Apsidal motion and a light curve solution for eighteen SMC eccentric eclipsing binaries^{★,★★}

P. Zasche¹, M. Wolf¹, J. Vraštil¹, J. Liška², M. Skarka², and M. Zejda²

¹ Astronomical Institute, Charles University in Prague, Faculty of Mathematics and Physics, 180 00 Praha 8, V Holešovičkách 2, Czech Republic
e-mail: zasche@irrah.troja.mff.cuni.cz

² Department of Theoretical Physics and Astrophysics, Masaryk University, Kotlářská 2, 611 37 Brno, Czech Republic

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ABSTRACT

Aims. The Danish 1.54-meter telescope at the La Silla observatory was used for photometric monitoring of selected eccentric eclipsing binaries located in the Small Magellanic Cloud. The new times of minima were derived for these systems, which are needed for accurate determination of the apsidal motion. Moreover, many new times of minima were derived from the photometric databases OGLE and MACHO. Eighteen early-type eccentric-orbit eclipsing binaries were studied.

Methods. Their O–C diagrams of minima timings were analysed and the parameters of the apsidal motion were obtained. The light curves of these eighteen binaries were analysed using the program PHOEBE, giving the light curve parameters. For several systems, the additional third light also was detected.

Results. We derived for the first time and significantly improved the relatively short periods of apsidal motion from 19 to 142 years for these systems. The relativistic effects are weak, up to 10% of the total apsidal motion rate. For one system (OGLE-SMC-ECL-0888), the third-body hypothesis was also presented, which agrees with high value of the third light for this system detected during the light curve solution.

Key words. binaries: eclipsing – stars: early-type – stars: general – stars: fundamental parameters – Magellanic Clouds

1. Introduction

Other galaxies have become the most prominent battlefields in current astrophysical research, mainly due to the large and long-lasting photometric surveys. These surveys like MACHO or OGLE have discovered thousands of new eclipsing binaries in the Magellanic Clouds, hence, we know only about twice more eclipsing binaries in our own Milky Way than in other galaxies (see Pawlak et al. 2013; or Graczyk et al. 2011).

On the other hand, the chemical composition of the Magellanic Clouds differs from that of the solar neighborhood (e.g. Ribas 2004), and the study of the massive and metal-deficient stars in the Small Magellanic Cloud (SMC) checks our evolutionary models for these abundances. All eclipsing binaries analysed here have properties that make them important astrophysical laboratories for studying the structure and evolution of massive stars (Ribas 2004).

Eccentric eclipsing binaries (EEBs) with an apsidal motion can provide us with an important observational test of theoretical models of stellar structure and evolution. A long-term collection of the times of EEBs minima observed for several years throughout the apsidal motion cycle and a consecutive detailed analysis of the period variations of EEB can be performed, yielding both the orbital eccentricity and the period of rotation of the apsidal line with high accuracy (Giménez 1994). Many different

sets of stellar evolution models have been published in recent years, such as for Maeder (1999), or Claret (2005); however, to distinguish between them and to test, which one is more suitable, it is still rather difficult. The internal structure constants, as derived from the apsidal motion analysis, could serve as one independent criterion. On the other hand, only stellar parameters for EEBs with an accuracy of 1% can be used to discriminate between the models.

Here, we analyse the observational data and rates of apsidal motion for eighteen SMC detached eclipsing systems. All these systems are early-type objects, having eccentric orbits, which also exhibits an apsidal motion. Similar studies of Large Magellanic Cloud (LMC) EEBs have been presented by Michalska & Pigulski (2005), by Michalska (2007), and recently also by Zasche & Wolf (2013). As far as we know, only several eclipsing binaries with apsidal motion were analysed in SMC galaxy until now: SC3 139376, SC5 311566 (Graczyk 2003), and nine other systems by North et al. (2010).

2. Observations of minimum light

Monitoring of faint EEBs in external galaxies became almost routine nowadays with quite moderate telescopes of 1–2 m class, which are equipped with a modern CCD camera. However, a large amount of observing time is needed, which is usually unavailable at larger telescopes. During the last two observational seasons, we have accumulated 2660 photometric observations and derived 29 precise times of minimum light for selected eccentric systems. New CCD photometry was obtained at the

[★] Based on data collected with the Danish 1.54-m telescope at the ESO La Silla Observatory.

