A&A 456, 1077–1083 (2006)
DOI: 10.1051/0004-6361:20065327

Astronomy & Astrophysics

Apsidal motion in eccentric eclipsing binaries: CW Cephei, V478 Cygni, AG Persei, and IQ Persei⋆

M. Wolf[1], H. Kučáková[2], M. Kolasa[2], P. Šťastný[2], Z. Bozkurt[3], P. Harmanec[1,4], M. Zejda[5], L. Brát[6], and K. Hornoch[7]

[1] Astronomical Institute, Charles University of Prague, 180 00 Praha 8, V Holešovičkách 2, Czech Republic
e-mail: wolf@cesnet.cz
[2] Johann Palisa Observatory and Planetarium, Technical University Ostrava, 708 33 Ostrava, Czech Republic
[3] Department of Astronomy and Space Sciences, Ege University, Faculty of Science, 35100 Bornova, Izmir, Turkey
[4] Astronomical Institute, Academy of Sciences, 251 65 Ondřejov, Czech Republic
[5] Institute of Theoretical Physics and Astrophysics, Masaryk University, 611 37 Brno, Czech Republic
[6] Private Observatory, Velká Úpa 193, 542 21 Pec pod Sněžkou, Czech Republic
[7] Private Observatory, 664 31 Lelekovice 393, Czech Republic

Received 30 March 2006 / Accepted 6 June 2006

ABSTRACT

Aims. About thirty new times of minimum light recorded with photoelectric or CCD photometers were obtained for four early-type eccentric-orbit eclipsing binaries CW Cep ($P = 2\overset{\mathrm{d}}{.}73$, $e = 0.029$), V478 Cyg ($2\overset{\mathrm{d}}{.}88, 0.016$), AG Per ($2\overset{\mathrm{d}}{.}03, 0.071$), and IQ Per ($1\overset{\mathrm{d}}{.}74, 0.076$).

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

Results. We confirm relatively short periods of apsidal motion of about 46, 27, 76, and 124 years for CW Cep, V478 Cyg, AG Per, and IQ Per, respectively. The corresponding internal structure constants, log k_2, are then found to be –2.12, –2.25, –2.15, and –2.36, under the assumption that the component stars rotate pseudosynchronously. The relativistic effects are negligible, being up to 8% of the total apsidal motion rate in all systems. Using the light-time effect solution, we have predicted a faint third component orbiting with a period of about 39 years for CW Cep.

Key words. stars: binaries: eclipsing – stars: individual: CW Cep – stars: individual: V478 Cyg – stars: individual: AG Per – stars: individual: IQ Per – stars: fundamental parameters

1. Introduction

The study of apsidal motion in detached eclipsing binary systems with eccentric orbits (EEB) is a rewarding area of research, which requires only moderate or small telescopes equipped with a photoelectric photometer or a CCD camera. A detailed analysis of the period variations can be performed using 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 massive stars. In particular, the four northern hemisphere objects are bright, hot, and massive eclipsing binaries with short orbital periods of less than 3 days. These variables are also frequently observed early-type eclipsing binaries, those orbits have been known to be slightly eccentric and to exhibit apsidal motion. With the exception of IQ Per, other systems studied are also members of an open cluster or an OB association. These systems are also included in the latest catalogue of apsidal motion in double stars of Petrova & Orlov (1999); their current O−C diagrams were also published by Kreiner et al. (2001). See also the Catalogue of Eccentric Eclipsing Binary Stars updated recently by Hegedüs et al. (2005). Our study is part of a series of papers on apsidal motion in eclipsing binaries (Wolf et al. 2004; Wolf & Zejda 2005). Similar studies of apsidal motion were published in the past by Giménez et al. (1987).

⋆ Partly based on photoelectric observations secured at the San Pedro Mártir Observatory, Baja California, Mexico, and Ege University Observatory, Izmir, Turkey.

2. Observations of minimum light

To enlarge the number of times of minimum light, new observations for all systems were carried out. New photoelectric photometry was obtained at several different observatories with the aim of securing several new, well-covered primary and secondary minima for all variables:

- San Pedro Mártir Observatory (hereafter SPM), Baja California, Mexico: the 0.84-m Cassegrain reflector equipped with the photon-counting photometer Cuentapulsos (utilizing a RCA 31034 photomultiplier) and Johnson *UBV* filters.
- Ege University Observatory, Izmir, Turkey: the 0.48-m Cassegrain telescope with the uncooled SSP-5 photometer (including a Hamamatsu R4457 detector) and *BV* filters.
- Johann Palisa Observatory and Planetarium of Technical University, Ostrava, Czech Republic: the 0.09-m or

Table 1. New times of minimum light.

