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Apsidal motion in five eccentric eclipsing binaries

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ABSTRACT

Aims. As part of the long-term Ondřejov and Ostrava observational projects, we aim to measure the precise times of minimum light for eccentric eclipsing binaries, needed for accurate determination of apsidal motion. Over fifty new times of minimum light recorded with CCD photometers were obtained for five early-type and eccentric-orbit eclipsing binaries: V785 Cas ($P = 2\overset{\mathrm{d}}{.}70$, $e = 0.09$), V821 Cas ($1\overset{\mathrm{d}}{.}77, 0.14$), V796 Cyg ($1\overset{\mathrm{d}}{.}48, 0.07$), V398 Lac ($5\overset{\mathrm{d}}{.}41, 0.23$), and V871 Per ($3\overset{\mathrm{d}}{.}02, 0.24$).

Methods. O−C diagrams of binaries were analysed using all reliable timings found in the literature, and new elements of apsidal motion were obtained.

Results. We derived for the first time or improved the relatively short periods of apsidal motion of about 83, 140, 33, 440, and 70 years for V785 Cas, V821 Cas, V796 Cyg, V398 Lac, and V871 Per, respectively. The internal structure constants, $\log k_2$, for V821 Cas and V398 Lac are then found to be –2.70 and –2.35, under the assumption that the component stars rotate pseudosynchronously. The relativistic effects are weak, up to 7% of the total apsidal motion rate.

Key words. binaries: eclipsing – stars: fundamental parameters – stars: general – binaries: close

1. Introduction

The study of apsidal motion in eccentric eclipsing binaries (EEB) provides an important observational test of theoretical models of stellar structure and evolution. A detailed analysis of the period variations of EEB can be performed using the times of minimum light observed throughout the apsidal motion cycle, and from this, both the orbital eccentricity and the period of rotation of the periastron can be obtained with high accuracy (Giménez 1994). All eclipsing binaries analysed here have properties that make them important “astrophysical laboratories” for studying the structure and evolution of stars.

Here we analyse the observational data and rates of apsidal motion for five detached eclipsing systems. These systems are all relatively bright northern-hemisphere early-type objects known to have eccentric orbits and to exhibit apsidal motion. With the exception of V821 Cas and V398 Lac, no spectroscopic observations have been published for these binary systems. Our study is part of a series of papers on apsidal motion in eclipsing binaries (Wolf et al. 2008, 2010).

2. Observations of minimum light

Monitoring of eccentric eclipsing binaries is a long-term observational project, which requires only moderate or small telescopes equipped with a photoelectric photometer or a CCD camera. Moreover, a large amount of observing time is needed, which is unavailable presently at large telescopes but is more practical for small amateur telescopes equipped with modern detectors. During the past ten years, we have accumulated over 8000 photometric observations at selected phases during primary and secondary eclipses and derived over 50 precise times of minimum light for selected eccentric systems. New CCD photometry was obtained at several observatories in the Czech Republic:

- Ondřejov Observatory, Czech Republic: the 0.65-m ($f/3.6$) reflecting telescope with the CCD cameras SBIG ST-8, Apogee AP7p or Moravian Instruments G2-3200 and *BVRI* photometric filters;
- Johann Pallisa Observatory and Planetarium Ostrava, Czech Republic: 0.2-m or 0.3-m telescopes with the CCD camera SBIG ST-8XME and *VRI* filters;
- Observatory and Planetarium Hradec Králové, Czech Republic: 0.4-m ($f/5$) reflector with the CCD camera G2-1600 and *BVRI* filters;
- Observatory Valašské Meziříčí, Czech Republic: the 0.3-m Celestron Ultima telescope with the CCD camera SBIG ST-7 or G2-1600 and *VRI* filters;
- Private observatory of PS at Brno, Czech Republic: 0.2-m Cassegrain telescope with the CCD camera ST-7XME and Johnson-Cousins $BV(RI)_{\rm c}$ filters;
- Private Observatory of MZ at Brno, Czech Republic: Helios 2/58 lens obscured to 0.035-m with the CCD camera G2-402 and *UBVRI* filters.

CCD measurements at most observatories were dark-subtracted and then flat-fielded using sky exposures taken at either dusk or dawn. Several comparison stars were chosen in the same frame

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as the variables. The C-Munipack[1] (Motl 2007) was used to reduce most of our CCD images. APHOT, a synthetic aperture photometry and astrometry software developed by M. Velen and P. Pravec, was routinely used for data obtained at Ondřejov observatory. No correction for differential extinction was applied, because of the proximity of the comparison stars to the variable and the resulting negligible differences in air mass.

