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ASTRONOMY AND ASTROPHYSICS

Apsidal motion in the eclipsing binaries V1136 Cygni, ES Lacertae, MZ Lacertae and EQ Vulpeculae

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Abstract. About thirty new times of minimum light recorded with photoelectric means have been gathered for the early-type eccentric eclipsing binaries V1136 Cyg ($P = 3.46^d, e = 0.33$), ES Lac ($P = 4.46^d, e = 0.20$), MZ Lac ($P = 3.16^d, e = 0.42$) and EQ Vul ($P = 9.30^d, e = 0.36$). The $O - C$ diagrams are analyzed using all reliable timings found in the literature and new values for the elements of the apsidal motion are computed. We find new periods of apsidal motion of about 520, 300, 440 and 2200 years for V1136 Cyg, ES Lac, MZ Lac and EQ Vul, respectively.

Key words: stars: binaries: eclipsing – stars: individual: V1136 Cyg, ES Lac, MZ Lac, EQ Vul – stars: fundamental parameters

1. Introduction

Eclipsing binaries are excellent laboratories for studying a wide variety of processes in stellar astrophysics. Their usefulness extends far beyond their textbook role in the determination of stellar masses and radii. The study of apsidal motion in detached eclipsing binary systems with eccentric orbit is an important source of information on the stellar internal structure as well as for the possibility of verification of the theory of General Relativity. Suitable objects for this research were tabulated by Giménez (1994). Similar studies were published by Busch (1975, 1976).

In this paper, we report new results for our observational project initiated in 1993 with the main purpose of monitoring eclipsing binaries with eccentric orbits. In particular, the four nothern-hemisphere summer objects V1136 Cyg, ES Lac, MZ Lac and EQ Vul analysed here are little studied and rather faint early-type binaries. All these systems have periods of more than 3 days and a relatively large orbital eccentricity. Unfortunately, some of these systems have not been studied in detail since their discovery. No spectroscopic observations have been published for these systems as far as we know.

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2. Observations of minimum light

In order to enlarge the number of times of minimum light, new observations for all four systems were carried out. Our new photoelectric and CCD photometry was performed at three observatories with the aim of securing at least one well-covered primary and secondary minimum for each variable:

- Ondřejov Observatory, Czech Republic: 65cm reflecting telescope with Cousins V, R filters and CCD-camera SBIG ST-6 or ST-8 at its primary focus,
- R. Szafraniec Observatory, Metzerlen, Switzerland: 35cm Schmidt-Cassegrain telescope with unfiltered CCD-camera SBIG ST-6, and
- Tian-Shan High Altitude Station of Sternberg Astronomical Institute, Kazakhstan: 50cm telescope with photoelectric photometer.

The CCD measurements in Ondřejov were done using primarily the standard Cousins R filter with typically 60^s exposure times. Exceptionally, V1136 Cyg was measured in the V filter. Flat fields for the reduction of the CCD frames were routinely obtained from exposures of regions of the sky taken at dusk or dawn. Several comparison stars were chosen on the same frame as the variables. During the observations, no variations in the brightness of these stars exceeding the possible error of measurements (typical $\sigma \simeq 0.005$ mag) were detected. No correction was allowed for differential extinction, due to the proximity of the comparison stars to the variable and the resulting small differences in the air mass.

The photoelectric measurements of the binaries MZ Lac and ES Lac at Tian-Shan were done in the V filter of the $WBVR$-photometric system. Concerning this equipment see Khaliullin et al. (1985) for more details.

The new times of primary and secondary minimum and their errors were determined using the least squares fit of the data, by the bisecting cord method and the Kwee-van Woerden algorithm. These 29 times of minimum are presented in Table 1. As an example of our CCD measurements, Fig. 1 shows the differential V-magnitude during the primary minimum of V1136 Cyg obtained at JD 24 49896.