System	JD Hel.- 2 400 000	Error [day]	Epoch	Method Filter	Observatory Source
CW Cep	48 688.891	0.005	2572.0	pe, *H*	this paper, Hipparcos
	52 568.398	0.001	3993.5	CCD, –	Ostrava
	52 976.394	0.001	4143.0	CCD, –	Ostrava
	53 504.4873	0.0006	4336.5	CCD, *R*	Ostrava
	53 519.4994	0.0007	4342.0	CCD, *R*	Ostrava
	53 609.560	0.001	4375.0	CCD, *R*	Ostrava
V478 Cyg	45 892.3972	0.0005	387.0	pe, *V*	this paper, Zakirov (2002)
	45 905.3624	0.0005	391.5	pe, *V*	this paper, Zakirov (2002)
	46 654.3833	0.0005	651.5	pe, *V*	this paper, Zakirov (2002)
	46 667.3601	0.0005	656.0	pe, *V*	this paper, Zakirov (2002)
	48 501.0376	0.0010	1292.5	pe, *H*	this paper, Hipparcos
	48 502.510	0.002	1293.0	pe, *H*	this paper, Hipparcos
	48 512.559	0.002	1296.5	pe, *H*	this paper, Hipparcos
	52 071.9180*	0.0003	2532.0	pe, *UBV*	SPM
	52 385.932*	0.001	2641.0	pe, *UBV*	SPM
	52 505.5132	0.0002	2682.5	CCD, *R*	Lelekovice
	52 748.927*	0.001	2767.0	pe, *UBV*	SPM
	53 254.5509	0.0007	2942.5	CCD, *R*	Brno
	53 545.5149	0.001	3043.5	CCD, *R*	Pec
AG Per	52 977.4584	0.0003	5052.0	CCD, –	Ostrava
	53 259.4459	0.0017	5191.0	CCD, *R*	Brno
	53 386.276	0.002	5253.5	CCC, –	Pec
	53 683.4594	0.0004	5400.0	CCD, *R*	Pec
	53 815.3269*	0.0003	5465.0	CCD, *VRI*	Brno
IQ Per	51 470.3731*	0.0001	4118.0	pe, *BV*	Izmir
	51 517.4470*	0.0003	4145.0	pe, *BV*	Izmir
	52 640.315	0.002	4789.0	CCD, –	Ostrava
	52 992.5111	0.0001	4991.0	CCD, –	Ostrava
	53 360.4033	0.0005	5202.0	CCD, –	Pec
	53 361.214	0.001	5202.5	CCD, –	Ostrava
	53 611.477	0.001	5346.0	CCD, –	Ostrava
	53 671.5664	0.0003	5380.5	CCD, *R*	Ostrava
	53 768.3986	0.0001	5436.0	CCD, *R*	Ostrava

Note: * mean value of *BV*, *UBV* or *VRI* measurements.

Newtonian 0.2-m telescopes with the CCD camera SBIG ST-7.
- Nicholas Copernicus Observatory and Planetarium, Brno, Czech Republic: the 0.08-m refractor or 0.4-m Nasmyth telescope with the CCD camera SBIG ST-8 and *R* filter.
- Private observatory of K.H. at Lelekovice, Czech Republic: the 0.35-m Newtonian telescope with the CCD camera SBIG ST-6V and *R* filter.
- Private observatory of L.B. at Pec pod Sněžkou, Czech Republic: 0.2-m Cassegrain telescope with the CCD camera SBIG ST-8 and *R* filter.

The CCD measurements in the Brno, Lelekovice, Ostrava, and Pec observatories were flat-fielded via sky exposures taken at dusk or dawn. Several comparison stars were chosen on the same frame as the variables. No variations in the brightness of these stars exceeding the expected error of measurements were detected (typically $\sigma \simeq 0.005$ mag in Ostrava). No correction for differential extinction was applied, due to the proximity of the comparison stars to the variable and the resulting negligible differences in air mass.

The new times of primary and secondary minima and their errors were generally determined by the classical Kwee-van Woerden algorithm. In some cases (Hipparcos data, scattered points), the light curve fitting by polynomials of the third order and the least-squares method were used. The new times are given in Table 1. Usually, only the bottom parts of the eclipses were used. All epochs in Table 1 are calculated from the light elements given in Table 2; the other columns are self-explanatory.

3. Apsidal motion analysis

The motion of the apsis of a binary star is a direct consequence of the finite size of its components. This effect has been well known for a long time (Cowling 1938; Sterne 1939). The rate of motion of the apsis is dependent on the internal structure of each component. Determination of the characteristics of a binary thus provides an observational test of the theory of stellar structure and evolution. Moreover, there is a relativistic contribution for the periastron advance in a similar way that occurs in the orbit of the planet Mercury.

The apsidal motion in all systems was studied by means of an O−C diagram analysis. For a more accurate calculation of the apsidal motion rate, the method described by Giménez & García-Pelayo (1983), and revised by Giménez & Bastero (1995), was used. This is a weighted least-squares iterative procedure, including terms in the eccentricity up to the fifth order. There are five independent variables $(T_0, P_s, e, \dot{\omega}, \omega_0)$

Table 2. Apsidal motion elements for CW Cep, V478 Cyg, AG Per and IQ Per.

Parameter	Unit	CW Cep	V478 Cyg	AG Per	IQ Per
T_0	HJD	2 441 669.5722 (5)	2 444 777.4852 (7)	2 442 728.3306 (7)	2 444 290.3644 (4)
P_s	days	2.72913959 (11)	2.88090063 (8)	2.02872951 (12)	1.74356214 (8)
P_a	days	2.7295811 (2)	2.8817387 (2)	2.0288769 (3)	1.7436292 (2)
e	–	0.0297 (5)	0.0158 (7)	0.0709 (6)	0.0763 (8)
$\dot{\omega}$	deg cycle^{-1}	0.0582 (5)	0.1047 (10)	0.0262 (4)	0.0138 (3)
$\dot{\omega}$	deg yr^{-1}	7.79 (7)	13.27 (5)	4.71 (8)	2.90 (15)
ω_0	deg	201.6 (0.5)	48.3 (0.5)	292.4 (0.8)	62.8 (0.4)
U	years	46.2 (0.4)	27.1 (0.5)	76.4 (0.8)	124.2 (6.5)

determined in this procedure. The periastron position ω is defined 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

$$U = 360° P_a/\dot{\omega}.$$

We have collected all reliable times of minimum light available in the literature. All new precise photoelectric and 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 1 or 0 because of the large scatter in these data.

