyclic light-curve variations were later confirmed by Samec & Bookmyer (1987). However, they argued that the variations might be caused by an O'Connell effect (O'Connell 1951) with a possible period of about 5 yr. Based on a starspot hypothesis, Samec et al. (1989) and later Elias & Koch (2000) modelled the asymmetry of the light curves.

The large period changes of V523 Cas have been indicated by many authors (Hoffman 1981; Samec & Bookmyer 1987; Lister et al. 2000; Elias & Koch 2000). A very recent period study of the system was contributed by Samec et al. (2001). Based on a large collection of minimum light timings with a time-span of about 100 yr, their period study confirmed the long-term period increase of the system. In addition to the secular period changes,

★E-mail: xzhang@bao.ac.cn

they further found a sinusoidal variation from the O–C residuals. Samec et al. (2001) thus suggested that V523 Cas could be a triple star system containing a third companion with a period of about 101 ± 8 yr.

For the peculiar behaviour in light-curve variations and period changes, V523 Cas has been listed as one of the programming targets of our long-term photometric observations. Since 1986, we have observed this system for 10 campaigns in 15 yr and collected a large amount of measurements. In this paper we shall report the observations and investigate the long-term photometry of V523 Cas. Our aim is to study the main characteristics of the period and light-curve variations, and to derive the photometric solution for the system based on the Wilson–Devinney code (Wilson & Devinney 1971; Wilson 1979, 1990).

2 OBSERVATIONS

All the observations were carried out at the Xinglong Station of the National Astronomical Observatories, Chinese Academy of Sciences. From 1986 to 2000, we have observed V523 Cas in 10 observing seasons of 1986, 1988, 1990, 1991, 1992 (three), 1994, 1996 and 2000. In Table 1, we give the relevant information about the long-term photometry.

All the observations from 1986 to 1994 were made on the 60-cm reflector equipped with a single-channel photoelectric photometer. In these observations, we used two nearby stars, GSC 3257−1068 ($\alpha_{2000} = 00^{\mathrm{h}}40^{\mathrm{m}}24^{\mathrm{s}}$, $\delta_{2000} = +50^\circ17'53''$) and GSC 3257−1326 ($\alpha_{2000} = 00^{\mathrm{h}}40^{\mathrm{m}}24^{\mathrm{s}}$, $\delta_{2000} = +50^\circ20'21''$), as comparison and check stars, respectively. Usable data were obtained in 21 nights. The differences in magnitude between the variable and comparison stars were corrected for differential extinction and transformed into the *UBV* system. The deviations of the magnitude difference between the comparison and the check stars are generally less than 0.01 mag.

The 1996 observations were made on the 85-cm Cassegrain telescope with a three-channel photometer. We used the star GSC 3257−1262 ($\alpha_{2000} = 00^{\mathrm{h}}40^{\mathrm{m}}15^{\mathrm{s}}$, $\delta_{2000} = +50^\circ07'15''$) as comparison. No check star was monitored for instrumental reasons. The exposure times were set as 10 s. A single *V* filter was used. The charge-coupled device (CCD) photometry in 2000 was carried out also on the 85-cm telescope with a red-sensitive Thomson TH7782 576 × 384 CCD photometer (Wei, Chen & Jiang 1990; Zhang, Zhang & Fang 2002; Zhang & Zhang 2003). A Johnson *V* filter was used. The exposure time was 30 s for each measurement. The comparison and check stars are the same as that used for the 1986–1994 observations. The data reductions for the 1996 and 2000 observations were made following that described by Zhang et al. (2002).

3 THE ORBITAL-PERIOD CHANGE

A total of 47 epochs of minimum light were determined from our data, including 24 primary and 23 secondary eclipses. By using the K-W method (Kwee & van Woerden 1956), the times of minima were derived. These are listed in Table 2 along with all the available photoelectric and CCD times of minimum light published since Lavrov & Zhukov (1976). The collected times of minima in Table 2 cover a time interval of about 30 yr, spanning nearly 43 000 orbits. This enables us to discuss the long-term period variations of V523 Cas precisely.

Using the method of least squares, we calculated the following new linear and quadratic ephemerides

$$\text{Min. I (HJD)} = 2446708.7768(\pm5) + 0^{\mathrm{d}}.23369162(\pm3)E,$$

$$\text{Min. I (HJD)} = 2446708.7708(\pm2) + 0^{\mathrm{d}}.23369169(\pm1)E + 2.83(\pm6)\times10^{-11}E^2.$$

The O–C residuals for all the times of minimum light with respect to the linear and quadratic ephemerides are given in Table 2. In Fig. 1, we present the O–C diagrams of the period analysis. The left panel in Fig. 1 illustrates the quadratic fit to the linear O–C residuals from the second ephemeris, and the right panel plots the final residuals calculated from the quadratic ephemeris. It strongly suggests that the system was undergoing a long-term, strictly continuous period increase during the past 30 yr. The rate of the orbital-period increase turns out to be $\mathrm{d}P/\mathrm{d}E = 5.66\times10^{-11}$ d cycle^{-1}, or $\mathrm{d}P/\mathrm{d}t = 8.84\times10^{-8}$ d yr^{-1}. This value is close to the results recently obtained by Lister et al. (2000) but much larger than that derived by Samec et al. (2001). Moreover, unlike Samec et al. (2001), we did not find any obvious evidence for cyclic period variations from the final O–C residuals of the present study.

4 THE LIGHT CURVES AND PHOTOMETRIC ANALYSIS

4.1 The asymmetry and variations of the light curves

Using the new quadratic ephemeris derived above, we calculated the phases for all the measurements obtained from the long-term photometry. These observations were finally formed into eight *V*-band and five *B*-band complete covered light curves. They are presented in the left panel of Fig. 2 as Δm versus phase. In Table 3 we list the main feature parameters of the *V*-band light curves observed in the eight different epochs, including the depths of eclipses to the primary maximum light (Max. I − Min. I and Max. I − Min. II) and the differences between the primary and secondary maximum

Table 1. Information on the observations of V523 Cas.