Table 1. New times of minimum light

System	JD Hel.- 2400000	Error [day]	Min. type	Filter	Observatory Source
V1136 Cyg	49896.4865	0.0003	I	V	Ondřejov
	49896.4879 [b]	0.0010	I	-	Metzerlen
	49919.38 [a]	0.01	II	V	Ondřejov
	50599.4321 [b]	0.0008	I	-	Metzerlen
ES Lac	46301.2636	0.0005	II	V	Tian-Shan
	46325.2685 [a]	0.0008	I	V	Tian-Shan
	46347.566 [a]	0.005	I	V	Tian-Shan
	48876.032	0.005	I	V	Tian-Shan
	48880.5035 [a]	0.0008	I	V	Tian-Shan
	48883.273	0.005	II	V	Tian-Shan
	49246.166	0.005	I	V	Tian-Shan
	49625.2204	0.0005	I	V	Tian-Shan
	49634.1435	0.0005	I	V	Tian-Shan
	49919.525 [ab]	0.010	I	-	Metzerlen
	49928.460	0.005	I	R	Ondřejov
	49935.693	0.005	II	R	Ondřejov
	50426.227	0.005	II	V	Tian-Shan
MZ Lac	46340.2605	0.0008	II	V	Tian-Shan
	49244.4032	0.0008	I	V	Tian-Shan
	49246.2996	0.0002	II	V	Tian-Shan
	49622.1855	0.0002	II	V	Tian-Shan
	49920.3905	0.0003	I	R	Ondřejov
	49925.4237	0.0007	II	R	Ondřejov
	50304.458 [b]	0.005	II	-	Metzerlen
	50754.3179 [b]	0.0009	I	-	Blättler (1998)
	50754.3185 [b]	0.0013	I	-	Metzerlen
EQ Vul	49113.82:	0.02	I	V	Diethelm (1993)
	49913.368 [a]	0.005	I	R	Ondřejov
	50323.451	0.003	II	R	Ondřejov

a normal minimum,
b published also in BBSAG Bull. Nos. 109, 113, 115, 116

3. Apsidal motion analysis

The apsidal motion in all systems was studied by means of an $O-C$ diagram analysis. We have collected all reliable times of minimum light gathered from the literature as well as from current databases of AAVSO, BAV, BBSAG and BRNO observers.

Suitable numerical methods for the apsidal motion analysis were described by Giménez & García-Pelayo (1983) and Lacy (1992). Improved expressions for the prediction of eclipse times are also presented in Giménez & Bastero (1995). We used the method first mentioned, which is a weighted least squares iterative procedure, including terms in the eccentricity up to the fifth order. Due to the relatively large value of the orbital eccentricity of all studied systems, we used all terms in our calculation. Our formula for the prediction of the times of minimum, used for the minimization by the least-squares method, is also given in Wolf & Šarounová (1995). There are five independent variables $(T_0, P_s, e, \dot{\omega}, \omega_0)$ to be determined in this procedure. The relation between the sidereal and the anomalistic period, P_s and P_a, is given by

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

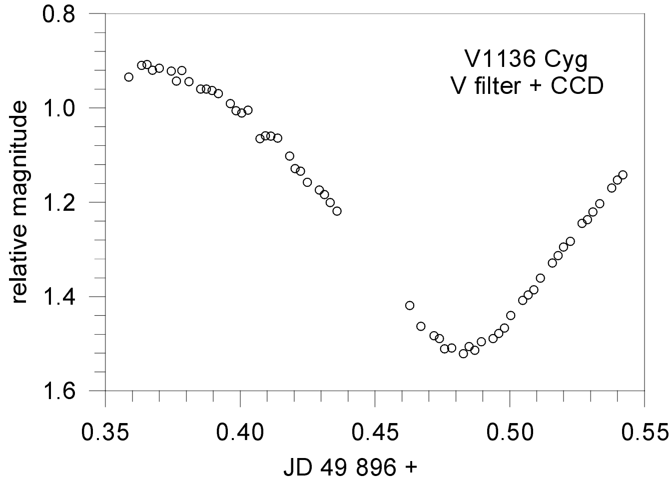

Fig. 1. A plot of the differential V-magnitudes observed during primary eclipse of V1136 Cyg.

and the period of apsidal motion by

$$U = 360° P_a/\dot{\omega}.$$

We employed the following data reduction procedure. All photoelectric times of minimum were used with a weight of 10 in our computation. The current photographic as well as some of our less precise measurements were weighted with a factor of 5, while the earlier visual and photographic times of minimum were given a weight of 1 due to the large scatter in these data.