We tested the stability of the results with respect to our – somewhat arbitrarily chosen – weighting scheme. It turned out that the results for well-covered phase curves of all systems under study are insensitive to the weighting scheme used.

3.1. CW Cep

The detached and double-lined eclipsing binary CW Cephei (also HD 218066, BD+62°2163, HIP 113907, FL 3459; $\alpha_{2000} = 23^h4^m2^s$, $\delta_{2000} = +63°23'49''$, $V_{max} = 7.67$ mag; Sp. B0.5V+B0.5V) is a well-known bright eclipsing binary with eccentric orbit ($e = 0.029$) and a short orbital period of about 2.73 days. It was first discovered to be a double-lined spectroscopic binary by Petrie (1947), and later Gaposchkin (1949) found eclipses on photographic plates. The system CW Cep is also a member of the Cep OB3 association (Clausen & Giménez 1991). Photoelectric observations of CW Cep were carried out by many investigators (Abrami & Cester 1960; Nha 1975; Söderhjelm 1976; Han 1984; Clausen & Giménez 1991; Soydugan et al. 2001; Han et al. 2002). See also a history of work on this binary in Clausen & Giménez (1991), where the following linear light elements are also given

$$\text{Pri.Min.} = \text{HJD } 2\,441\,669.5725 + 2\overset{d}{.}7291384 \cdot E.$$

Precise absolute dimensions of the components of CW Cep were derived spectroscopically and discussed by Popper & Hill (1991), Terrell (1991), and Clausen & Giménez (1991), who obtained components with similar mass and size:

$$M_1 = 11.82 \pm 0.14\, M_\odot,\ M_2 = 11.09 \pm 0.14\, M_\odot,$$
$$R_1 = 5.48 \pm 0.12\, R_\odot,\ R_2 = 4.99 \pm 0.12\, R_\odot.$$

The apsidal motion in CW Cep was studied by Söderhjelm (1976), Scarfe (1986), Giménez et al. (1987), Clausen & Giménez (1991), and Han et al. (2002). A detailed study of the apsidal motion of CW Cep was recently carried out by Erdem et al. (2004), but we decided to perform a re-analysis in light of the new times of minima now available. Besides those given in Table 1, we have added the times of minimum obtained by Han et al. (2002, their Table 1), Agerer & Hübscher (2003), Hübscher (2005), and Hübscher et al. (2005).

A total of 71 reliable times of minimum are now available, of which 39 correspond to primary eclipses and 32 to secondary eclipses. The computed apsidal motion elements and the internal errors of the least-squares fit (in brackets) are given in Table 2. 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 or 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 as continuous and dashed curves for primary and secondary eclipses, respectively. Subtracting the influence of the rapid apsidal motion, the O−C$_2$ diagram in Fig. 2 can be plotted. The sinusoidal variation of these values are remarkable and could be caused by a light-time effect. A preliminary analysis of the third body circular orbit gives the following elements (for this solution we used only the precise photoelectric or CCD timings):

P_3 (period) = 14 070 ± 550 days
= 38.5 ± 1.5 years
T_0 (time of conjunction) = J.D. 2 448 110 ± 300
A (semiamplitude) = 0.00243 ± 0.0005 day
e_3 (eccentricity) = 0.0 (fixed).

These values were obtained by the least-squares method. Our analysis of the third body orbit does not support the highly eccentric orbit of Han et al. (2002).

Assuming a coplanar orbit ($i_3 = 90°$) and a total mass of the eclipsing pair, $M_1 + M_2 = 22.91\, M_\odot$ (Clausen & Gimenéz 1991), we can obtain a lower limit for the mass of the third component $M_{3,min}$. The mass function has a small value of $f(M) = 5 \times 10^{-5}\, M_\odot$, from which the minimum mass of the third body follows as 0.30 $M_\odot$. A possible third component of spectral type M3, with the bolometric magnitude of $m_3 = 9.0$ mag (Harmanec 1988), is certainly invisible in a binary system with B0.5V components. Moreover, assuming an inclination of the third body orbit of $i_3 = 30°$, the mass of the third body follows as 0.61 $M_\odot$. Such a component of a spectral type K5 with bolometric magnitude $m_3 = 6.8$ mag produces the third light

