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First study of 54 new eccentric eclipsing binaries in our Galaxy

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ABSTRACT

We present an analysis of the apsidal motion and light curve parameters of 54 never-before-studied galactic Algol-type binaries. This is the first analysis of such a large sample of eccentric eclipsing binaries in our Galaxy, and has enabled us to identify several systems that are worthy of further study. Bringing together data from various databases and surveys, supplemented with new observations, we have been able to trace the long-term evolution of the eccentric orbit over durations extending back up to several decades. Our present study explores a rather different sample of stars to those presented in the previously published catalogue of eccentric eclipsing binaries, sampling to fainter magnitudes, covering later spectral types, sensitive to different orbital periods with more than 50% of our systems having periods longer than six days. The typical apsidal motion in the sample is rather slow (mostly of order of centuries long), although in some cases this is less than 50 years. All of the systems, except one, have eccentricities less than 0.5, with an average value of 0.23. Several of the stars also show evidence for additional period variability. In particular we can identify three systems in the sample, HD 44093, V611 Pup, and HD 313631, which likely represent relativistic apsidal rotators.

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

1. Introduction

For independent testing of general relativity, as well in confronting stellar structure models, eccentric eclipsing binary systems are often mentioned as being ideal astrophysical laboratories. However, in the last few decades the exploitation of eccentric eclipsing binaries (hereafter EEBs) to current astrophysical research problems has been developed, thanks to the large photometric surveys and availability of precise data, including for fainter targets. Studies have focused on, in particular, the period-eccentricity distribution of the binary systems, which provides a crucial test of our models of star formation, theory of orbital circularization, and dynamical evolution of binaries and multiple systems, amongst others. These studies have asked questions such as: Is the formation of binary and multiple star systems solely a matter of fragmentation, accretion, or some N-body dynamics, or is it a fruitful combination of all these mechanisms? Is the subsequent orbit migration crucial for explaining the observed orbital properties of binaries and multiples? The distribution of eccentricity can provide strong constraints on star forming theories and can be compared with stellar formation models and N-body simulations (see e.g. Tokovinin 2008, or Kiminki & Kobulnicky 2012). The number of known systems suitable for detailed modelling is still rather limited, and studies like the present one significantly extend the available sample and help us to answer some of the questions above.

Study of the light curves (hereafter LCs) of eclipsing binaries and their modelling with available tools (i.e. a well-known Wilson-Devinney algorithm, see Wilson & Devinney 1971 and Wilson 1979) can be used for deriving the value of orbital eccentricity. On the other hand, the orbital period is mostly a known quantity. Moreover, the LC modelling also provides information about the physical properties of both components, their relative luminosities or relative radii (with respect to the semimajor axis). Additionally, the results of such an analysis can help to estimate the internal structure constants for the particular system.

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The investigation of period changes in EEB systems on the basis of their minima timings variation (both primary and secondary) alone is a familiar method in stellar astrophysics as described in several seminal papers, for example, Giménez & García-Pelayo (1983), or Giménez & Bastero (1995). As a very short description of the method, the sidereal and anomalistic periods of the binary are connected with the relation $P_s = P_a(1 - \dot{\omega}/2\pi)$, where $\dot{\omega}$ is the rate of the apsidal motion $\omega = \omega_0 + \dot{\omega}E$. The period of such revolution is then $U = 2\pi P_a/\dot{\omega}$. The individual equations for the computation of the time of primary and secondary minima were published, for example in Giménez & García-Pelayo (1983). We also suppose that the apsidal motion remains linear in time.

The number of new photometric observations of eclipsing binaries is increasing rapidly year-on-year. This is partly due to non-professional astronomers, but mostly because of new photometric surveys covering the whole sky. Using these data, it is possible to derive many new times of eclipses at various time epochs, and to trace periodic changes in these systems, that is, detect the third bodies, or study the apsidal motion in them. Examples of such studies have been published quite frequently during the last few years, see for example Pilecki et al. (2007), Zasche et al. (2014a), or Borkovits et al. (2016).

However, despite increasing the number of data points, a detailed analysis is still lacking for some of the systems . Hence, for our analysis we have used observations from automated photometric surveys, from satellites, from our new ground-based observations, as well as from previously published data from various publications.

The advantage of our method for deriving the eccentricity is obvious. Without having any information about the masses (no spectroscopy and RV solutions available for these systems), our solution still has to be considered preliminary. However, having an estimate of the eccentricity from the LC solution, it becomes possible to perform a period analysis of the eclipse times to refine its value, and vice versa. Sometimes the LC coverage is insufficient to derive a reliable value of the eccentricity, but the $O - C$ diagram with times of eclipses can help us. Sometimes the change of ω is so slow that a trustworthy analysis cannot be done using only minima times, but the LC solution can reveal the eccentricity more reliably.