^{★★} Table A.1 is only available at the CDS via anonymous ftp to [cdsarc.u-strasbg.fr](ftp://cdsarc.u-strasbg.fr) (130.79.128.5) or via <http://cdsarc.u-strasbg.fr/viz-bin/qcat?J/A+A/572/A71>

La Silla Observatory in Chile, where the 1.54-m Danish telescope (hereafter DK154) with the CCD camera and R filter was used (remotely from the Czech Republic).

All CCD measurements were reduced in a standard way using the bias frames and then the flat fields. The comparison star was chosen to be close to the variable one and with similar spectral type. A synthetic aperture photometry and astrometry software developed by Velen and Pravec APHOT, was routinely used for reducing the data. 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 and their similar spectral types.

The new times of primary and secondary minima and their respective errors were determined by the classical Kwee & van Woerden (1956) method or by our new approach (see Sect. 4.2). All new times of minima are given in Table A.1.

3. Photometry and light curve modelling

The core of our analysis lies on the huge photometric data sets, as obtained during the MACHO (Faccioli et al. 2007), OGLE II (Wyrzykowski et al. 2004), and OGLE III (Graczyk et al. 2011) surveys. These photometric data were used both for minima time analysis and for light curve analysis. The method of how the individual times of minima for the particular system were computed is presented in Sect. 4.2. Our new observations obtained at the Danish 1.54-m telescope were used only for deriving the times of minima for the selected targets.

The analysis of the light curves (LC) for the systems was carried out using the program PHOEBE, ver. 0.31a (Prša & Zwitter 2005), which is based on the Wilson-Devinney algorithm (Wilson & Devinney 1971) and its later modifications, but some of the parameters have to be fixed during the fitting process. The albedo coefficients A_i remained fixed at value 1.0, the gravity darkening coefficients $g_i = 1.0$. The limb darkening coefficients were interpolated from the van Hamme tables (van Hamme 1993), and the synchronicity parameters (F_i) were also kept fixed at values of $F_i = 1$. The temperature of the primary component was derived from the photometric indices or other sources (see below). The problematic issue of the mass ratio was solved by fixing $q = 1$ because no spectroscopy for most of these selected systems exists, and for detached eclipsing binaries the LC solution is almost insensitive to the photometric mass ratio (see e.g. Terrell & Wilson 2005).

4. Methods used for the analysis

4.1. Apsidal motion analysis

For the analysis, we used the approach as presented below.

1. At the beginning, all of the available photometric data were analysed, resulting in a set of minima times. Preliminary apsidal motion parameters were derived (with the assumption $i = 90^\circ$).
2. Secondly, the eccentricity (e), argument of periastron (ω), and apsidal motion rate ($\dot{\omega}$) that resulted from the apsidal motion analysis were used for the preliminary light curve analysis.
3. As the third step, the inclination (i) from the LC analysis was used for the final apsidal motion analysis.
4. Finally, the resulted e , ω , and $\dot{\omega}$ values from the apsidal motion analysis were used for the final LC analysis.

Moreover, this simple approach was a bit complicated because the minima times were also derived using the light curve template (see the AFP method in Sect. 4.2). Hence, the LC solution from step 2 allows us to derive the better times of minima for the step 3. The whole process run iteratively until the changes are negligible (usually it was enough to run these four steps two times).

The O–C diagrams of all available times of minima were analysed using the method presented by Giménez & García-Pelayo (1983). 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, E is the epoch, 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

$$P_s = P_a (1 - \dot{\omega}/360^\circ)$$

and the period of apsidal motion by $U = 360^\circ P_a / \dot{\omega}$.

All new precise CCD times of minima were used with a weight of 10 in our computation; some of our less precise measurements were weighted by a factor of five, while the poorly covered minima were given a weight of 1.

4.2. Method of minima fitting

We developed and routinely used a method for deriving the times of minima for selected stars observed during the MACHO and OGLE surveys. This semi-automatic fitting procedure (hereafter AFP) has harvested the fact that the number of data points obtained during these two photometric surveys is large (typically thousands of data points) but obtained during many orbital revolutions of the close pair (a so-called sparse photometry).

Therefore, we can construct the phased light curve of the eclipsing binary in different time epochs. If the apsidal motion is prominent in the system, the shape of the light curve also slightly varies between the different epochs.

The first step is to divide the whole data set of photometry into several different “subsets”, which are used for constructing the individual light curves. Then, we usually choose the data set closest to the half of the time interval covered with observations and use these data points for constructing the light curve to be analysed.