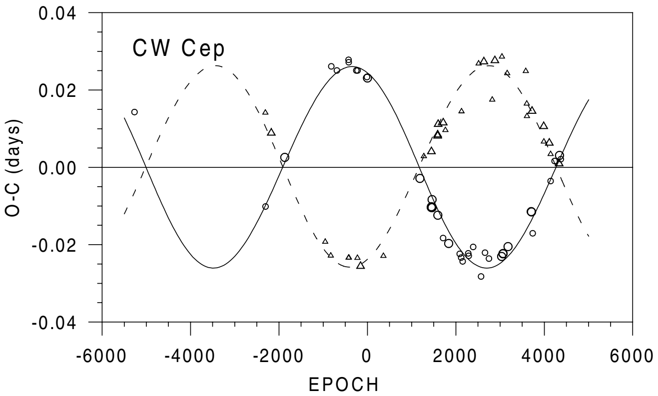

Fig. 1. The O−C diagram for the times of minimum of CW Cep. The continuous and dashed curves represent predictions for the primary and secondary eclipses, respectively. The individual primary and secondary minima are denoted by circles and triangles, respectively. Larger symbols correspond to the photoelectric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

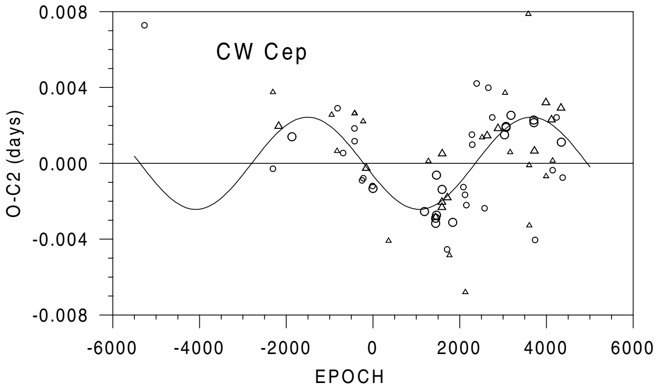

Fig. 2. O−C residuals of CW Cep after removing the influence of apsidal motion. The sinusoidal curve represents a light-time effect for the third body circular orbit with a period of 37 years and an amplitude of about 0.002 days. The individual primary and secondary minima are denoted by circles and triangles, resp.

of L_3 = 0.0005% only, which is still in contradiction with the contribution of the third light of about 3–5% given in Han et al. (2002) or about 1% derived by Erdem et al. (2004).

3.2. V478 Cyg

The double-lined detached eclipsing binary V478 Cygni (also HV 11091, HD 193 611, BD+37°3890, HIP 100 227, FL 3030, ADS 13 711 AB; α_{2000} = $20^{\rm h}19^{\rm m}38\overset{\rm s}{.}7$, δ_{2000} = $+38°20'9''\!.2$, $V_{\rm max} = 8\overset{\rm m}{.}7$; Sp. B0V + B0V) is a relatively bright binary system with a slightly eccentric orbit (e = 0.02). It was discovered to be variable spectroscopically by J. A. Pearce (1941). Analyses of extensive series of photometric observations have been carried out by Popper & Etzel (1981) and by Sezer et al. (1983) with similar results. Precise absolute dimensions of the components of V478 Cyg were derived spectroscopically by Popper & Hill (1991), who obtained components with identical mass and size

$$M_1 = 16.6 \pm 0.9\, M_\odot,\ M_2 = 16.3 \pm 0.9\, M_\odot,$$
$$R_1 = 7.43 \pm 0.12\, R_\odot,\ R_2 = 7.43 \pm 0.12\, R_\odot.$$

Zakirov (1993) in his photometric study presented only a phase of the primary minimum as 0.0042 ± 2 according to the ephemeris of Popper & Etzel (1981). Finally,

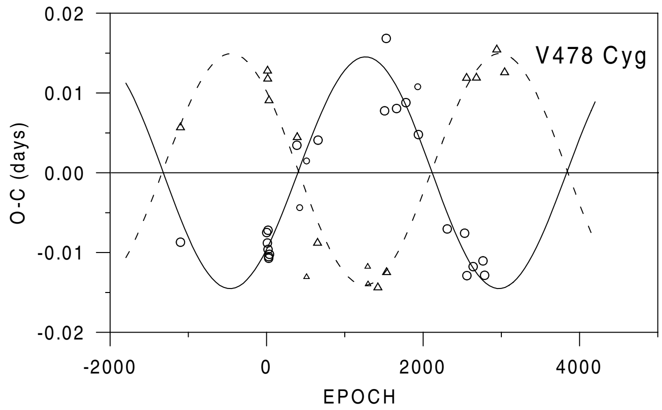

Fig. 3. O−C residuals for the times of minimum of V478 Cyg. See caption for Fig. 1.

Mossakovskaya & Khaliullin (1996) derived an apsidal motion rate of 13.7 deg/yr, in good agreement with their theoretical result (11.3 deg/yr). Since the above-mentioned papers were published, a substantial number of new times of minima have been obtained, which allowed us to reduce the observational uncertainties.

Our new photoelectric observations of V478 Cyg were carried out at San Pedro Mártir Observatory in June 2001, April 2002, and April 2003. The comparison star HD 228807 (also BD+37°3873, Sp. B5, V = 8.94, $B - V$ = 0.12, $U - B$ = −0.47), also selected by Sezer et al. (1983), was used. These observations consisted of 10-second integrations in each filter. They were carefully reduced to the standard *UBV* system and corrected for differential extinction using the reduction program HEC 22 rel.13.2 (Harmanec & Horn 1998).