For our target selection the selected systems should not have been studied before, meaning that no LC or period analysis has been published. Although some of the systems have had their orbital periods mentioned in previous publications, no further information or analysis was available. All the systems are well detached (as needed for an eccentric-orbit binary), located in both the southern and northern hemispheres, and their respective orbital periods range from several days to several dozen days. The only input parameters needed for the analysis are the period and an estimate of the primary temperature (see below). In the whole study, we see rather heterogeneous effort from the various observers (mainly professionals, but sometimes also non-professionals) and observational strategies (sometimes dedicated observations, sometimes only by chance products of observing another target in the field). Some of the selected stars are relatively faint, although several of these systems are sufficiently bright (mag < 10) that they were observed by the Hipparcos satellite (ESA 1997). We consider the present paper as a starting point for some future, more focused, observational effort, or to aid the target selection for a future dedicated studies of these targets.

An overview of the basic parameters of the analysed systems is presented in Table 1, where the individual values are taken from the available databases and catalogues (SIMBAD, GCVS - Samus et al. 2017). The primary temperature needed for the LC analysis was in most cases estimated from the photometric indices, but for those systems for which a spectral classification has been published, this was used for a temperature estimation of the fixed T_1 value used for the LC analysis. For most systems, the GCVS designation is still missing, hence we used some most common catalogue information taken from CDS/SIMBAD, together with the precise J2000.0 coordinates for better identification of the star.

For analysis of the LC as well as deriving new minima times, several different sources and databases were used together. These data, along with our new observations, present material that is sometimes very suitably complementary. For example, sometimes the phase coverage is poor in one source, but it may have good photometry in another, and vice versa. See our final plots below in Figures 1, and A.1 to A.8.

2. Approach for the analysis

Despite the fact that several of the systems have rather low photometric variation amplitudes, and some are also relatively faint targets, usually some of the automatic photometric surveys can provide us with reliable photometry to facilitate LC modelling. Hence, when having different sources of data from different surveys, databases, and publications, we used the best of these for the LC solution (i.e. those with the lowest scatter and the best phase coverage of the complete light curve).

For the light-curve analysis we used the code PHOEBE (Prša & Zwitter 2005), which is originally based on the Wilson-Devinney algorithm (Wilson & Devinney 1971 and Wilson 1979) and its later modifications. For those systems where photometry in different filters was used, we analysed these data simultaneously.

Because spectroscopic studies with radial velocities are missing for all these systems, there are several assumptions which have to be considered. At first, the mass ratio of all the systems was kept at a value of unity. This approach is justified because all the systems are well-detached and the ellipsoidal variations outside of their minima are almost negligible. For such systems the photometric mass ratio can only be approximately estimated, as quoted for example by Terrell & Wilson 2005. Other physical parameters were instead estimated and derived in a relative sense, rather than in absolute units (e.g. radii, luminosities), hence these values are still only approximate estimates and should not be used as fundamental parameter sources.

Due to all these reasons we used the following approach for the analysis. Firstly, a very first rough LC analysis was performed. Second, the initial LC analysis was used to estimate the available minima, which were then analysed to estimate preliminary apsidal motion parameters (with the assumption $i = 90°$). Third, the eccentricity (e), argument of periastron (ω) and apsidal motion rate ($\dot{\omega}$) resulting from the apsidal motion analysis were used for the preliminary light curve analysis. Fourth, a further parameter from the LC analysis, the inclination (i), was then used for the apsidal motion analysis. And finally, the resulting e, ω, and $\dot{\omega}$ values from the apsidal motion analysis were used for the final LC analysis.

The AFP (automatic fitting procedure) method for deriving the individual times of minima was the same as presented in Zasche et al. (2014b), applied to different photometric databases. All the minima times used for the analysis were given in Table 2.

For all of the systems, the presence of the third light was tested. This new free parameter was only applied during the last step of the fitting process, because it is a very sensitive second-order light curve parameter, which could only be conclusively detected in high quality LCs.

3. Results

The selection of targets for the present analysis was straightforward, and did not depend on where the star is located, nor how bright or faint it is. The criterion was based only whether the star had been previously studied, as our main aim was to enlarge the existing set of eclipsing binaries in the period - eccentricity diagram.