Then, this light curve is analysed using the PHOEBE code, and the theoretical light curve template is being constructed. This LC model is then being used for deriving the individual times of minima easily by fitting this phased light curve to the phased light curves for the individual data sets. The best fit is obtained with the simplex algorithm and the least squares fitting method by only shifting the theoretical and observed light curve in two axis (phase and magnitude). If the star has constant magnitude over the whole time range of our data, there is no need to fit the magnitude shift, and only one free parameter is computed. When we find the best fit, then the times of minima are computed easily according to the ephemerides for a particular data set. Of course, for eccentric orbit binaries, both primary and secondary minima are being computed separately.

For the input, there are the data points, the time intervals, the ephemerides, and also parameters of the method. These are the duration of eclipse (how large portion of the phase curve around

An illustrative example: OGLE-SMC-ECL-0720

Fig. 1. How the AFP method works.

minima is being used for computing), minimum number of data points (if lower, the minimum is not computed), and the depth of minima. If 1/5 of the depth of minima is covered with data points, then this particular minimum is being computed.

Hence, by using this technique, we can usually obtain both primary and secondary minima for each data subset from an original photometry file. Moreover, this method can also be used in these cases, where the minimum is covered only very poorly, or only a descent to the minimum is covered. In these cases, the classical Kwee-van Woerden method would not work properly, so we can obtain more useful data points. On the other hand, we would like to emphasize that the method is suitable only for systems with low eccentricity, where the shape of the light curve is changing only slightly. Otherwise, we have to construct a separate light curve template for each of the data subset.

The whole method is graphically shown in Fig. 1, where an illustrative example of OGLE-SMC-ECL-0720 is being presented. All of the derived times of minima are stored in Table A.1. There are also given the errors of individual minima times, which are being computed also by AFP in the following way. The set of different solutions was computed for a particular

minimum with different parameters of the code (length of interval around each minimum used for the analysis, number of data points according to their precision, etc.), yielding a set of times of minima, which is usually more than 10. From these minima data set, an average and its variance were computed. The variance is then taken as an approximate error estimation for the particular minimum.

5. Notes on individual systems

All of the eclipsing systems were analysed using a similar approach, hence we cannot focus on every star in detail. See Table 1 for information and cross-identification of these stars. The abbreviations of the star names were used for all of the systems for a better brevity. That is, OGLE-SMC-ECL-0720 was shortened as #0720, etc. Only the most important results are summarized below. The final light curve fits, and the O-C diagrams are presented in Figs. 2 and 3; the parameters are given in Tables 2 and 3. The whole set of eighteen analysed systems can be divided into a few subsets according to available spectral information.

The largest group in our sample of stars comprise these stars, which were never observed spectroscopically, hence no spectral classification or radial velocity study was published so far. These systems are #0781, #1001, #1298, #1407, #2225, #2251, #2524, and #5233. Most of them were discovered as eclipsing binaries by Udalski et al. (1998), Wyrzykowski et al. (2004), or Faccioli et al. (2007). Several of them were mentioned as eccentric ones with apsidal motion in some of the above mentioned papers. Owing to having no information about their spectra, we only roughly estimated the spectral types from the measurements in photometric filters, as seen in Table 1. These observations were usually taken from Massey (2002) and from the dereddened photometric indices the spectral types were estimated (Popper 1980; Ducati et al. 2001; or Cox 2000). For some of the systems, there resulted a non-negligible third light contribution (e.g. #2225, #2251).

For some of the systems, the spectral types were published, so we can use them for a better primary temperature estimation for a subsequent light curve analysis. These systems are #0720, #2534, #3677, #4955, #5422, and #5434 (to this group of stars, two systems #0888 and #3951 also belong, but these were given a special focus in the following subsections). These binaries were also discovered by Udalski et al. (1998) and Faccioli et al. (2007); for some of them, a short note about their apsidal motion was published. The spectral types for these systems given by Evans et al. (2004) and Bonanos et al. (2010) are in good agreement with our spectral types that are estimated from the dereddened photometric indices.