Using the HIPPARCOS photometry (ESA 1997) and NSVS data (Wozniak et al. 2004), we were able to derive several additional times of minimum light with less precision. The new times of primary and secondary minima and their errors were generally determined by the classical Kwee-van Woerden (1956) algorithm. In some cases (HIPPARCOS, NSVS or SWASP data, scattered points), the light-curve fitting by Gaussians or polynomials of the third or fourth order applied on the original and reflected curve, together with the least squares method, were used. All new times are given in Tables A.1–A.5, where epochs are calculated from the ephemeris given in Table 1, and the other columns are self-evident.

3. Apsidal motion analysis

The apsidal motion in all eccentric systems was studied by means of an O−C diagram analysis. For an accurate calculation of the apsidal motion rate, the method described by Giménez & García-Pelayo (1983) was routinely used. This is a weighted least-squares iterative procedure, including terms in the eccentricity up to the fifth order. There are five independent variables ($T_0, P_s, e, \dot{\omega}, \omega_0$) determined in this procedure. The periastron position ω is given by the linear equation

$$\omega = \omega_0 + \dot{\omega}\, E,$$

where $\dot{\omega}$ is the rate of periastron advance, and the position of periastron for the zero epoch T_0 is denoted as ω_0. The relation between the sidereal and the anomalistic period, P_s and P_a, is given by

$$P_s = P_a\,(1 - \dot{\omega}/360°)\,,$$

and the period of apsidal motion by

$$U = 360° P_a/\dot{\omega}.$$

In addition, new timings are available in the literature and in the O−C Gateway[2] database, maintained by Paschke and Brát, Czech Astronomical Society. All new precise CCD times of minima were used with a weight of 10 or 20 in our computation. Some of our less precise measurements were weighted by a factor of 5, while the earlier visual and photographic times (esp. the times of the mid-exposure of a photographic plate) were given a weight of one or nought because of the large scatter in these data.

3.1. V785 Cassiopeiae

The detached eclipsing binary V785 Cas (also BD+64°302, HIP 10173; $V_{\max} = 9\overset{\mathrm{m}}{.}28$; Sp. B5V) is a relatively bright binary with eccentric orbit ($e = 0.09$) and a short orbital period of 2.7 days. It belongs to the older photometric discoveries of the HIPPARCOS project (ESA 1997). The following linear light elements were derived:

$$\text{Pri. Min.} = \text{HJD}\,2\,452\,218\overset{\mathrm{d}}{.}3299 + 2\overset{\mathrm{d}}{.}702515 \times \text{E}.$$

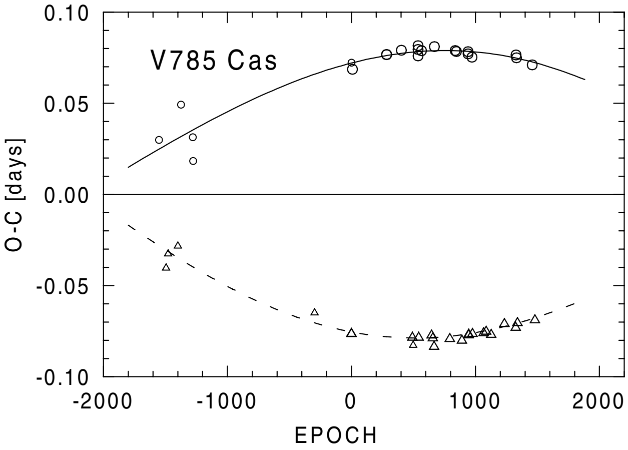

Fig. 1. The O−C diagram for the times of minimum of V785 Cas. The continuous and dashed curves represent predictions for the primary and secondary eclipses, respectively. The individual primary and secondary minima are denoted by circles and triangles, respectively. Larger symbols correspond to the photoelectric or CCD measurements, which were given higher weights in the calculations.

All photoelectric times of minimum light given in Sobotka (2007), Brát et al. (2007, 2008), and Zasche et al. (2011) were incorporated into our calculation. Using HIPPARCOS photometry (ESA 1997), we were able to derive additional times of minimum light using the light-curve profile fitting method. A total of 46 photoelectric times of minimum light given in Table A.1 were used in our analysis.

The computed apsidal motion parameters and their internal errors of the least-squares fit are given in Table 1. In this table, P_s denotes the sidereal period, P_a the anomalistic period, e represents the eccentricity, and $\dot{\omega}$ is the rate of periastron advance (in degrees per cycle and in degrees per year). The zero epoch is given by T_0, and the corresponding position of the periastron is represented by ω_0. The O−C residuals for all times of minimum with respect to the linear part of the apsidal motion equation are shown in Fig. 1. The non-linear predictions, corresponding to the fitted parameters, are plotted for primary and secondary eclipses.