Year	Obs. time (UT)	Telescope	Photometer	Filter	Comparison	Note
1986	Dec. 5, 6	60 cm	single channel	B, V	GSC 3257−1068	LC1986
1988	Nov. 19, 20, 21	60 cm	single channel	B, V	GSC 3257−1068	LC1988
1990	Dec. 15, 17	60 cm	single channel	B, V	GSC 3257−1068	LC1990
1991	Oct. 8, 11	60 cm	single channel	B, V	GSC 3257−1068	no complete LC
1992	Jan. 7, 8, 13	60 cm	single channel	B, V	GSC 3257−1068	LC1992a
1992	Oct. 20, 22	60 cm	single channel	B, V	GSC 3257−1068	LC1992b
	Nov. 19, 20	60 cm	single channel	B, V		
1994	Jan. 3, 4, 6	60 cm	single channel	B, V	GSC 3257−1068	LC1994
1996	Dec. 17, 18	85 cm	three channel	V	GSC 3257−1262	LC1996
2000	Sep. 16	85 cm	CCD	V	GSC 3257−1068	LC2000

Table 2. Photoelectric and CCD times of minima for V523 Cas and residuals calculated from the linear and quadratic ephemerides.

HJD 240 0000+	*E*	$(O–C)_1$ (d)	$(O–C)_2$ (d)	Ref.[a]	HJD 240 0000+	*E*	$(O–C)_1$ (d)	$(O–C)_2$ (d)	Ref.[a]
41213.5271	−23515.0	0.0088	0.0008	1	48243.1908	6566.0	−0.0055	−0.0009	5
41220.3028	−23486.0	0.0075	−0.0005	1	48503.4087	7679.5	−0.0034	0.0007	6
41223.4570	−23472.5	0.0068	−0.0012	1	48503.5245	7680.0	−0.0043	−0.0002	6
41225.4430	−23464.0	0.0065	−0.0015	1	48538.2288	7828.5	−0.0032	0.0008	5
41226.4944	−23459.5	0.0063	−0.0017	1	48541.1482	7841.0	−0.0050	−0.0010	5
41585.4447	−21923.5	0.0062	0.0001	1	48541.2660	7841.5	−0.0040	0.0000	5
41588.2470	−21911.5	0.0042	−0.0019	1	48629.0171	8217.0	−0.0041	−0.0003	5
41593.3901	−21889.5	0.0061	0.0000	1	48629.1354	8217.5	−0.0027	0.0011	5
41599.3503	−21864.0	0.0071	0.0011	1	48630.0704	8221.5	−0.0024	0.0014	5
41942.5247	−20395.5	0.0054	0.0010	1	48634.9775	8242.5	−0.0029	0.0009	5
41945.3300	−20383.5	0.0064	0.0020	1	48635.0939	8243.0	−0.0033	0.0005	5
41945.4480	−20383.0	0.0075	0.0032	1	48916.1082	9445.5	−0.0032	−0.0001	5
41950.3535	−20362.0	0.0055	0.0012	1	48916.2249	9446.0	−0.0033	−0.0002	5
41966.3606	−20293.5	0.0047	0.0005	1	48918.0968	9454.0	−0.0010	0.0021	5
41968.4640	−20284.5	0.0049	0.0007	1	48918.2122	9454.5	−0.0024	0.0007	5
41972.5531	−20267.0	0.0044	0.0002	1	48918.3284	9455.0	−0.0031	0.0000	5
41973.4876	−20263.0	0.0041	−0.0001	1	48946.0206	9573.5	−0.0033	−0.0003	5
41975.5925	−20254.0	0.0058	0.0016	1	48946.1384	9574.0	−0.0024	0.0007	5
41983.4188	−20220.5	0.0034	−0.0007	1	48946.2555	9574.5	−0.0021	0.0009	5
41985.5215	−20211.5	0.0029	−0.0012	1	48946.9553	9577.5	−0.0034	−0.0004	5
42036.4668	−19993.5	0.0034	−0.0005	1	48947.0714	9578.0	−0.0041	−0.0011	5
42037.1687	−19990.5	0.0043	0.0004	1	48947.1892	9578.5	−0.0032	−0.0001	5
44060.8134	−11331.0	−0.0037	−0.0005	2	48947.3049	9579.0	−0.0043	−0.0013	5
44062.8004	−11322.5	−0.0031	0.0001	2	49356.0360	11328.0	0.0001	0.0020	5
44102.7609	−11151.5	−0.0039	−0.0005	2	49356.1522	11328.5	−0.0005	0.0013	5
44117.7180	−11087.5	−0.0031	0.0003	2	49356.9686	11332.0	−0.0021	−0.0002	5
44132.6742	−11023.5	−0.0031	0.0003	2	49357.0817	11332.5	−0.0058	−0.0039	5
44133.8424	−11018.5	−0.0034	0.0001	2	49359.0724	11341.0	−0.0015	0.0004	5
44136.6469	−11006.5	−0.0032	0.0003	2	50434.9907	15945.0	0.0005	−0.0014	5
44136.7633	−11006.0	−0.0036	−0.0002	2	50435.1062	15945.5	−0.0008	−0.0028	5
44136.8802	−11005.5	−0.0036	−0.0001	2	50435.2233	15946.0	−0.0006	−0.0025	5
44140.7352	−10989.0	−0.0045	−0.0010	2	50436.0394	15949.5	−0.0024	−0.0044	5
44154.6409	−10929.5	−0.0034	0.0001	2	50436.1577	15950.0	−0.0009	−0.0029	5
44154.7573	−10929.0	−0.0039	−0.0004	2	50770.6912	17381.5	0.0030	−0.0004	7
44162.5858	−10895.5	−0.0040	−0.0005	2	50770.8094	17382.0	0.0043	0.0009	7
44162.7030	−10895.0	−0.0037	−0.0002	2	50772.6782	17390.0	0.0036	0.0002	7
44191.3291	−10772.5	−0.0048	−0.0012	3	50772.7956	17390.5	0.0042	0.0007	7
44194.4828	−10759.0	−0.0060	−0.0024	3	50773.7307	17394.5	0.0045	0.0011	7
44195.5363	−10754.5	−0.0041	−0.0005	3	50774.6647	17398.5	0.0037	0.0003	7
44200.3262	−10734.0	−0.0048	−0.0012	3	50774.7814	17399.0	0.0036	0.0001	7
46706.6682	−9.0	−0.0056	0.0006	4	51071.6881	18669.5	0.0051	0.0002	8
46707.7191	−4.5	−0.0063	−0.0001	4	51071.8047	18670.0	0.0048	0.0000	8
46707.8367	−4.0	−0.0056	0.0006	4	51071.9222	18670.5	0.0055	0.0007	8
46707.9531	−3.5	−0.0060	0.0002	4	51072.7395	18674.0	0.0049	0.0000	8
46708.6544	−0.5	−0.0058	0.0004	4	51072.8566	18674.5	0.0051	0.0003	8
46708.7714	0.0	−0.0057	0.0006	4	51073.7928	18678.5	0.0065	0.0017	8
46769.9989	262.0	−0.0054	0.0008	5	51073.9081	18679.0	0.0050	0.0002	8
46770.1154	262.5	−0.0057	0.0005	5	51142.2632	18971.5	0.0053	0.0001	9
46770.2329	263.0	−0.0051	0.0011	5	51142.3795	18972.0	0.0041	−0.0011	9
46771.0505	266.5	−0.0054	0.0008	5	51146.4695	18989.5	0.0051	0.0000	9
46771.1674	267.0	−0.0053	0.0009	5	51146.5855	18990.0	0.0043	−0.0009	9
46771.2847	267.5	−0.0049	0.0013	5	51162.2431	19057.0	0.0046	−0.0007	10
47424.2178	3061.5	−0.0062	−0.0004	5	51162.3609	19057.5	0.0055	0.0003	9
47424.3348	3062.0	−0.0060	−0.0003	5	51162.4768	19058.0	0.0046	−0.0007	9
47425.1521	3065.5	−0.0067	−0.0009	5	51171.3579	19096.0	0.0054	0.0001	9
47425.2696	3066.0	−0.0060	−0.0002	5	51468.3824	20367.0	0.0078	0.0010	11
47426.2043	3070.0	−0.0061	−0.0003	5	51747.8792	21563.0	0.0094	0.0011	12
48241.0877	6557.0	−0.0054	−0.0008	5	51804.0833	21803.5	0.0107	0.0021	5
48241.2044	6557.5	−0.0056	−0.0009	5	51804.1987	21804.0	0.0092	0.0006	5
48243.0771	6565.5	−0.0024	0.0022	5	51822.4267	21882.0	0.0093	0.0006	13