5.1. OGLE-SMC-ECL-2186

Two systems, #2186 and #3594, were even published with their light and radial velocity curves solutions. The first one (#2186) was analysed by Wytke & Wilson (2001), who presented a preliminary light curve solution with an eccentric orbit with $e = 0.068$. Graczyk (2003) analysed the LC of #2186, yielding an eccentricity of 0.251, no third light, and the luminosity ratio of $L_2/L_1 = 0.843$. Wyrzykowski et al. (2004) presented a note about its apsidal motion but with no estimation of its period. Concerning the spectral type, Graczyk (2003) estimated the types of about O9V+O9V but dealt only with the photometry. Later, Hilditch et al. (2005) published its spectral type to be B0+B0-3 based on 15 spectra of the star. They also analysed

Fig. 2. Light curves of the analysed systems, the data taken from the OGLE III survey, and the I filter.

the light curve, yielding a value of the eccentricity of the orbit to be 0.063. However, their LC solution is not very convincing due to poor fit of the secondary minimum.

5.2. OGLE-SMC-ECL-3594

The second system (#3594) was also studied by Wyithe & Wilson (2001), who included this star into their sample of SMC eclipsing binaries with the light curve solution, which result in

orbital inclination of 88.9° and an eccentricity of 0.144. Hilditch et al. (2005) analysed the system in more detail, resulting in an orbital eccentricity of 0.19 (based on photometry and spectroscopy together) and the spectral types of both components as B1+B1-3.

5.3. OGLE-SMC-ECL-0888

The object #0888 was first mentioned by Wyrzykowski et al. (2004), who also noted about its apsidal motion. Its spectral type

Fig. 3. O–C diagram for the times of minima for the analysed systems. The continuous and dashed curves represent predictions for the primary and secondary eclipses, respectively. The individual primary and secondary minima are denoted by dots and open circles, respectively. Larger symbols correspond to the measurements, which were given higher weights.

was derived to be about O9V by Evans et al. (2004). We found that the pure apsidal motion is not able to describe the O–C diagram in detail, hence another effect has also to be included. We also tried to fit the parabolic fit to the ephemerides, with the apsidal motion hypothesis (can be interpreted as a mass transfer between the components, despite improbable for detached binary). However, this fit was also not very satisfactory. Therefore, we used a different code that computes the apsidal motion parameters with the third-body orbit (a so-called “light travel time” effect), as seen in for example Irwin (1959) or Mayer (1990). Ten

parameters were fitted (five from the apsidal motion, five from the third body hypothesis); thus, this approach led to an acceptable solution with the lowest sum of squares residuals. The final parameters of the fit are given in Tables 3 and 4; the complete O–C diagrams are shown in Figs. 3 and 4.

From the third-body parameters, we could also compute the mass function of the distant component, which resulted in $f(m_3) = 0.059 \pm 0.015 M_\odot$. From this value, one can calculate a predicted minimal mass of the third body (i.e. assuming coplanar orbits $i_3 = 90^\circ$), which resulted in $m_{3,\min} = 4.9 M_\odot$. If we

Table 1. Relevant information for the analysed systems.