3.1. V1136 Cyg

The detached eclipsing binary V1136 Cygni (= GSC 2150.3565 = HBV 421 = FL 2790; $\alpha_{2000} = 19^h 37^m 50^s$, $\delta_{2000} = +28°$ 50.6', V_{max} = 12.2 mag; Sp. A0) is a little studied, rather faint early-type binary with an eccentric orbit ($e = 0.32$) and a period of about 3.46 days. It was discovered to be a variable by Wachmann (1966), but no period was found. A reworking of the individual observation by Bossen & Klawitter (1972) lead to the following light elements:

$$\text{Pri. Min.} = \text{HJD } 24\ 35453.235 + 3.^{d}462766 \cdot E.$$

They obtained also the first photographic light curve and determined an orbital eccentricity of e = 0.32. The next photographic times of minimum were found by Busch (1976) on the plates of the Sonnenberg and Hartha Observatories. He also announced the possibility of apsidal motion in this system and determined a smaller value of the orbital eccentricity: e = 0.27. Four new CCD times are given in Table 1.

All photographic times of Wachman (1966), Bossen & Klawitter (1972) and Busch (1976) were incorporated in our calculation. A total of 40 times of minimum light were used in our analysis, with 19 secondary eclipses among them. The computed apsidal motion elements and their internal errors of the least squares fit are given in Table 2. In this table P_s denotes the sidereal period, P_a the anomalistic period, e represents the

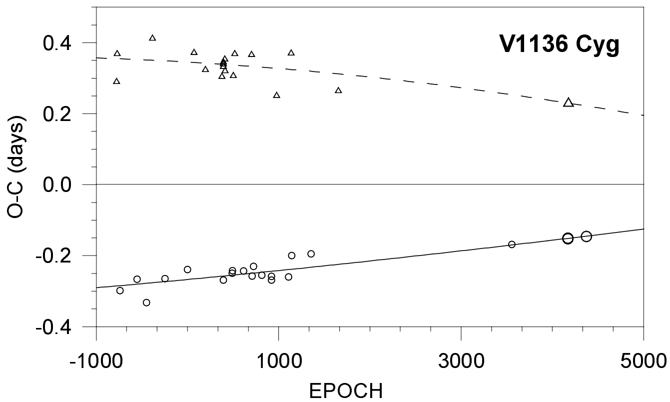

Fig. 2. $O - C$ residuals for the times of minimum of V1136 Cyg with respect to the linear part of the apsidal motion equation. The continuous and dashed curves represent predictions for primary and secondary eclipses, respectively. The individual primary and secondary minima are denoted by circles and triangles, respectively. Larger symbols correspond to the photoelectric measurements which were taken into calculations with higher weight.

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 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. 2. The non-linear predictions, corresponding to the fitted parameters, are plotted as continuous and dashed curves for primary and secondary eclipses, respectively.

3.2. *ES Lac*

The eclipsing binary ES Lacertae (= GSC 3983.386 = CVS 5570 = S 4593 = FL 3391; $\alpha_{2000} = 22^h32^m16^s$, $\delta_{2000} = +53° 57.9'$, V_{max} = 11.4 mag; Sp. A3) is also a relatively little known, early-type detached binary with an orbital eccentricity $e = 0.20$ and a period of about 4.46 days. It was discovered to be a variable star photographically by Filin (1952). Next times of minimum light were found on the plates of the Vatican Observatory by Miller and Wachmann (1971), who obtained also the first photographic light curve. Pugach (1974) derived the light elements

$$\text{Pri. Min.} = \text{HJD } 24\,34240.416 + 4\overset{\text{d}}{.}459349 \cdot E$$

and found a relatively large value of the orbital eccentricity. Very extensive photometric observations of this variable, covering several seasons, were done by one of us (V.K.) at Tian-Shan Observatory. In this paper, we present the newly derived times of minimum only. A total of 43 times of minimum light were used in our analysis, with 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. 3 as explained above.