3.2. V821 Cassiopeiae

The detached and double-lined eclipsing binary V821 Cas (also HD 224557, BD+52°3571, HIP 118223; $V_{\max} = 8\overset{\mathrm{m}}{.}26$; Sp. A1V+A4V) is a bright eclipsing binary with an eccentric orbit ($e = 0.14$) and a short orbital period of 1.8 days. The eccentric orbit and apsidal motion of V821 Cas was discovered by Otero (2005) using the publicly available HIPPARCOS and NSVS data. The first *BVR* photometry and period analysis of V821 Cas were obtained by Degirmenci et al. (2003, 2007) at the Baja and Ege observatories. They confirmed the eccentric orbit and derived improved eclipse ephemeris

$$\text{Pri. Min.} = \text{HJD}\,2\,451\,767\overset{\mathrm{d}}{.}4106 + 1\overset{\mathrm{d}}{.}7697534 \times \text{E}.$$

The light curve analysis was also presented by Bulut & Demircan (2008), who obtained similar eccentricity of the system $e = 0.115$. Recently in their spectroscopic study, Cakirli et al. (2009) determined the precise absolute parameters of the components

$$\begin{aligned} M_1 &= 2.05 \pm 0.07\, M_\odot, \quad M_2 = 1.63 \pm 0.06\, M_\odot, \\ R_1 &= 2.31 \pm 0.03\, R_\odot, \quad R_2 = 1.39 \pm 0.02\, R_\odot. \end{aligned}$$

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[1] `http://c-munipack.sourceforge.net/`

[2] `http://var.astro.cz/ocgate/`

Table 1. Apsidal motion elements for V785 Cas, V821 Cas, V796 Cyg, V398 Lac, and V871 Per.

Element	Unit	V785 Cas	V821 Cas	V796 Cyg	V398 Lac	V871 Per
T_0	HJD	2 452 218.3305 (7)	2 447 964.1801 (6)	2 452 434.1014 (7)	2 453 577.4281 (8)	2 451 421.5607 (5)
$P_{\rm s}$	days	2.7025147 (7)	1.76973889 (8)	1.48086907 (15)	5.4060558 (8)	3.0238820 (5)
$P_{\rm a}$	days	2.702756 (2)	1.7697999 (2)	1.4810497 (2)	5.406239 (3)	3.024233 (4)
e	–	0.0916 (5)	0.1432 (12)	0.078 (2)	0.2284 (7)	0.2353 (5)
$\dot\omega$	deg cycle^{-1}	0.0322 (6)	0.0124 (9)	0.044 (1)	0.0122 (10)	0.0418 (8)
$\dot\omega$	deg yr^{-1}	4.35 (9)	2.56 (0.18)	10.8 (0.2)	0.82 (6)	5.05 (10)
ω_0	deg	159.6 (0.4)	116.6 (0.7)	2.0 (0.4)	222.4 (0.8)	144.8 (0.4)
U	years	83.0 (1.6)	141.0 (10)	33.3 (0.7)	437 (35)	71.0 (1.5)

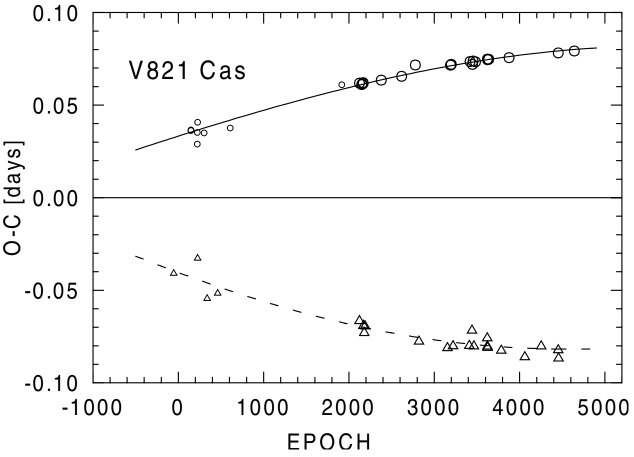

Fig. 2. O−C residuals for the times of minimum of V821 Cas. See legend to Fig. 1.