[a]1, Lavrov & Zhukov (1976); 2, Bradstreet (1981); 3, Hoffman (1981); 4, Samec & Bookmyer (1987); 5, present study; 6, Agerer (1992); 7, Elias & Koch (2000); 8, Samec et al. (2001); 9, Lister et al. (2000); 10, Blatter (1999); 11 Agerer & Hubscher (2001); 12, Nelson (2001); 13, Probulla et al. (2001).

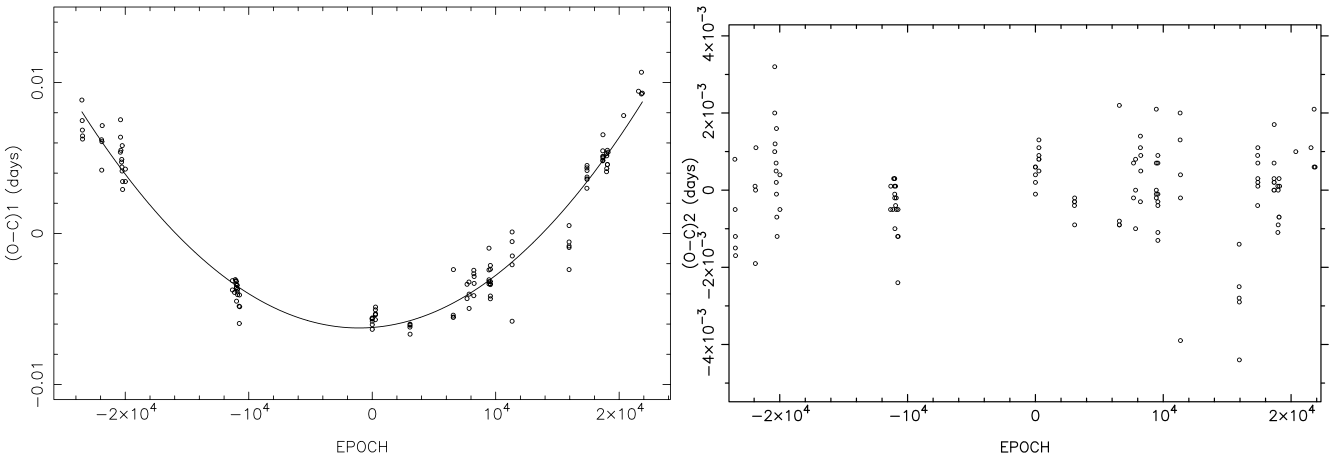

Figure 1. Period behaviour of V523 Cas. The left panel illustrates the linear O–C residuals and the quadratic fit. Circles represent the photoelectric and CCD times of minima. The right panel represents the final residuals calculated from the quadratic ephemeris.