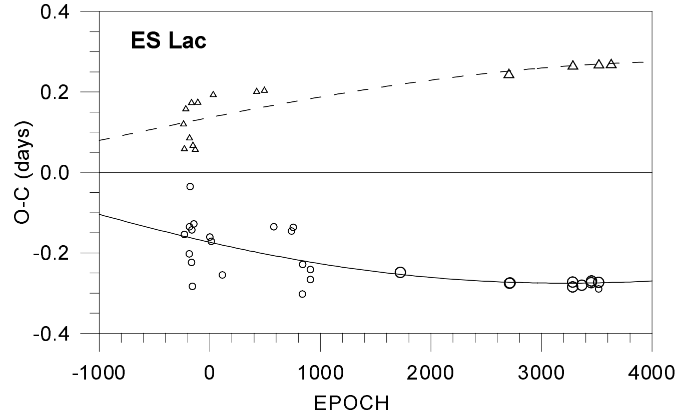

Fig. 3. $O - C$ graph for ES Lac. See legend for Fig. 2

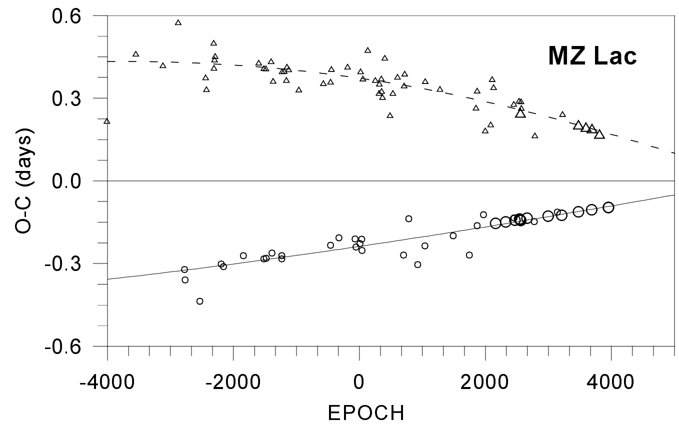

Fig. 4. $O - C$ residuals for the times of minimum for MZ Lac. See legend for Fig. 2

3.3. *MZ Lac*

The detached eclipsing binary MZ Lacertae (= GSC 3983.2132; $\alpha_{2000} = 22^h28^m02^s$, $\delta_{2000} = +53° 40.9'$, V_{max} = 11.2 mag; Sp. A0) has also gathered little attention, it being a rather faint early-type binary with a large orbital eccentricity ($e = 0.47$) and a period of about 3.16 days. It was discovered to be a variable photographically on the plates of the Vatican Observatory by Miller and Wachmann (1971), who obtained also the first photographic light curve. Šilhán (1990, 1992) studied MZ Lac on the plates of the Sonnenberg Sky Survey and carried out a new analysis of the period, including new photographic times of minimum. He found the following linear light elements:

$$\text{Pri. Min.} = \text{HJD } 24\,38264.3452 + 3\overset{\text{d}}{.}1588204 \cdot E$$

and the substantial value for orbital eccentricity of $e = 0.47 \pm 0.12$. Šilhán also found an apsidal motion with the period of $U = 570 \pm 170$ years.

All times of minimum light published by Šilhán (1992) were incorporated into our analysis with the weighting scheme mentioned in Sect. 3. A total of 101 times of primary and secondary minima were incorporated into our calculations. The apsidal motion elements are also given in Table 2, the corresponding $O - C$ diagram is plotted in Fig. 4.

Table 2. Apsidal motion elements of V1136 Cyg, ES Lac, MZ Lac and EQ Vul

	V1136 Cyg	ES Lac	MZ Lac	EQ Vul
T_0 [HJD]	2435453.4895 ± 0.0007	2434240.5889 ± 0.0008	2438264.5807 ± 0.0006	2435344.7108 ± 0.0012
P_s [days]	3.4627546 ± 0.0000011	4.4593930 ± 0.0000012	3.1587846 ± 0.0000007	9.2971844 ± 0.0000018
P_a [days]	3.4628182 ± 0.0000011	4.4595764 ± 0.0000012	3.1588462 ± 0.0000007	9.2972924 ± 0.0000018
e	0.326 ± 0.007	0.192 ± 0.009	0.421 ± 0.005	0.359 ± 0.011
$\dot{\omega}$ [deg cycle^{-1}]	0.0066 ± 0.0005	0.0148 ± 0.0016	0.0070 ± 0.0004	0.0042 ± 0.0004
$\dot{\omega}$ [deg yr^{-1}]	0.696 ± 0.053	1.21 ± 0.13	0.812 ± 0.046	0.164 ± 0.016
ω_0 [deg]	31.7 ± 0.5	304.0 ± 0.6	45.7 ± 0.4	213.7 ± 0.8
U [years]	517 ± 39	297 ± 36	444 ± 25	2190 ± 210