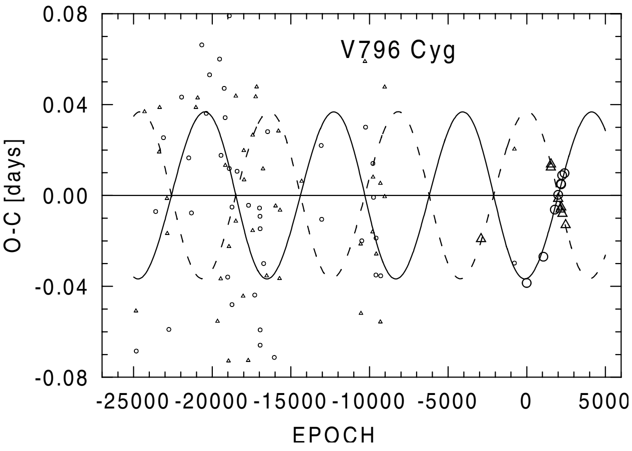

Fig. 3. O−C graph for the times of minimum of V796 Cyg. See legend to Fig. 1. Only modern data after the epoch –5000 were used for the apsidal motion solution.

They also derived the first apsidal motion period $U = 118 \pm 19$ years and the value of internal structure constant log $k_{2,\rm obs} = -2.56$. Since the above-mentioned papers were published, new times of minima have been obtained, which allowed us to reduce the uncertainties in the derived parameters. We collected numerous times of minimum light given in Ak & Filiz (2003), Bakis et al. (2003), Bulut & Demircan (2003), Degirmenci et al. (2003, their Table 1), Degirmenci et al. (2007, their Table 3), Brát et al. (2007, 2008), Cakirli et al. (2009, their Table 2), Dvorak (2009, 2011), Diethelm (2010, 2012), and Lampens et al. (2010). These are all listed in Table A.2. Using HIPPARCOS photometry (ESA 1997), we were able to derive additional times of minimum light using the light-curve profile-fitting method. A total of 50 precise times of minimum light were used in our analysis including 22 secondary eclipses. The orbital inclination was adopted to be $i = 82\overset{\circ}{.}6$, based on the analysis of Cakirli et al. (2009). The computed apsidal motion parameters are given in Table 1, the complete O−C diagram is shown in Fig. 2.

3.3. V796 Cygni

The detached eclipsing binary V796 Cyg (also BV 345, S 4782, GSC 3560-0777, FL 2778; $V_{\rm max} = 10\overset{\rm m}{.}95$; Sp. A0) is a seldom studied binary system with a short orbital period ($P = 1.5$ d) and a slightly eccentric orbit ($e = 0.07$). It was discovered to be variable by Hoffmeister (1949) at Sonneberg and later independently by Strohmeier (1961) at Bamberg observatory. Busch & Haussler (1966) derived the first ephemeris with the correct orbital period:

$$\text{Pri. Min.} = \text{HJD}\,2\,437\,997\overset{\rm d}{.}108 + 1\overset{\rm d}{.}480834 \times \text{E}.$$

To our knowledge no modern photometric, spectroscopic, or period study exists so far. All prevous times of minimum light are collected in the O−C Gateway database. Only those given in Table A.3 were taken into consideration, and other numerous photographic times obtained by Busch & Haussler (1966), Strohmeier (1966), and Strohmeier & Bauernfeind (1968) were not used in our analysis due to large scatter of these data. A total of 18 reliable times of minimum light were included in our analysis, with 9 secondary eclipses among them. The computed apsidal motion parameters are given in Table 1, and the O−C diagram is shown in Fig. 3.

3.4. V398 Lacertae

The detached eclipsing binary V398 Lac (also HD 210 180, BD+51°3251, HIP 109 193; $V_{\rm max} = 8\overset{\rm m}{.}79$; Sp. A0V) is a relatively bright binary system with an eccentric orbit ($e = 0.2$) and longer orbital period $P = 5.4$ days. Its variability was discovered during the HIPPARCOS mission (ESA 1997). The precise absolute dimensions of components of V398 Lac were derived spectroscopically by Cakirli et al. (2007), who obtained components with similar mass and different size

$$M_1 = 3.83 \pm 0.35\ M_\odot, M_2 = 3.29 \pm 0.32\ M_\odot,$$
$$R_1 = 4.89 \pm 0.18\ R_\odot, R_2 = 2.45 \pm 0.11\ R_\odot.$$

In the latter paper, the following linear ephemeris is also given

$$\text{Pri. Min.} = \text{HJD}\,2\,453\,577\overset{\rm d}{.}476 + 5\overset{\rm d}{.}40624 \times \text{E}.$$

The light curve analysis of V398 Lac was later presented by Bulut & Demircan (2008), who confirmed the moderate eccentricity of the system $e = 0.273$. Our new times of minimum