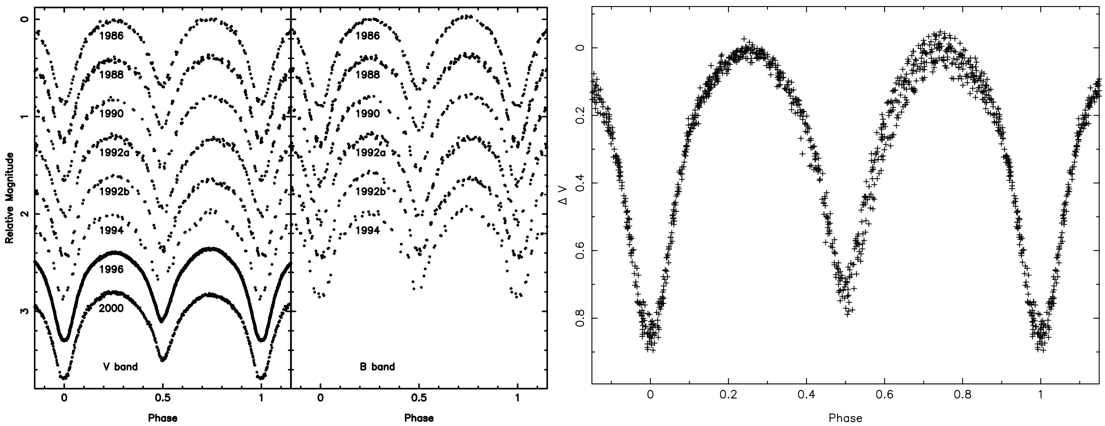

Figure 2. All the light curves obtained in 1986–2000 (left) and the compound *V* light curve of V523 Cas (right).

Table 3. Main feature parameters of the *V*-band light curves of V523 Cas obtained in different epochs.

Epoch	Max. I − Min. I	Max. I − Min. II	Max. II − Min. I	Max. II − Min. II	Max. I − Max. II
1986.93	−0.86	−0.69	−0.84	−0.67	l0.02
1988.88	−0.85	−0.70	−0.82	−0.67	l0.03
1990.96	−0.85	−0.70	−0.85	−0.67	l0.03
1992.03	−0.85	−0.72	−0.88	−0.75	−0.03
1992.83	−0.85	−0.72	−0.88	−0.75	−0.03
1994.01	−0.89	−0.70	−0.86	−0.67	l0.03
1996.96	−0.89	−0.70	−0.85	−0.66	l0.04
2000.70	−0.89	−0.70	−0.93	−0.74	−0.04

light (Max. I − Max. II) for each light curve. Here, the primary and secondary maxima are defined as that following the primary and secondary minima, respectively.

The general feature of the light curves is typical of W UMa systems. It is clear that almost all the light curves detected show marked asymmetry and obvious variations from one epoch to another. It seems that the asymmetry and variations of the light curves in different epochs occur in a 'same' range of phase. From Table 3, we find that the eclipse depths to the primary maximum seem to remain nearly constant, while the difference between the primary and secondary maxima varies obviously with time. In some epochs (1986, 1988, 1990, 1994 and 1996), the secondary maximum is brighter than the primary; in the other seasons (1992 and 2000), the secondary is clearly fainter than the primary. To show the light-curve variations more clearly, we plot all the eight *V*-band light curves together in one panel after zero-point shift corrections (Fig. 2b). It is found that all the light curves fit each other well in most parts of a cycle except the part with phases between 0.6 and 0.9. This

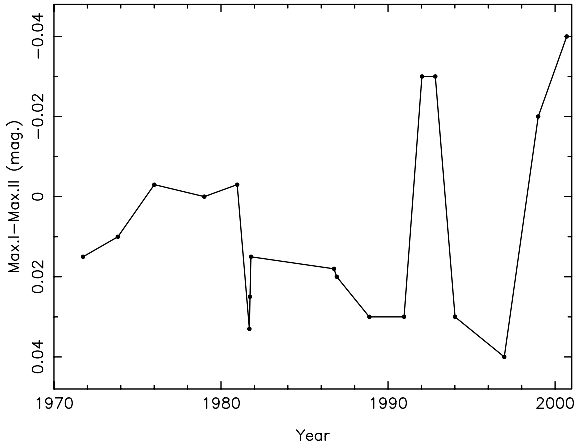

Figure 3. The variations of δm = Max.I − Max.II of the light curve of V523 Cas in different epochs.

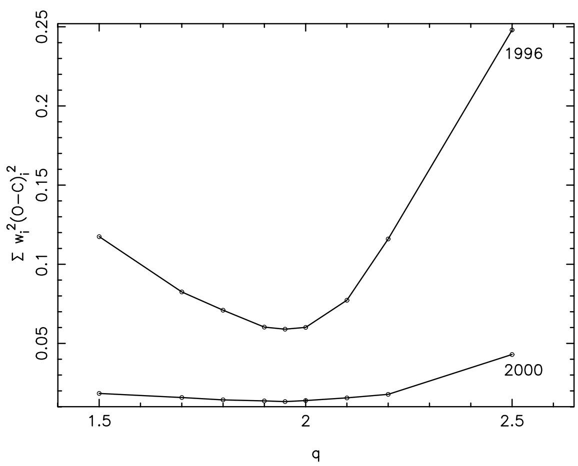

Figure 4. The plot of $\sum w_i^2(\mathrm{O-C})_i^2$ versus q_i for the test solutions of the 1996 and 2000 light curves.

indicates that the light-curve variations of V523 Cas may depend mainly on the brightness changes of the maximum light following the secondary eclipse.