Using Hipparcos photometry (Perryman et al. 1997), we were able to derive three additional times of minimum light using the light-curve profile fitting method. Based on unpublished photometric data of Zakirov (2002), we were then able to obtain four new times of minimum light. The epochs in Table 1 were computed according to the ephemeris of Sezer et al. (1983)

$$\text{Pri.Min.} = \text{HJD } 2\,444\,777\overset{\rm d}{.}4779 + 2\overset{\rm d}{.}880795 \cdot E.$$

All photoelectric times of minimum light given in Sezer et al. (1982, 1983), Mossakovskaya & Khaliulin (1996), Agerer & Hübscher (1996, 1998, 2001), Ak & Filiz (2003), and Bakis et al. (2003) were incorporated in our calculation. A total of 40 photoelectric times of minimum light were used in our analysis, with 15 secondary eclipses among them. The orbital inclination was adopted to be i = $77\overset{\circ}{.}73$, based on the photometric analysis (Zakirov 1993). The computed apsidal motion parameters and their internal errors of the least-squares fit are given in Table 2. The O−C diagram is shown in Fig. 3. The differences of O−C values from the apsidal motion are substantially larger than the standard errors of many observed times of minimum.

3.3. AG Per

The detached eclipsing binary AG Persei (also HD 25833, BD+33°785, HIP 19201, ADS 2990 AB, FL 336; α_{2000} = $4^{\rm h}6^{\rm m}56^{\rm s}$, δ_{2000} = $+33°26'47''$, $V_{\rm max}$ = 6.7 mag; Sp. B4V) is another well-known bright and double-lined eclipsing binary with a modest eccentric orbit (e = 0.07) and a short orbital period of about 2.03 days. AG Per is generally accepted as a member of the Per OB2 association and is a brighter component of the visual

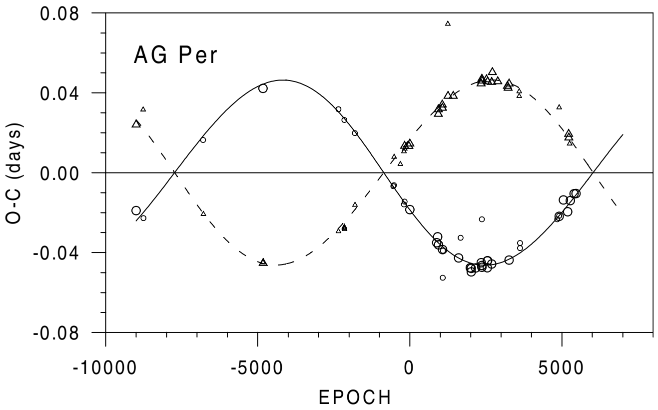

Fig. 4. O−C residuals for the times of minimum of AG Per. See caption for Fig. 1.

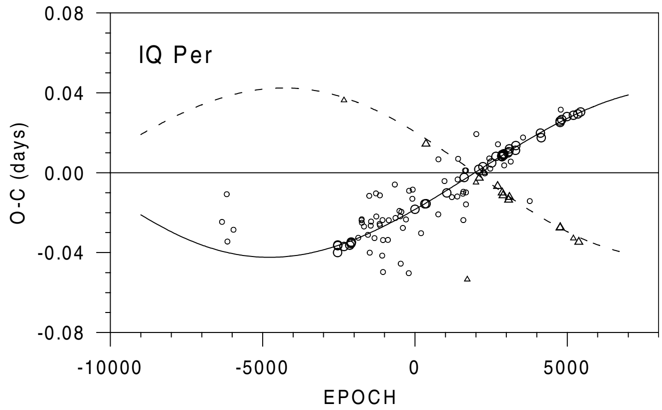

Fig. 5. O−C residuals for the times of minimum of IQ Per. See caption for Fig. 1.

double star ADS 2990. The apsidal motion of AG Per was discussed by Martin (1938), Oosterhoff (1943), Ashbrook (1949), Morley (1966), Semeniuk (1968), Güdür (1978), and Woodward & Koch (1987).

Giménez & Clausen (1994) derived orbital elements and precise physical parameters of the system. They also confirm the membership of AG Per in Per OB2 association and confirmed the period of apsidal motion of $U = 75.6 \pm 0.6$ yr. The next apsidal motion study was presented by Lee & Jeong (1996), who derived the apsidal motion period of $U = 76.17$ years. Finally, Tudose et al. (2000) derived $U = 82 \pm 3$ years and the internal structure constant $\log k_2 = -2.18$. The history of investigation of this binary can be found in Giménez & Clausen (1994), where the following linear lights elements are also given:

$$\text{Pri.Min.} = \text{HJD } 2\,442\,728\overset{\rm d}{.}3298 + 2\overset{\rm d}{.}0287298 \cdot E.$$

We include all times of minimum light collected in Tudose et al. (2000, their Table 4) and Lee & Jeong (1996, their Table 2) in our analysis, as well as new timings presented by Agerer & Hübscher (2003), Borkovits et al. (2003), and Bíró et al. (2006), and our new times given in Table 1. A total of 85 reliable times of minimum are now available, of which 42 correspond to primary eclipses and 43 to secondary eclipses. The orbital inclination was adopted to be $i = 81\overset{\circ}{.}4$, based on the photometric analysis of Giménez & Clausen (1994). The computed apsidal motion parameters and the internal errors of the least-squares fit are given in Table 2. The O−C diagram is shown in Fig. 4.