System	OGLE II*	MACHO	RA	Dec	$I_{\max}$	$(B - V)$	$(U - B)$	$(B - V)_0$	Sp.type**	Ref.
#0720	SC3 139376	213.15620.12	00 ^h 44 ^m 08 ^s .67	-73° 14' 18".5	14 ^m .47	-0.16	-0.91	-0.26	B0(IV)	1, 2
#0781	SC3 157218	212.15624.89	00 ^h 44 ^m 39 ^s .73	-72° 59' 58".5	17 ^m .03	-0.10	-0.78	-0.23	B2	1
#0888	SC4 29231	212.15680.18	00 ^h 45 ^m 30 ^s .72	-73° 03' 29".7	15 ^m .52	-0.09	-0.82	-0.25	O9V	1, 2
#1001		208.15744.1836	00 ^h 46 ^m 11 ^s .29	-72° 35' 17".3	18 ^m .44	-0.31	-0.58	-0.12	<i>late B/early A</i>	3
#1298	SC4 163754	212.15848.1258	00 ^h 47 ^m 52 ^s .73	-73° 16' 34".0	17 ^m .22	-0.04	-0.89	-0.29	B0	1
#1407		208.15861.734	00 ^h 48 ^m 19 ^s .26	-72° 21' 40".2	17 ^m .02	-0.04	-0.67	-0.21	B3	1
#2186	SC5 311566	208.16083.86	00 ^h 51 ^m 34 ^s .84	-72° 45' 46".4	16 ^m .06	-0.04	-0.79	-0.25	B0+B0-3	1, 4
#2225	SC6 72782	208.16084.117	00 ^h 51 ^m 41 ^s .80	-72° 41' 06".1	16 ^m .71	-0.128		-0.22	B3	5, 6
#2251	SC6 61418		00 ^h 51 ^m 46 ^s .64	-72° 51' 21".7	16 ^m .23	-0.14	-0.91	-0.27	B1	1
#2524	SC6 158178	208.16141.60	00 ^h 52 ^m 42 ^s .32	-72° 41' 27".9	16 ^m .53	-0.176	-0.86	-0.24	B2	3
#2534		208.16147.22	00 ^h 52 ^m 43 ^s .85	-72° 18' 08".6	16 ^m .57	-0.04	-0.81	-0.26	B1	1
#3594	SC7 255621	207.16428.1423	00 ^h 57 ^m 26 ^s .41	-72° 36' 46".2	16 ^m .26	-0.21	-0.72	-0.19	B1+B1-3	1, 4
#3677	SC8 52815	207.16490.6	00 ^h 57 ^m 49 ^s .25	-72° 16' 55".7	15 ^m .11	-0.16	-0.84	-0.24	B2	1, 7
#3951	SC8 160725		00 ^h 59 ^m 14 ^s .98	-72° 11' 35".3	15 ^m .90	-0.18	-0.84	-0.24	B1V	8, 9
#4955	SC10 94636	206.16886.52	01 ^h 04 ^m 59 ^s .18	-72° 25' 29".3	17 ^m .11	-0.16	-0.68	-0.19	B3	1
#5233		206.17061.14	01 ^h 07 ^m 12 ^s .54	-72° 11' 42".0	15 ^m .34	-0.08	-0.91	-0.28	B0	1
#5422	SC11 111907	206.17170.8	01 ^h 08 ^m 45 ^s .74	-72° 31' 22".4	14 ^m .99	-0.22	-0.93	-0.26	B1	1
#5434	SC11 118966	206.17173.10	01 ^h 08 ^m 50 ^s .47	-72° 17' 26".1	15 ^m .56	-0.11	-0.86	-0.26	B1	1

Notes. (*) The full name from OGLE II survey should be OGLE SMC-SCn nnnnnn, (**) Spectral types given in italics were only estimated from the photometric indices for the first time in the present paper.

References. (1) Massey (2002); (2) Evans et al. (2004); (3) Zaritsky et al. (2002); (4) Hilditch et al. (2005); (5) Udalski et al. (1998); (6) Massey et al. (1995); (7) Bonanos et al. (2010); (8) Massey et al. (1989); (9) Massey et al. (2012).

Table 2. Light curve parameters for the analysed systems.