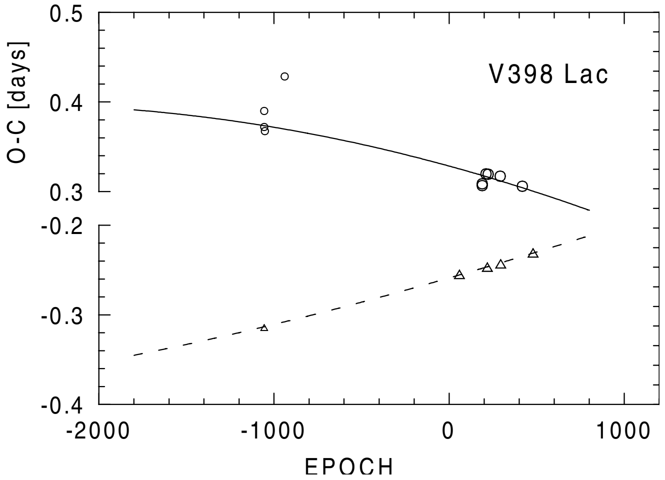

Fig. 4. O−C graph of V398 Lac. See legend for Fig. 1.

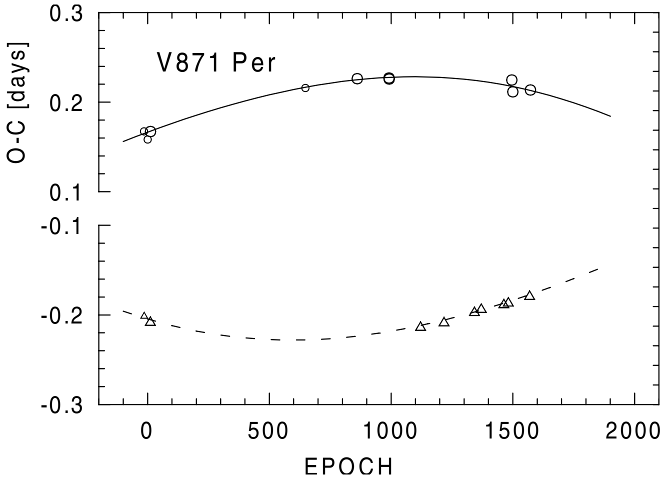

Fig. 5. O−C diagram for V871 Per. See legend to Fig. 1.

light, as well as timings of previous observers (Cakirli et al. 2007; Parimucha et al. 2009; Brát et al. 2011; Zasche et al. 2011) given in Table A.4, were incorporated into our calculation. Using HIPPARCOS photometry (ESA 1997), we were also able to derive additional times of minimum light using the light-curve profile fitting method. Only 15 times of minimum light given in Table A.4 were used in our analysis. The orbital inclination was adopted to be $i = 84\overset{\circ}{.}6$, based on the analysis of Cakirli et al. (2007). The resulting apsidal motion parameters are given in Table 1, and the current O−C diagram is shown in Fig. 4.

3.5. V871 Persei

The detached eclipsing binary V871 Per (also BD+56°704, GSC 3708-1325; $V_{\max} = 10\overset{\mathrm{m}}{.}89$; Sp. B) is a fairly neglected binary system with a moderate eccentric orbit ($e = 0.24$) and a short orbital period ($P \simeq 3$ day). It was discovered to be an eclipsing binary by Otero et al. (2004) in the NSVS database. To our knowledge, the precise absolute parameters of the components of V871 Per are unknown. The following linear ephemeris was derived and used in the epoch calculation

Pri. Min. = HJD 2 451 421.5604 + $3\overset{\mathrm{d}}{.}0238818 \times$ E.

We used the times of minimum light published in the last several years by Zejda et al. (2006), Brát et al. (2007), and Diethelm (2009, 2010, 2011a,b, 2012), which are included in Table A.5. A total of 20 reliable times of minimum light were used in our analysis including nine secondary eclipses. The final apsidal motion elements are given in Table 1, and the O−C graph is shown in Fig. 5.

Table 2. Basic physical properties of V821 Cas and V398 Lac and their internal structure constant.

Parameter	Unit	V821 Cas	V398 Lac
M_1	$M_\odot$	2.05 (0.07)	3.83 (0.35)
M_2	$M_\odot$	1.63 (0.06)	3.29 (0.32)
r_1		0.243 (2)	0.1960 (12)
r_2		0.147 (2)	0.0982 (13)
Source		Cakirli et al. (2009)	Cakirli et al. (2007)
$\dot{\omega}_{\rm rel}$	deg cycle^{-1}	0.00091	0.00069
$\dot{\omega}_{\rm rel}/\dot{\omega}$	%	7.3	5.7
$\log k_{2,\rm obs}$		−2.70 (5)	−2.35 (4)
$\log k_{2,\rm theo}$		−2.43 (2)	−2.32 (4)