Zhukov (1985) stated that V523 Cas displays a strong O'Connell effect. He inspected the behaviour of the difference between the maxima of the light curves observed between epochs 1971.74 and 1981.79, and declared a 10–12 yr cyclic variation. Samec & Bookmyer (1987) studied the subject again on V523 Cas and suggested a probable period of about 5 yr for its light-curve variations, although they found that such a cyclic variation is not apparent. They argued that, to evaluate the true nature of the variations, more light curves over a longer time are needed. In Fig. 3, we add our data for δm = Max.I − Max.II to those published by Zhukov (1985) and Samec & Bookmyer (1987) and plot the diagram of the long-term variations of δm. In this figure, a data point of $\delta m = -0.02$ with epoch of 1998.99 is estimated from the figure of light curves published by Lister et al. (2000). It shows that the amplitude of Max. I − Max. II was indeed undergoing a systematic and continuous variation in the past 30 yr, which appears to be somewhat cyclic but not strictly periodic. The time-scale of the light curve variations is about 8 yr or so.

The asymmetry of the light curves of V523 Cas is generally suggested to be caused by starspot activity (Zhukov 1985; Samec & Bookmyer 1987). With the starspot hypothesis, Samec et al. (1989) and Elias & Koch (2000) successfully modelled the asymmetry of their light curves. Following them, we will analyse the light curves in the present work also based on a starspot model.

4.2 Photometric solutions

We used the Wilson–Devinney (WD) method for light-curve analysis. The 1992 version of the WD code (Wilson & Devinney 1971; Wilson 1979, 1990) was employed. All the individual light curves were combined into normal points and were used for further analysis.

According to photometric analysis by previous authors, V523 Cas is a W-subtype contact system. The less-massive component has the higher surface temperature and contributes less brightness for the system. It should be the star eclipsed during the primary minimum. Thus we defined the less-massive component as star 1 and the massive component as star 2 in the following analysis. The following assumptions were made in the computation of photometric solutions. The temperature of star 2 was set at $T_2 = 4410$ K, corresponding to the spectral type of K5V of the system (Cox 2000). The gravity darkening exponents were taken to be $g_1 = g_2 = 0.32$ (from Lucy 1967), and albedos $A_1 = A_2 = 0.5$ were adopted (following Rucinski 1969). The limb-darkening coefficients were taken as $x_1 = 0.80$, $x_2 = 0.82$ in V band and $x_1 = 0.89$, $x_2 = 0.91$ in B band, based on the new result from Diaz-Cordovés, Claret & Giménéz (1995). The adjustable parameters are the orbital inclination i, the mean temperature of the first star T_1, the potentials Ω_1 and Ω_2 of the components, and the non-dimensional luminosities L_1 and L_2.

The first step is to derive the geometrical system parameters through the unspotted light-curve synthesis. Because of the unequal maxima, we could not obtain a satisfactory fit to both quadratures of the light curves simultaneously with the unspotted synthesis. To solve this problem, we removed all the points around the secondary maximum in each light curve (i.e., to set the weights of the normal points between phases 0.6 and 0.9 as zero) and fit the first quadratures only. This could be the right way to obtain the proper solutions as we have discussed in the above section. We began the test solutions with the 1996 and 2000 light curves since they were obtained from high-speed photometry and have higher accuracies than others.

Around the new spectroscopic mass ratio of Rucinski et al. (2003), a set of test solutions was made at the outset to search for an approximate mass ratio for our photometric solutions. The test solutions were computed at a series of mass ratios $q = m_2/m_1$ with values 1.5, 1.7, 1.8, 1.9, 1.95, 2.0, 2.1, 2.2 and 2.5. At each assumed mass ratio, the differential correction (DC) program started from mode 2 (detached) and rapidly ran into mode 3 (contact). After several runs in iteration, a converged solution was reached for each assumed q. Fig. 4 plots the relation between the resulting sum of weighted residuals $\sum w^2(\mathrm{O-C})^2$ and the assumed q for all the test solutions made for the 1996 and 2000 light curves. For both the light curves, it seems that the most probable solutions would be obtained somewhere around $q = 1.95$. Then we ran the DC program again and let the mass ratio be adjusted freely along with the other adjustable parameters and got the best-fitting solutions for the 1996 and 2000 light curves. Subsequently we adopted the solutions as the initial inputs for the unspotted synthesis to the remaining light curves. In this way, the geometrical solutions were carried out for all the light curves.

After that, the starspot model was employed to perform a further analysis for all the observations of the light curves. Following Samec

Table 4. The light curve solutions of V523 Cas.