3.4. IQ Per

The detached eclipsing binary IQ Persei (also HD 24909, BD+47°920, HIP 18662, FL 322; $\alpha_{2000} = 3^{\rm h}59^{\rm m}45^{\rm s}$, $\delta_{2000} = +48°9'4''$, $V_{\rm max} = 7.73$ mag; Sp. B8+A6) is a well-known bright eclipsing binary with eccentric orbit ($e = 0.076$) and a short orbital period of about 1.7 days. IQ Per is also mentioned as a brighter member of a visual binary with BD+47°921 (V = 9.3 mag). It was discovered to be a variable star by Hoffmeister (1949), and Hall et al. (1970) obtained complete *UBV* light curves and found a short orbital period of 1.7435673 days. They also estimated an apsidal period of about 70 years. The first spectroscopic orbit was determined by Young (1975) based on eleven spectrograms. The absolute parameters were published in Lacy & Frueh (1985) who derived an apsidal motion period of $U = 140 \pm 30$ years. Later, an apsidal motion study was presented by Drozdz et al. (1990), who improved the period of apsidal motion to be $U = 119 \pm 9$ years. Degirmenci (1997) in his photometric study obtained the apsidal motion period $U = 122 \pm 7$ years with good agreement with the previous authors. Finally, Lee et al. (2003) obtained four new CCD times of minima, and improved the apsidal motion period to $U = 122.2 \pm 0.3$ years. The review of the investigation of this binary can be found in the paper by Degirmenci (1997), where the following linear light elements are given

$$\text{Pri.Min.} = \text{HJD } 2\,444\,290.3640 + 1\overset{\rm d}{.}7435620 \cdot E.$$

Two new primary minima were obtained photoelectrically at the Ege University Observatory in October and December 1999. The nearby comparison star HD 24980 = BD+47°923 (Sp. A2, $V = 8\overset{\rm m}{.}36$, $B-V = 0\overset{\rm m}{.}23$) was used during these B, V observations, which consisted of 10-second integrations in each filter. Next, precise CCD times of minima obtained recently at Ostrava in December 2003, October 2005, and February 2006 are given in Table 1.

We include all times of minimum light collected in Degirmenci (1997, his Table 4) in our analysis, as well as new timings presented by Müyesseroglu et al. (1996), Agerer & Hübscher (2003), and Lee et al. (2003), and our new times given in Table 1. The orbital inclination was adopted to be $i = 89\overset{\circ}{.}3$, based on the last photometric analysis of Degirmenci (1997).

Altogether, 115 times of minimum light were collected in our analysis, with only 15 secondary eclipses among them. The resulting apsidal motion parameters are again given in Table 2. The O−C residuals for all times of minimum with respect to the linear part of the apsidal motion equation are shown in Fig. 5, as explained above. Approximately 30% of the apsidal motion period is now covered by precise photoelectric or CCD measurements.

4. Internal structure constant

The internal structure constant (ISC) k_2, which is related to the variation of the density within the star, is an important parameter of stellar evolution models. However, the period of rotation of the periastron in eccentric eclipsing binaries does not allow us to derive the individual internal stellar constant of the component stars. The observed average value of $k_{2,\rm obs}$ can be derived using the following expression:

$$k_{2,\rm obs} = \frac{1}{c_{21} + c_{22}} \frac{P_a}{U} = \frac{1}{c_{21} + c_{22}} \frac{\dot{\omega}}{360}, \qquad (1)$$

where c_{21} and c_{22} are functions of the orbital eccentricity, fractional radii, the masses of the components, and the ratio between

Table 3. Adopted basic physical properties of the binary components and the internal structure constant.

Parameter	Unit	CW Cep	V478 Cyg	AG Per	IQ Per
M_1	$M_\odot$	11.82 (14)	16.6 (0.9)	5.36 (16)	3.51 (4)
M_2	$M_\odot$	11.09 (14)	16.3 (0.9)	4.90 (13)	1.73 (2)
r_1		0.235 (5)	0.272 (2)	0.2045 (45)	0.231 (2)
r_2		0.214 (5)	0.272 (2)	0.1779 (45)	0.142 (6)
i	deg	82.5 (1.0)	78.0 (0.6)	81.4 (6)	89.3 (8)
Source		Clausen & Giménez (1991)	Popper & Hill (1991) Zakirov (1993)	Giménez & Clausen (1994)	Lacy & Frueh (1985)
$\dot{\omega}_{\rm rel}$	deg cycle^{-1}	0.00225	0.00277	0.00161	0.00114
$\dot{\omega}_{\rm rel}/\dot{\omega}$	%	3.9	2.7	6.2	8.3
log $k_{2,\rm obs}$		–2.109	–2.256	–2.145	–2.380
Δ log $k_{2,\rm obs}$		0.052	0.034	0.053	0.065
log $k_{2,\rm theo}$		–2.08	–2.22	–2.14	–2.32

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. Taking the value of the eccentricity and the masses of the components into account, one has to subtract a relativistic correction $\dot{\omega}_{\rm rel}$ (Levi-Civita 1937; Giménez 1994):

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

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 all systems are given in Table 3. Their errors were evaluated according to the relation given in Wolf & Zejda (2005). The uncertainity in the eccentricity was neglected due to the presence of its higher terms. One can find the complete relation for the calculation of the ISC error in the paper of Tudose et al. (2000). Theoretical values $k_{2,\rm theo}$ according to available theoretical models for the internal stellar structure computed by Claret (1995) for given masses of components are presented in Table 3. The chemical composition of $X = 0.70$ and $Z = 0.02$ was supposed to be in agreement with previous studies.