4. Discussion

The detection of apsidal motion in EEB provides the opportunity to test models of stellar internal structure. The internal structure constant (ISC), $k_{2,\rm obs}$, which is related to the variation in the density inside the star, can be derived using the following expression:

$$k_{2,\rm obs} = \frac{1}{c_{21} + c_{22}} \frac{P_{\rm a}}{U} = \frac{1}{c_{21} + c_{22}} \frac{\dot{\omega}}{360}, \tag{1}$$

where c_{21} and c_{22} are functions of the orbital eccentricity, fractional radii, the masses of the components, and the ratio between rotational velocity of the stars and Keplerian velocity (Kopal 1978). We also assume that the component stars rotate pseudosynchronously with the same angular velocity as the maximum orbital value at periastron. In addition to the classical Newtonian contribution, the observed rate of rotation of the apses includes the contribution from General Relativity, $\dot{\omega}_{\rm rel}$ (Giménez 1985):

$$\dot{\omega}_{\rm rel} = 5.45 \times 10^{-4} \frac{1}{1-e^2} \left(\frac{M_1 + M_2}{P} \right)^{2/3}, \tag{2}$$

where M_i denotes the individual masses of the components in solar units and P is the orbital period in days.

The values of $\dot{\omega}_{\rm rel}$ and the resulting mean internal structure constants $k_{2,\rm obs}$ for V821 Cas and V398 Lac are given in Table 2. Theoretical values $k_{2,\rm theo}$ according to available theoretical models for the internal stellar structure computed by Claret (2004) for given masses of components are presented in Table 2. The chemical composition of $X = 0.70$ and $Z = 0.02$ was assumed to be in agreement with previous studies.

5. Conclusions

The apsidal motion in EEB has been used for decades to test evolutionary stellar models. This study provides accurate information on the apsidal motion rates of five main-sequence early-type binary systems: V785 Cas, V821 Cas, V796 Cyg, V398 Lac and V871 Per. With the exception of V821 Cas, the apsidal motion period has been published here for the first time. For V821 Cas we derived a longer apsidal motion period of $U = 141 \pm 9$ years than was given in Cakirli et al. (2009). On the other hand, substantional discrepancy between the observed and theoretical ISC still remains. From the observational point of view, the apsidal motion period has not been covered satisfactorily. The index $n = \Delta T/U$, expressing the coverage of the apsidal motion period by precise photoelectric measurements, is only 15%. For instance, the shorter apsidal motion period of 80 years could explain the difference between observed and theoretical ISC satifactorily. None of the analysed binaries presents a large relativistic contribution of up to 7% of the total apsidal motion rate.

In spite of the considerable amount of observational data collected for decades, the absolute dimensions of massive binary components are known with low accuracy. It is also highly desirable to obtain new, high-dispersion, and high-S/N spectroscopic observations, and to apply modern disentangling methods to obtain radial velocity curves of both components for these systems.

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Appendix A: Tables of minima

Table A.1. The list of minima timings of V785 Cas.

JD Hel. – 2 400 000	Error [day]	Epoch	Weight	Source observatory
48 021.355	0.005	−1553.0	1	Hipparcos
48 176.680	0.005	−1495.5	1	Hipparcos
48 219.928	0.005	−1479.5	1	Hipparcos
48 433.431	0.005	−1400.5	1	Hipparcos
48 502.422	0.005	−1375.0	1	Hipparcos
48 759.143	0.005	−1280.0	1	Hipparcos
48 764.535	0.005	−1278.0	1	Hipparcos
51 414.268	0.005	−297.5	1	ROTSE
52 214.2011	0.0010	−1.5	1	Ondřejov
52 218.4027	0.0008	0.0	5	Ondřejov
52 219.60613	0.0001	0.5	20	Ondřejov
52 237.31675	0.0006	7.0	10	Ondřejov
52 983.21878	0.0003	283.0	10	Ondřejov
52 983.21889	0.0001	283.0	10	Ondřejov
53 307.523	0.0007	403.0	5	Ondřejov
53 546.53876	0.0005	491.5	10	Ondřejov
53 565.452	0.001	498.5	1	Sobotka (2007)
53 672.35941	0.0001	538.0	10	Ostrava
53 672.36295	0.0001	538.0	10	Ostrava
53 672.36498	0.0001	538.0	10	Ostrava
53 684.367	0.001	542.5	5	Ostrava
53 745.33007	0.0003	565.0	10	Ondřejov
53 965.4297	0.001	646.5	5	Brát et al. (2007)
53 992.4534	0.0007	656.5	10	Brno, Ostrava
54 019.4738	0.0004	666.5	5	Brno
54 026.3939	0.0006	669.0	5	Ostrava
54 365.40007	0.001	794.5	5	Brát et al. (2007)
54 480.4142	0.0007	837.0	5	Ostrava
54 507.4388*	0.0003	847.0	10	Brát et al. (2008)
54 627.54297	0.0008	891.5	5	Brát et al. (2008)
54 761.47516	0.0001	941.0	10	Ostrava
54 761.47393	0.0001	941.0	10	Ostrava
54 773.4821	0.0007	945.5	5	Ostrava
54 773.4817	0.0001	945.5	5	Ostrava
54 845.250*	0.001	972.0	5	Valašské Meziříčí
54 857.2605*	0.0008	976.5	5	Ostrava
55 100.4872*	0.0001	1066.5	10	Ostrava
55 154.5383	0.0002	1086.5	10	Ondřejov
55 265.3397	0.0001	1127.5	10	Valašské Meziříčí
55 554.51465	0.0001	1234.5	10	Valašské Meziříčí
55 800.44143	0.00118	1325.5	5	Zasche et al. (2011)
55 807.3465	–	1328.0	10	Valašské Meziříčí
55 815.45253	0.0001	1331.0	10	Ostrava
55 835.57676*	0.0001	1338.5	10	Ostrava
56 161.37043	0.0001	1459.0	5	Ostrava
56 219.3354*	0.0002	1480.5	10	Valašské Meziříčí