System	T_1 [K]	T_2 [K]	i [deg]	Ω_1	Ω_2	L_1 [%]	L_2 [%]	L_3 [%]
#0720	31 500 (fixed)	31 700 (400)	84.57 (0.30)	5.524 (0.061)	7.356 (0.085)	66.87 (0.83)	33.13 (0.68)	0
#0781	23 100 (fixed)	16 700 (300)	85.08 (0.18)	7.265 (0.086)	8.690 (0.120)	71.90 (1.25)	28.10 (0.98)	0
#0888	33 200 (fixed)	38 100 (1100)	77.77 (0.38)	6.119 (0.101)	6.128 (0.112)	22.01 (1.85)	26.94 (3.46)	51.05 (4.98)
#1001	11 000 (fixed)	9700 (500)	79.13 (0.92)	5.064 (0.204)	6.661 (0.397)	67.48 (1.37)	32.52 (1.02)	0
#1298	30 000 (fixed)	19 900 (700)	74.68 (0.45)	6.364 (0.138)	6.701 (0.174)	70.46 (1.32)	29.54 (0.77)	0
#1407	19 000 (fixed)	19 100 (700)	75.60 (0.50)	5.907 (0.147)	6.833 (0.177)	56.26 (1.06)	39.10 (1.00)	4.64 (1.87)
#2186	30 100 (fixed)	28 500 (300)	87.02 (0.22)	6.843 (0.058)	8.040 (0.097)	62.73 (3.14)	36.00 (1.25)	4.03 (2.59)
#2225	11 600 (fixed)	7100 (200)	80.33 (0.53)	5.678 (0.100)	11.334 (0.490)	60.98 (2.87)	4.58 (0.57)	34.45 (1.55)
#2251	26 200 (fixed)	30 600 (900)	79.62 (0.26)	6.149 (0.080)	10.184 (0.184)	48.35 (3.02)	17.91 (1.26)	33.73 (4.05)
#2524	23 100 (fixed)	24 600 (600)	83.32 (0.37)	6.128 (0.085)	7.165 (0.112)	56.63 (1.26)	41.53 (2.03)	1.85 (5.76)
#2534	26 200 (fixed)	18 300 (300)	76.23 (0.28)	5.690 (0.050)	6.150 (0.052)	61.67 (1.79)	28.64 (1.58)	9.69 (2.63)
#3594	25 500 (fixed)	22 000 (200)	83.60 (0.41)	7.095 (0.040)	6.668 (0.055)	50.50 (1.56)	48.00 (1.03)	1.49 (1.96)
#3677	23 100 (fixed)	25 100 (300)	73.60 (0.22)	5.029 (0.029)	7.833 (0.064)	74.51 (1.07)	25.49 (0.94)	0
#3951	26 200 (fixed)	24 400 (200)	78.50 (0.24)	6.699 (0.055)	6.789 (0.056)	53.76 (0.97)	46.24 (1.16)	0
#4955	19 000 (fixed)	17 400 (500)	80.01 (0.31)	7.868 (0.165)	8.591 (0.180)	58.97 (0.75)	41.03 (0.79)	0
#5233	30 000 (fixed)	29 400 (300)	80.52 (0.21)	8.762 (0.098)	7.843 (0.093)	44.09 (1.02)	55.91 (0.93)	0
#5422	26 200 (fixed)	20 400 (300)	79.18 (0.33)	7.076 (0.098)	7.070 (0.102)	54.69 (2.34)	36.51 (4.57)	8.80 (7.82)
#5434	26 200 (fixed)	24 200 (400)	71.72 (0.40)	5.400 (0.061)	5.516 (0.059)	53.49 (1.14)	43.86 (1.62)	2.65 (2.01)

propose such a body in the system, one can ask whether it is detectable somehow in the already obtained data. The period is long for continuous monitoring of the radial velocity changes, but detecting the third light in the light curve solution would be promising. Assuming a normal main sequence star, its luminosity would be of about only $L_{3,\min} = 1-2\%$ of the total system luminosity. Such a weak third light would be hardly detectable in our poor-quality photometric data, but it is worth of try. Hence, we performed a new light curve solution with a special focus on the value of the third light for a LC solution. The value was really obtained, and its value is not negligible at all. As one can see from the parameters presented in Table 2, the third light represents about one half of the total light. This finding naturally explains why both the eclipses are so shallow. On the other hand, one can ask to which body the estimated spectral type of O9V belongs. If the third body is the dominant source, this is probably

the O9V component, but the primary temperature of 33 200 K was assumed using the O9V primary, which now seems to be incorrect. However, having no other relevant information about the individual spectral types, one cannot easily assume a different primary temperature. Thus, we can conclude that the third body is probably present and orbits around the EB pair on orbit which is mildly inclined from the originally assumed 90°. It is hard to say anything more about such a body because of the high errors of the parameters (period, third light, etc.). More precise photometry or radial velocities would be very welcome for a final confirmation of our hypothesis.

5.4. OGLE-SMC-ECL-3951

The object #3951 is a part of the SMC open cluster NGC 346. Its eclipsing nature and orbital period was first presented by

Table 3. Parameters of the apical motion for the individual systems.