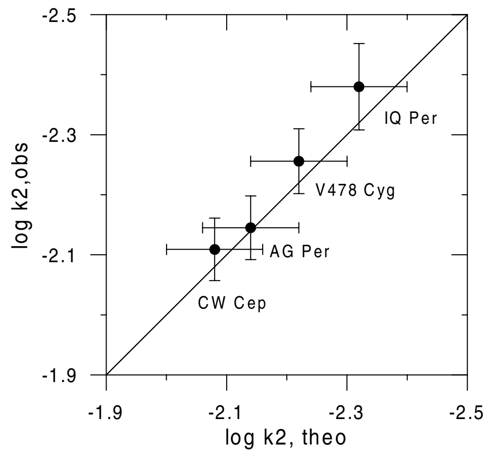

Fig. 6. A comparison between the observed and theoretical average values of log k_2 using models of stellar evolution.

5. Conclusions

The apsidal motion in eccentric eclipsing binaries has been used for decades to test evolutionary stellar models. This study provides accurate information on the apsidal motion rates and the internal structure constants of four main-sequence hot and massive binary systems: CW Cep, V478 Cyg, AG Per, and IQ Per. Compared to similar studies by previous authors, the database has been enlarged in time at least by 500 orbital cycles, or about 10% of the apsidal motion period. None of the analysed binaries presents an important relativistic contribution of up to 8% of the total apsidal motion rate. The obtained values of the internal structure constant $k_{2,\rm obs}$ are compared to their theoretical values $k_{2,\rm theo}$, according to available models for the internal stellar structure presented for a variety of masses and chemical compositions by Claret (1995) (Fig. 6). The individual systems seem slightly more centrally condensed than predicted by models, which may be affected by the assumption of the same chemical composition for all the systems. Moreover, the value of k_2 is very dependent on convective overshooting for the more massive stars. The resulting uncertainties in log $k_{2,\rm theo}$ (typically 0.08) are also plotted in Fig. 6. We can conclude that the internal structure constant in all cases agrees well with that taken from the theoretical models.

In all binaries studied, V478 Cyg has one of the smallest known periods of apsidal motion. Only the systems U Oph (20.1 yr, Wolf et al. 2002) and GL Car (25.2 yr, Giménez & Clausen 1986) have shorter periods. Concerning the orbital parameters, AG Per seems to be very similar to the system of U Oph or V760 Sco, which are other well-studied detached main sequence systems available in the 4–6 $M_\odot$ interval. Our result indicates that CW Cep is probably the next member of an interesting group of triple eccentric eclipsing binaries (e.g. RU Mon, U Oph, YY Sgr, and DR Vul) deserving regular photometric and spectroscopic monitoring. For the systems CW Cep and IQ Per, a slight improvement in the apsidal period has been derived. The third body effect observable in the apsidal motion of CW Cep excludes the possibility of the third light detected by Clausen & Giménez (1991) and other authors.

In spite of the considerable amount of observational data collected for decades, the absolute dimensions of massive binary components are known with low accuracy. More than 15 years has elapsed since the last spectroscopic studies of these binaries by Popper & Hill (1991) and Giménez & Clausen (1991). Thus, it is also highly desirable to obtain new, high-dispersion, and high-S/N spectroscopic observations, and apply modern disentangling methods to obtain radial velocity curves of both components for these systems.

Acknowledgements. This investigation was supported by the Grant Agency of the Czech Republic, grants No. 205/04/2063 and No. 205/06/0217. MW wishes to thank the staff at San Pedro Mártir Observatory, Mexico, for unfailing hospitality and help with the equipment. Dr. T. Gráf and L. Král, Johann Palisa Observatory, are acknowledged for their support of our CCD observations at Ostrava. We are very indebted to Ms. Bartošíková, Mr. Hynek, and Mr. Kalisch for their CCD observations made in Ostrava. We are also thankful to M. M. Zakirov for sending us his original photometric data of V478 Cyg, as well as to the referee Dr. A. Giménez for his comments that improved the paper. This research has made use of the SIMBAD database, operated at CDS, Strasbourg, France, and of NASA's Astrophysics Data System Bibliographic Services.