Parameter	LC1986	LC1988	LC1990	LC1992a	LC1992b	LC1994	LC1996	LC2000
T_2 (K)[a]	4410	4410	4410	4410	4410	4410	4410	4410
$g_1 = g_2$[a]	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32
$A_1 = A_2$[a]	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
x_{1B}[a]	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89
x_{1V}[a]	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
x_{2B}[a]	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91
x_{2V}[a]	0.82	0.82	0.82	0.82	0.82	0.82	0.82	0.82
i (degree)	83.02 (20)	82.94 (17)	83.06 (21)	83.28 (26)	83.20 (24)	82.85 (43)	83.68 (12)	83.08 (12)
$q = m_2/m_1$	1.956 (8)	1.954 (10)	1.951 (11)	1.967 (7)	1.940 (15)	1.965 (12)	1.947 (7)	1.953 (4)
T_1 (K)	4706 (25)	4695 (12)	4681 (34)	4652 (51)	4660 (32)	4678 (40)	4752 (8)	4736 (5)
$\Omega_1 = \Omega_2$	5.0910 (61)	5.0950 (98)	5.0613 (54)	5.0550 (45)	5.0407 (88)	5.0821 (136)	5.0870 (40)	5.0875 (51)
r_1 (pole)	0.3103 (6)	0.3097 (8)	0.3126 (5)	0.3145 (4)	0.3135 (8)	0.3119 (13)	0.3103 (4)	0.3108 (5)
r_1 (side)	0.3253 (7)	0.3246 (10)	0.3280 (7)	0.3305 (5)	0.3290 (10)	0.3272 (16)	0.3247 (5)	0.3259 (7)
r_1 (back)	0.3637 (11)	0.3625 (16)	0.3680 (10)	0.3727 (9)	0.3694 (16)	0.3672 (26)	0.3625 (6)	0.3647 (9)
r_2 (pole)	0.4209 (5)	0.4202 (8)	0.4228 (5)	0.4258 (4)	0.4228 (9)	0.4231 (12)	0.4207 (16)	0.4215 (11)
r_2 (side)	0.4487 (7)	0.4478 (10)	0.4510 (6)	0.4552 (5)	0.4511 (11)	0.4516 (16)	0.4473 (21)	0.4495 (15)
r_2 (back)	0.4803 (9)	0.4510 (14)	0.4836 (9)	0.4888 (7)	0.4839 (16)	0.4840 (22)	0.4801 (29)	0.4814 (19)
$L_1/(L_1 + L_2)_B$	0.463	0.459	0.455	0.456	0.450	0.452		
$L_1/(L_1 + L_2)_V$	0.443	0.440	0.436	0.436	0.432	0.434	0.0.445	0.443
Ω_{in}	5.1893	5.1865	5.1822	5.2049	5.1666	5.2021	5.1765	5.1850
Co-latitude[a]	90	90	90	90	90	90	90	90
Co-longitude	270.5 (0.8)	270.8 (0.8)	272.3 (1.1)	311.0 (1.5)	300.4 (1.7)	289.0 (2.1)	278.3 (0.6)	270.6 (0.5)
r_{spot}	8.7 (0.2)	8.9 (0.3)	7.5 (0.1)	18.5 (0.7)	18.2 (0.4)	5.8 (0.8)	11.8 (0.2)	16.8 (0.4
T_{spot}/T_2	1.21 (2)	1.22 (3)	1.21 (2)	0.80 (1)	0.86 (2)	1.25 (4)	1.15 (2)	0.88 (1)

[a]Assumed.

et al. (1989) we placed the assumed spot on the massive component (star 2). The adjusted parameters are the spot temperature T_s (given as a fraction of the surrounding photospheric temperature), the spot radius r_s (defined as half the angular diameter of the spot), the spot co-latitude (0–180°, measured from the north to the south pole of the star) and the spot longitude (0–360°, measured for each star anticlockwise from the meridian at the substellar point to the other component). In our hotspot model, the spot co-latitude is fixed at 90° (i.e. on the equator). The preliminary spot longitude could be found approximately from the phase of the maximum brightness of the light hump caused by the spot on the secondary component. The other two spot parameters, T_s and r_s, are calculated by adjusting the theoretical light curves to fit approximately the observed distorted light curves. Finally we obtained the photometric solutions for all the light curves. The results are given in Table 4. In Fig. 5, we plot all the light curves obtained in the eight epochs as well as their best fits based on the final solutions. For the 1996 light curve, we present here only the normal points, as the amount of individual data is too large.

5 RESULTS AND DISCUSSIONS

We have presented the long-term photometric study of V523 Cas. The results of period analysis and light-curve synthesis allow us to draw the following conclusions:

(1) Based on the starspot model, we modelled all the light curves obtained by the long-term photometry with the WD code. The solutions carried out for each individual light curve match each other very well. That implies the reliability of our results. The photometric solutions confirmed the W-subtype overcontact configuration for the short-period binary V523 Cas. The secondary component (the less-massive star, hereafter) has the higher surface temperature though it contributes less brightness than the primary. The difference of surface temperature between the two components is about 300 K. This result is very close to that derived from the solution (i) by Lister et al. (2000). The mass ratio derived from our photometric solutions is in broad agreement with Lister et al. (2000) and is very close to Rucinski et al. (2003).

Using the results of both the photometric and spectroscopic solutions, the absolute parameters of the system can be derived. If we take the average values of mass ratio of 1.954 and the orbital inclination of 83°.14 obtained from the photometric solutions for all the light curves, and adopt the mass function of $f(M) = 1.110 \pm 0.024$ $M_\odot$ from Rucinski et al. (2003), the masses, radii and luminosities of the components of V523 Cas are calculated as listed in Table 5. Based on these, it is possible for us to discuss the evolutionary status of the system.

The values of mass, radius and luminosity deduced for the massive primary component agree very well with those for a K5V main-sequence star according to the calibration of main-sequence stars (Cox 2000). As for the secondary component, the deduced values for its mass and radius strongly suggest that it could be a main-sequence star with a spectral type of M2V, while its luminosity is about four times larger than that of an M2V star. This situation is common for the W-subtype W UMa systems and used to be explained by an assumed energy transfer from the primary to the secondary based on the TRO theory (Lucy 1976; Robertson & Eggleton 1977; Vilhu 1982; Rucinski 1986; Eggleton 1996). If this were the case, for V523 Cas, it would require energy exchange with an amount of about 0.9 $L_\odot$, which is about half of the primary's luminosity! However, there is no evidence for underluminosity of