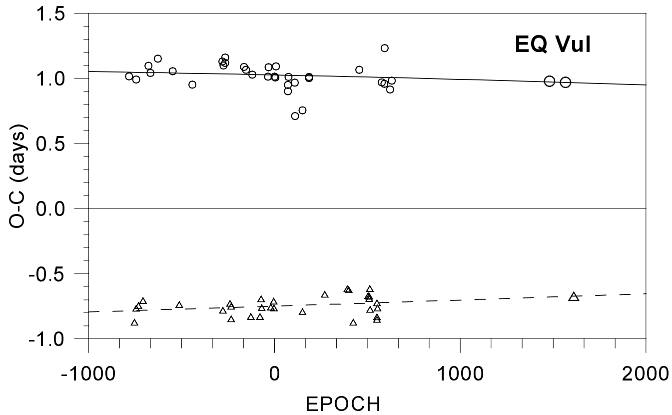

Fig. 5. $O-C$ diagram for EQ Vul. See legend for Fig. 2

3.4. EQ Vul

The detached eclipsing binary EQ Vulpeculae (= GSC 2149.1476 = CSV 4937 = FL 2916 = S 4475; $\alpha_{2000} = 19^h58^m24^s$, $\delta_{2000} = 28°$ 02.3', V_{max} = 11.2 mag; Sp. B8) has been seldom investigated since its discovery. It is an early-type binary with an eccentricic orbit ($e = 0.36$) and a relatively long period of about 9.3 days. It was discovered to be a variable star photographically by Hoffmeister (1947). The first light elements were obtained by Bossen & Klawitter (1972):

$$\text{Pri. Min.} = \text{HJD } 24\,35344.763 + 9^{\text{d}}.297164 \cdot \text{E}.$$

They also obtained the first photographic light curve and determined the orbital eccentricity at $e = 0.36$. The next photographic times of minimum were found by Busch (1975) on the plates of the Sonnenberg and Hartha Observatories, by Erleksova (1975) on the plates of the Tadjik Observatory and by Botsula (1962) on the plates of the Engelhard Observatory. No firm solution for the apsidal motion could be found. Two new CCD times obtained at Ondřejov Observatory are given in Table 1.

A total of 66 times of minimum light were used in our analysis, with 31 secondary eclipses among them. The apsidal motion parameters are given in Table 2, the corresponding $O-C$ diagram is plotted on Fig. 5.

4. Conclusions

We derive updated apsidal motion elements for four eccentric early-type eclipsing binaries by means of an $O-C$ diagram analysis. For the binaries V1136 Cyg, ES Lac and EQ Vul, the apsidal motion elements are given for the first time. The shortest period of apsidal motion among all the discussed binaries is found for ES Lac, the longest period is derived for EQ Vul. In the case of MZ Lac, our resulting orbital eccentricity and the period of apsidal motion is smaller than previously obtained by Šilhán (1990). Concerning the orbital and physical parametres, the system of MZ Lac seems to be very similar to the system FT Ori, which is another eclipsing binary with a large orbital eccentricity and an apsidal motion period of about 480 years (Wolf & Šarounová 1995).

Only a small part of the apsidal motion period is well-covered by the photographic or the more precise photoelectric and CCD observations. Therefore, new high-accuracy timings of these eclipsing systems are necessary in order to enlarge the timespan for a better analysis of the apsidal motion and to confirm the parameters given above. A spectroscopic orbit, allowing a precise mass determination, should be also obtained for a more thorough study and a more definitive determination of orbital and physical properties of all systems discussed in this paper.

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