References

Abrami, A., & Cester, B. 1960, Publ. Oss. Astron. Trieste, 300
Agerer, F., & Hübscher, J. 1996, IBVS, No. 4383
Agerer, F., & Hübscher, J. 1998, IBVS, No. 4562
Agerer, F., & Hübscher, J. 2001, IBVS, No. 5016
Agerer, F., & Hübscher, J. 2003, IBVS, No. 5484
Ak, H., & Filiz, N. 2003, IBVS, No. 5462
Ashbrook, J. 1949, AJ, 55, 2
Bakis, V., Bakis, H., Erdem, A., et al. 2003, IBVS, No. 5464
Bíró, I. B., Borkovits, T., Csizmadia, S., et al. 2006, IBVS, No. 5684
Borkovits, T., Bíró, I. B., Hegedüs, T., et al. 2003, IBVS, No. 5434
Claret, A. 1995, A&AS, 109, 441
Claret, A. 2004, A&A, 424, 919
Claret, A., & Giménez, A. 1992, A&AS, 96, 255
Claret, A., & Willems, B. 2002, A&A, 388, 518
Clausen, J. V., & Giménez, A. 1991, A&A, 241, 98
Cowling, T. G. 1938, MNRAS, 98, 734
Degirmenci, Ö. L. 1997, Ap&SS, 253, 237
Drozd, M., Krzesinski, J., & Pajdosz, G. 1990, IBVS, No. 3494
Erdem, A., Soydugan, E., Soydugan, F., et al. 2004, AN, 325, 336
Gaposchkin, S. 1949, Variable Stars, 7, 34
Giménez, A. 1985, ApJ, 297, 405
Giménez, A. 1994, Experim. Astron., 5, 91
Giménez, A., & Bastero, M. 1995, Ap&SS, 226, 99
Giménez, A., & Clausen, J. V. 1986, A&A, 161, 275
Giménez, A., & Clausen, J. V. 1994, A&A, 291, 795
Giménez, A., & García-Pelayo, J. M. 1983, Ap&SS, 92, 203
Giménez, A., Kim, Ch.-H., & Nha, I.-S. 1987, MNRAS, 224, 543
Güdür, N. 1978, Ap&SS, 57, 17
Hall, D. S., Gertken, R. H., & Burke, E. W. 1970, PASP, 82, 1077
Han, W. Y. 1984, J. Astr. Space Sci., 1, 41
Han, W., Kim, Ch.-H., Lee, W.-B., & Koch, R. H. 2002, AJ, 123, 2732
Harmanec, P. 1988, Bull. Astr. Inst. Czech., 39, 329
Harmanec, P., & Horn, J. 1998, J. Astron. Data, 4, CD-ROM file 5, Publ. by C. Sterken, Vrije Universiteit Brussel
Hegedüs, T., Giménez, A., & Claret, A. 2005, ASP Conf. Ser., 333, 88
Hoffmeister, C. 1949, Astr. Abh. Erg. Astr. Nach., 12, A21
Hübscher, J. 2005, IBVS, No. 5643
Hübscher, J., Paschke, A., & Walter, F. 2005, IBVS, No. 5657
Kreiner, J. M., Kim, C.-H., & Nha, I.-S. 2001, An Atlas of O−C diagrams of Eclipsing Binary Stars, Wydawnictwo Naukowe Akademii Pedagogicznej, Cracow, Poland
Kopal, Z. 1978, Dynamics of Close Binary Systems, Reidel, Dordrecht, Holland
Kwee, K. K., & van Woerden, H. 1956, Bull. Astron. Inst. Neth., 12, 327
Lacy, C. H., & Frueh, M. L. 1985, ApJ, 295, 569
Lee, K. H., & Jeong, J. H. 1996, J. Astron. Space Sci., 13, 63
Lee, Ch.-U., Kim, Ch.-H., Oh, K.-D., & Byun, Y.-I. 2003, J. Astron. Space Sci., 20, 261
Levi-Civita, T. 1937, Amer. J. Math., 59, 225
Mossakovskaja, L. V., & Khaliullin, Kh. F. 1996, Pisma Astr. Z., 22, 149
Martin, W. Ch. 1938, BAN, 8, 286
Morley, J. 1966, IBVS, No. 163
Müyesseroglu, Z., Gürol, B., & Selam, S. O. 1996, IBVS, No. 4380
Nha, I.-S. 1975, AJ, 80, 232
Oosterhof, P. Th. 1943, BAN, 9, 416
Pearce, J. A. 1941, PASP, 10, 233
Perryman, M. A. C., Høg, E., Kovalevsky, J., Lindegren, L., & Turon, C. 1997, ESA SP-1200 The Hipparcos and Tycho Catalogues
Petrie, R. M. 1947, Publ. Dom. Astrophys. Obs., 7, 305
Petrova, A. V., & Orlov, V. V. 1999, AJ, 117, 587
Popper, D. M., & Etzel, P. E. 1981, AJ, 86, 102
Popper, D. M., & Hill, G. 1991, AJ, 101, 600
Semeniuk, I. 1968, Acta Astron., 18, 1
Sezer, C., Güdür, N., Gülmen, Ö., & Sengonca, H. 1983, A&AS, 53, 363
Scarfe, C. D. 1986, Proc. IAU Symp. No. 118, ed. J. B. Hearnshaw, & P. L. Cottrell (Dordrecht, Holland: Reidel), 319
Soydugan, E., Demircan, O., Keskin, V., et al. 2001, IBVS, No. 5154
Söderhjelm, S. 1976, A&AS, 25, 151
Terrell, D. 1991, MNRAS, 250, 209
Tudose, V., Dumitrescu, A., & Rusu, M. 2000, Rom. Astron. J., 10, 35
Wolf, M., & Zejda, M. 2005, A&A, 437, 545
Wolf, M., Harmanec, P., Diethelm, R., Hornoch, K., & Eenens, P. 2002, A&A, 383, 533
Wolf, M., Harmanec, P., Šarounová, L., et al. 2004, A&A, 420, 619
Woodward, E. J., & Koch, R. H. 1987, Ap&SS, 129, 187
Young, A. 1975, PASP, 87, 717
Zakirov, M. M. 1993, Kinemat. Fiz. Neb. Tel, 9, 47
Zakirov, M. M. 2002, private communication