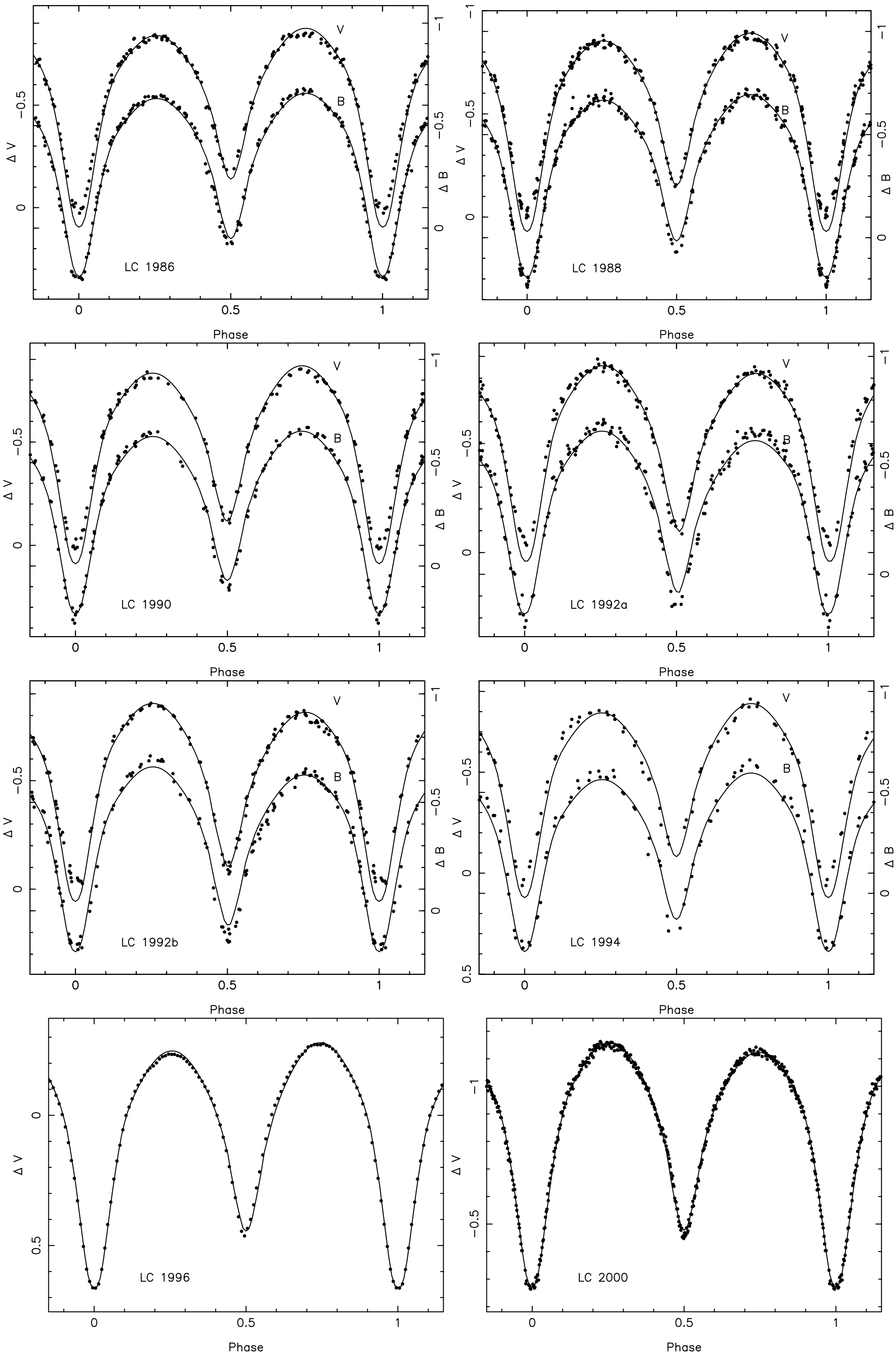

Figure 5. Observed and computed light curves for V523 Cas obtained in the eight epochs.

Table 5. Absolute parameters for V523 Cas.

Property	Primary	Secondary
Mass ($M_\odot$)	0.75 ± 0.03	0.38 ± 0.02
Radius ($R_\odot$)	0.74 ± 0.04	0.55 ± 0.02
Luminosity ($L_\odot$)	0.18 ± 0.02	0.13 ± 0.01

the primary component found according to our deduction. Thus we suggest that the secondary cannot be a normal main-sequence star but is an evolved, radial compressed star. This is to say that the star V523 Cas cannot be a zero-age contact system; rather, it should be formed through mass exchange after mass ratio reversal. If so, probable mass overflow and angular momentum loss could play important roles during the formation and evolution of this system.

(2) Our long-term photometry provides a large amount of new timings of minimum light for the system. That enables us to compile a large collection so as to investigate the long-term behaviour of the orbital-period changes to a high accuracy. The O–C analysis of the times of minimum light indicates that the binary V523 Cas is undergoing rapid continuous period increase. This period increase could be interpreted by mass transfer from the secondary to the primary component. If the mass transfer is conservative, neglecting the possible mass and momentum loss from the system, the lower limit value of the mass transfer rate is computed to be 9.17×10^{-8} $M_\odot$ yr^1. The time-scale of mass transfer thus turns to be about 4.2×10^6 yr, which is far less than the thermal time-scale of the secondary component (6.1×10^7 yr) but larger than the dynamical time-scale (of about 3.3×10^5 yr). It implies that the mass transfer is taking place in a time-scale shorter than the thermal time-scale. The secondary component does not remain in thermal equilibrium, and the mass transfer is expected to be continuing for a long time until the mass ratio of the system becomes small enough.

In addition to the secular period increase, Samec et al. (2001) reported a sinusoidal variation with an amplitude of 0.036 d in a period of about 101 yr. In our case, no such cyclic variations can be found within the residuals of ± 0.004 d (Fig. 1). We note that the data Samec et al. (2001) used for their period analysis were mainly obtained in visual and photographic observations and contained big gaps, though the time-base is long enough. The large scattering would thus be unavoidable in their fittings. However, our period study could not exclude the possibility of such a long-term sinusoidal variation, since the time-base of the data set we used is not sufficiently long. More observations on the star are still required.