Notes. *Mean value of VR or VRI measurements.

Table A.2. The list of minima timings of V821 Cas.

JD Hel. – 2 400 000	Error [day]	Epoch	Weight	Source observatory
47 867.689	0.005	−54.5	1	Hipparcos
48 224.368	0.005	147.0	1	Otero (2005)
48 224.3683	0.0008	147.0	1	Hipparcos
48 357.091	0.005	222.0	1	Otero (2005)
48 357.0973	0.005	222.0	1	Hipparcos
48 363.224	0.005	225.5	1	Otero (2005)
48 364.1818	0.003	226.0	2	Hipparcos
48 500.4459	0.001	303.0	1	ESA (1997)
48 561.413	0.005	337.5	2	Otero (2005)
48 777.324	0.005	459.5	2	Otero (2005)
49 040.219	0.005	608.0	3	Otero (2005)
51 353.291	0.001	1915.0	1	ROTSE
51 720.3851	0.0009	2122.5	10	Bulut & Demircan (2003)
51 721.3976	0.0003	2123.0	10	Bulut & Demircan (2003)
51 767.4100	0.0001	2149.0	10	Degirmenci et al. (2003)
51 774.4893	0.0002	2153.0	10	Degirmenci et al. (2003)
51 797.4962	0.0002	2166.0	10	Degirmenci et al. (2003)
51 797.4967	0.0004	2166.0	10	Degirmenci et al. (2003)
51 805.330	0.001	2170.5	5	Degirmenci et al. (2003)
51 819.4840	0.0008	2178.5	10	Degirmenci et al. (2003)
51 835.4153	0.0006	2187.5	10	Degirmenci et al. (2003)
52 174.4524	–	2379.0	10	Degirmenci et al. (2007)
52 597.4220	0.0008	2618.0	10	Ak & Filiz (2003)
52 882.3561	0.0004	2779.0	10	Bakis et al. (2003)
52 957.4215	–	2821.5	10	Degirmenci et al. (2007)
53 548.51078	0.0002	3155.5	10	Brát et al. (2007)
53 611.48840	0.0001	3191.0	10	Brát et al. (2007)
53 627.4166	–	3200.0	10	Degirmenci et al. (2007)
53 665.3146	–	3221.5	10	Degirmenci et al. (2007)
54 001.56512	0.0037	3411.5	10	Brát et al. (2007)
54 018.53044	0.0002	3421.0	10	Brát et al. (2007)
54 058.2050	–	3443.5	10	Cakirli et al. (2009)
54 066.3118*	–	3448.0	10	Cakirli et al. (2009)
54 080.4715*	0.0004	3456.0	10	Brát et al. (2008)
54 095.3610*	–	3464.5	10	Cakirli et al. (2009)
54 128.25402	0.0004	3483.0	10	Brno
54 371.4447*	–	3620.5	10	Cakirli et al. (2009)
54 378.5192	–	3624.5	10	Cakirli et al. (2009)
54 379.5584	–	3625.0	10	Cakirli et al. (2009)
54 380.2882	–	3625.5	10	Cakirli et al. (2009)
54 381.3278	–	3626.0	10	Cakirli et al. (2009)
54 404.3347	–	3639.0	10	Cakirli et al. (2009)
54 663.4449	0.0002	3785.5	10	Lampens et al. (2010)
54 825.5334	0.0002	3877.0	10	Dvorak (2009)
55 153.6590	0.0002	4062.5	10	Diethelm (2010)
55 491.6850	0.0001	4253.5	10	Dvorak (2011)
55 843.8610	0.0019	4452.5	5	Diethelm (2012)
55 844.9056	0.0006	4453.0	10	Diethelm (2012)
55 850.9355	0.0015	4456.5	5	Diethelm (2012)
56 179.3872*	0.0007	4642.0	5	Brno

Notes. (*) Mean value of BVR or VRI measurements.