System	$T_0 - 2\,400\,000$ [HJD]	P_s [days]	e	$\dot{\omega}$ [deg/cycle]	ω_0 [deg]	U [yr]
#0720	53 803.390 (21)	6.052322 (48)	0.062 (16)	0.2070 (300)	67.6 (5.0)	28.8 (5.5)
#0781	52 745.417 (32)	3.299923 (48)	0.310 (75)	0.0301 (37)	244.4 (10.3)	108.1 (15.1)
#0888	53 470.954 (15)	1.918337 (11)	0.143 (34)	0.0474 (193)	89.3 (4.7)	39.9 (11.6)
#1001	53 090.7643 (35)	1.1621122 (18)	0.072 (14)	0.0601 (69)	94.5 (7.8)	19.0 (2.4)
#1298	53 501.194 (14)	1.7532121 (99)	0.219 (42)	0.0677 (93)	130.0 (4.2)	25.5 (4.1)
#1407	53 470.497 (13)	2.100755 (11)	0.151 (47)	0.0427 (120)	115.9 (3.9)	46.3 (18.0)
#2186	53 470.314 (15)	3.291316 (20)	0.227 (82)	0.0258 (42)	91.9 (2.6)	125.7 (24.5)
#2225	53 089.914 (10)	1.491721 (8)	0.187 (48)	0.0351 (121)	291.9 (8.8)	41.9 (21.8)
#2251	54 179.695 (25)	2.336038 (33)	0.271 (22)	0.0484 (132)	99.8 (5.6)	47.6 (17.8)
#2524	53 471.664 (24)	2.169236 (23)	0.263 (68)	0.0475 (92)	81.5 (6.5)	45.0 (10.8)
#2534	53 277.1246 (72)	2.2967384 (72)	0.078 (24)	0.0357 (57)	265.0 (3.4)	63.3 (11.9)
#3594	53 280.315 (41)	4.330333 (80)	0.194 (69)	0.0300 (63)	238.1 (9.9)	142.1 (38.9)
#3677	53 278.036 (52)	5.241539 (117)	0.153 (55)	0.0554 (133)	40.2 (4.6)	93.3 (33.6)
#3951	53 277.2672 (75)	3.104291 (17)	0.092 (20)	0.0476 (165)	92.9 (4.0)	64.3 (33.9)
#4955	54 022.771 (52)	2.772183 (53)	0.338 (48)	0.0239 (84)	143.3 (5.0)	114.4 (51.5)
#5233	52 746.459 (45)	5.068362 (103)	0.199 (57)	0.1915 (321)	7.0 (8.7)	26.1 (5.2)
#5422	53 656.966 (26)	3.040295 (31)	0.199 (56)	0.0301 (83)	318.1 (6.0)	99.4 (37.9)
#5434	53 478.7191 (72)	2.886936 (9)	0.051 (16)	0.0747 (214)	129.6 (3.4)	38.1 (15.2)

Fig. 4. O-C diagram of #0888 after subtraction of the apical motion term. **Fig. 5.** O-C diagram of #3951 after subtraction of the apical motion term.

Udalski et al. (1998). Later, the star was classified as B1V by Massey et al. (2012). From the period analysis, a weak quasi-periodic signal also on the residuals after subtraction of the apical motion hypothesis (see Fig. 5) resulted. However, the variation is still too spurious for any final confirmation yet and we have not even try to fit the data with any additional variation, as in the previous case.

Table 4. Third body orbit parameters for #0888.

Parameter [Unit]	Value
p_3 [yr]	72.1 ± 28.0
A_3 [day]	0.030 ± 0.011
T_3 [HJD]	$2\,454\,900 \pm 8700$
e_3	0.709 ± 0.247
ω_3 [deg]	154.0 ± 15.6

6. Discussion and conclusions

Our study provides the parameters of the apical motion for eighteen early-type binary systems located in the SMC. For most of the binaries, this is the first attempt to estimate the apical motion rates, and the light curve solution. In our own Galaxy there are a few hundreds of apical motion eclipsing binaries known; however, in other galaxies their number is still very limited. Hence this study still presents an important contribution to the topic. However, for only three systems from our sample (#1001, #1298, and #5233), the apical motion was derived from adequately large data set covering almost one apical period. The relativistic effects for the selected systems are weak, being up to 10% of the total apical motion rate. For the system #0888, the third body hypothesis was also presented and discussed.

The apical motion in EEBs has been used for decades to test evolutionary stellar models. Thus, one can ask whether our results can be used for deriving the internal structure constants for these stars in SMC. However, dealing with no radial velocities for most of the systems and with rather poor data coverage during the apical motion period, the parameters are too uncertain and affected by large errors. For these systems where the apical period is well-covered, a detailed spectroscopic analysis is missing, and vice versa, for systems where the radial velocity study was performed, the apical period has yet to be only poorly covered with data. However, for any testing of the stellar structure models or for the general relativity tests, the quality of the input data has to be an order of magnitude better (which implies long-term collection of the observations and data that covers the whole apical period in the following decades). Some of the systems are bright enough for a spectral monitoring, hence

we encourage the observers to obtain new, high-dispersion, and high-signal-to-noise spectroscopic observations. With such data, methods, like spectral disentangling, can help us construct the radial velocity curves of both components, confirm the apsidal motion hypothesis, test the stellar structure models, or detect the third bodies, as indicated from our analysis.

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