(3) The spot assumption can give fairly good fittings to the asymmetric and varying light curves of V523 Cas. From the photometric solutions we note that the spot seems to remain at nearly the same position, but the size and temperature of the spot vary in different epochs. The radius of the hotspot is always small while that of the cool spot is systematically large. The average values of the hotspot and cool spot are $T_{spot}/T_2 = 1.22 \pm 0.03$, $r_{spot} = 8.5 \pm 3.3$ and $T_{spot}/T_2 = 0.85 \pm 0.05$, $r_{spot} = 17.8 \pm 1.0$, respectively. The asymmetry between the Max. I and Max. II of the light curve used to be suggested as due to the O'Connell effect (Zhukov 1985), and its variations were attributed to starspot cycle. However, the physical nature of the spot model is still open for discussion. In view of the rapid mass transfer between the components, as indicated above, a possible connection between the spot activity and the mass transfer could not be excluded. Because of the rapid mass transfer from the hot secondary, we suggested that there might be a large amount of gas upon the trail hemisphere of the cool, massive component. If the gas is optically thick, it could block part of the brightness from the star, and thus it presents as a cool spot. When the stream is captured by the component, while the kinetic energy as well as the thermal energy brought about by the mass flow would serve as an additional luminosity released from the star, that would present as a hotspot. However, to create such a model satisfactory for a comprehensive description of the mass transfer and the spot activity goes beyond the scope of the present work.

6 SUMMARY

We have presented a 15-yr photometric monitoring on the very short-period W UMa system V523 Cas. Our goal is to investigate the long-term light-curve and period variations of the star. The system displays obviously the O'Connell effect and cyclic variation with a time-scale of about 8 yr. Its orbital period is found to have been continuously increasing during the past three decades. Based on a one-spot model, all the light curves formed from the observations are analysed with the WD method. The photometric solutions reveal an overcontact, W-subtype configuration for the system. The mass ratio derived from the photometric solutions agrees with the new spectroscopic result of Rucinski et al. (2003) very well. Absolute parameters of the component stars are deduced according to the results of our photometric analysis. Based on these, the evolutionary status of the system, the mass transfer between the components as well as the probable spot activity of the star are discussed.

ACKNOWLEDGMENTS

This work was partly supported by the Chinese National Natural Science Foundation through grant 10173013.

REFERENCES

Agerer F., 1992, BAV Mitt., No. 60
Agerer F., Hubscher J., 2001, Inf. Bull. Var. Stars, No. 5016
Blattler E., 1999, BBSAG Bull., 119
Bradstreet D. H., 1981, AJ, 86, 98
Cox A. N., ed., 2000, Allen's Astrophysical Quantities, 4th edn. Springer, New York
Diaz-Cordovés J., Claret A., Gimenéz A., 1995, A&AS, 110, 329
Eggleton P. P., 1996, in Milone E. F., Mermilliod J.-C., eds, ASP Conf. Ser., Vol. 90, The Origins, Evolution, and Destinies of Binary Stars in Clusters. Astron. Soc. Pac., San Francisco, 257
Elias N. M., Koch R. H., 2000, AJ, 120, 1548
Giurincin G., Mardirossian F., Mezzetti M., 1982, A&AS, 49, 89
Haussler K., 1974a, Inf. Bull. Var. Stars, No. 887
Haussler K., 1974b, Mitt. Bruno H. Burgel Stermourte Hartha, 7, 12
Hoffman M., 1981, Inf. Bull. Var. Stars, No. 1976
Kwee K. K., van Woerden H., 1956, Bull. Astron. Inst. Neth., 12, 327
Lavrov M. I., Zhukov G. V., 1976, Publ. Kazan Univ. Obs., 42, 46
Lister T. A., McDermid R. M., Hilditch R. W., 2000, MNRAS, 317, 111
Lucy L. B., 1967, Z. Astrophys., 65, 89
Lucy L. B., 1976, ApJ, 205, 208
Maceroni C., 1986, A&A, 170, 43
Milone E. F., Hrivnak B. J., Fisher W. A., 1985, AJ, 90, 354
Nelson R. H., 2001, Inf. Bull. Var. Stars, No. 5040
O'Connell D. J. K., 1951, Publ. Riverview College Obs., 2, 85
Probulla T., Vanko M., Parimucha S., Chochol D., 2001, Inf. Bull. Var. Stars, No. 5056
Robertson J. A., Eggleton P. P., 1977, MNRAS, 179, 359
Rucinski S. M., 1969, Acta Astron., 19, 245
Rucinski S. M., 1986, in Cottrell P. L., Hearnshaw J. B., eds, Proc. IAU Symp. 118, Instrumentation and Research Programmes for Small Telescopes. Reidel, Dordrecht, p. 159

Rucinski S. M. et al., 2003, AJ, 125, 3258
Samec R. G., Bookmyer B. B., 1987, PASP, 99, 1310
Samec R. G., van Hamme W., Bookmyer B. B., 1989, AJ, 98, 2287
Samec R. G., Banks D. F., Hernandez R., Faulkner D. R., Williams D. B., 2001, Inf. Bull. Var. Stars, No. 5175
Vilhu O., 1982, A&A, 109, 17
Weber R., 1957, Bull. Soc. Astron. Fr., 71, 36
Wei M.-Z., Chen J.-S., Jiang Z. J., 1990, PASP, 102, 698
Wilson R. E., 1979, ApJ, 234, 1054
Wilson R. E., 1990, ApJ, 356, 613
Wilson R. E., Devinney E. J., 1971, ApJ, 166, 605
Zhang X.-B., Zhang R.-X., Fang M. J., 2002, A&A, 395, 587
Zhang X.-B., Zhang R. X., 2003, AJ, 125, 1431
Zhukov G. V., 1985, Sov. Astron. Lett., 11, 42

This paper has been typeset from a TEX/LATEX file prepared by the author.