Table A.3. The list of minima timings of V796 Cyg.

JD Hel. – 2 400 000	Error [day]	Epoch	Weight	Source observatory
48 134.37955	0.001	−2903.5	10	Hanžl (1991)
51 275.342	0.002	−782.5	2	NSVS
51 276.032	0.002	−782.0	2	NSVS
52 434.0629	–	0.0	10	Nakajima (2003)
54 002.3148	0.0004	1059.0	5	Hübscher & Walter (2007)
54 709.4698*	0.0007	1536.5	10	Brát et al. (2008)
54 712.4328*	0.0012	1538.5	10	Brát et al. (2008)
55 074.4847	0.0001	1783.0	10	Hübscher & Monninger (2011)
55 391.39716	0.0008	1997.0	10	Ondřejov
55 399.54095	0.0005	2002.5	10	Ondřejov
55 624.62836*	0.0003	2154.5	10	Hradec Králové
55 650.55423*	0.0001	2172.0	10	Hradec Králové
55 670.53619*	0.0003	2185.5	10	Hradec Králové
55 687.5756	0.0008	2197.0	10	Hübscher et al. (2012)
55 776.4318	0.0002	2257.0	10	Hübscher & Lehmann (2012)
55 799.3690*	0.0003	2272.5	5	Hradec Králové
55 992.63960*	0.0005	2403.0	10	Hradec Králové
56 101.46132*	0.0004	2476.5	10	Hradec Králové

Notes. (*) Mean value of BVRI measurements.

Table A.4. The list of minima timings of V398 Lac.

JD Hel. – 2 400 000	Error [day]	Epoch	Weight	Source observatory
47 863.599	0.005	−1057.0	1	HIPPARCOS
47 863.617	0.005	−1057.0	1	HIPPARCOS
47 865.616	0.005	−1056.5	4	HIPPARCOS
47 885.2188	0.005	−1053.0	1	HIPPARCOS
48 501.57	0.01	−939.0	0	ESA (1997)
53 893.4275	0.0004	58.5	10	Cakirli et al. (2007)
54 599.48131	0.0001	189.0	5	Ostrava
54 599.47930	0.0001	189.0	5	Ostrava
54 718.42557	0.0001	211.0	5	Ostrava
54 758.4046	0.0001	218.5	10	Brno
54 783.2979	0.0002	223.0	10	Parimucha et al. (2009)
55 156.3135*	0.0004	292.0	5	Brát et al. (2011)
55 169.2686*	0.0005	294.5	5	Brát et al. (2011)
55 837.4652	0.0008	418.0	10	Zasche et al. (2011)
56 169.40107	0.0001	479.5	10	Ostrava

Notes. (*) Mean value of BVR or VRI measurements.

Table A.5. The list of minima timings of V871 Per.

JD Hel. – 2 400 000	Error [day]	Epoch	Weight	Source observatory
51 376.3698	0.001	−15.0	1	NSVS
51 377.5141	0.001	−14.5	1	NSVS
51 421.719	0.005	0.0	1	ROTSE
51 456.1285	0.0044	11.5	5	NSVS
51 458.0144	0.0015	12.0	5	NSVS
53 381.2520	0.0012	648.0	1	Zejda et al. (2006)
54 025.34925	0.0003	861.0	10	Brát et al. (2007)
54 418.45455	0.0006	991.0	5	SWASP
54 421.47743	0.0008	992.0	5	SWASP
54 812.6321	0.0002	1121.5	10	Diethelm (2009)
55 102.9297	0.0004	1217.5	10	Diethelm (2010)
55 480.9263	0.0009	1342.5	10	Diethelm (2011a)
55 565.5985	0.0025	1370.5	5	Diethelm (2011b)
55 846.8248	0.0003	1463.5	10	Diethelm (2012)
55 901.2566	0.0002	1481.5	10	Ondřejov
55 945.5128	0.0055	1496.0	5	Ondřejov
55 957.5952	0.0004	1500.0	5	Ondřejov
56 167.36575	0.0003	1569.5	10	Ostrava
56 175.3167	0.0004	1572.0	10	Ostrava
56 193.46022	0.0001	1578.0	20	Ondřejov