Another selection criterion was the data coverage of the particular binary. Only those systems with well-sampled phase light curve were included into our sample. This means that photometry should exist and especially that it should be adequately precise near both eclipses, so that their duration and depths could be recovered. Sometimes we had to use more data sources for this analysis (because in one dataset the coverage of minima is only poor).

The stars included in our sample can be divided into three groups according to their discoveries of photometric periodicity. Some have already been mentioned in the former ASAS database (Pojmanski 2002), a second group were serendipitous discoveries already mentioned in the literature (mainly the so-called CzeV catalogue, Skarka et al. 2017), and finally the third group consists of stars which have not yet been reported as eclipsing binaries, and this is for the first time that such stars have been identified as being an EEB system.

For the analysis we usually used some of the following available databases and surveys: ASAS (Pojmanski 2002), SuperWASP (Pollacco et al. 2006), NSVS (Woźniak et al. 2004), ASAS-SN (Shappee et al. 2014 and Kochanek et al. 2017), TAROT (Boër et al. 2001), INTEGRAL-OMC (Mas-Hesse et al. 2003), Bochum Galactic Disk Survey (Hackstein et al. 2015), CRTS (Drake et al. 2009), and sometimes also Hipparcos (Perryman et al. 1997) when available for brighter sources. For one system (V1268 Tau) the photometry from the STEREO satellite (Kaiser et al. 2008 and Wraight et al. 2011) was also used. Our new photometry was obtained with various telescopes at different observatories (BOOTES in Spain, FRAM[1] in Argentina, Danish 1.54-m telescope in Chile, 65-cm telescope in Ondřejov, Czech Republic), but also with a non-negligible contribution by several amateur observers with their small telescopes. For some of the systems we collected the data for more than ten years. The already known stars with published minima timings were checked and the data downloaded from the $O-C$ gateway[2] (Paschke & Brát 2006).

The crucial parameters resulting from our light curve and apsidal motion fits are listed in Table 3. For those stars where the apsidal motion is very slow, we have only indicated that the apsidal period is very long (> 1000yr), and that our data coverage is still too poor to facilitate a reliable analysis. This can clearly be seen in the Figs. 1, and A.1 to A.8 with the $O-C$ diagrams. The parameters HJD_0 and P stand for the average ephemerides representing the value $O-C = 0$ in the $O-C$ diagrams, meaning that these are not suitable for planning the observations.

[1] FRAM (Ebr et al. 2014) telescope is part of the Pierre Auger Observatory (The Pierre Auger Collaboration 2015).

[2] See http://var2.astro.cz/ocgate/

Table 2. Heliocentric minima of the systems used for our analysis.

Star	HJD - 2400000	Error	Type	Filter	Reference
V1137 Cas	51473.568		P	V	IBVS 5570
V1137 Cas	53613.4050	0.0002	S	R	IBVS 5741
V1137 Cas	53613.40344	0.0002	S	R	OEJV 74
V1137 Cas	53615.45611	0.0003	P	R	New - This study
V1137 Cas	53746.48711	0.0009	S	R	New - This study
...					

Note: Table is published in its entirety in the electronic supplement of the journal. A portion is shown here for guidance regarding its form and content.

Concerning the presented solutions given in Table 3, we still have to emphasize that these are still only the preliminary results, based on photometry only. The same applies for the errors of individual parameters given in Table 3, which are based on the errors given by the PHOEBE program. Sometimes these errors are rather underestimated.

What definitely should be mentioned is that several systems have quite unrealistic parameters concerning their temperatures, radii, and luminosities. We are aware of the fact that the solution presented here (having q = 1.0) is unlikely, or at least improbable. Hence, for these problematic cases we decided to use the approach for deriving the mass ratio from the luminosity ratio given in Graczyk (2003). This method uses the assumption that both components are located on the main sequence. However, using this approach we found out that for a few such cases even this method is not able to describe the observed data adequately and provide us with physically unreliable result. These are the cases like V1137 Cas, or CzeV 1279. It may be caused by the fact that the mass ratio derivation is based on the assumption of the main sequence components. For some others (such as e.g. NO Per, CzeV 364, SS TrA, V1301 Sco, V1344 her, or PS Vul) the components are probably giants, or some overluminous stars according to their effective temperatures. Only further, more detailed, study would be able to reveal their true nature. Because the number of systems is rather large, we cannot focus on all of the systems in detail, hence we would like to point out here only the most interesting targets.

Amongst the systems reported in this study, several systems were found to contain additional close visual components. These are: V1018 Cas, V1268 Tau, HD 55338, V611 Pup, V839 Cep, V922 Cep, and V389 And, respectively. For some of them a non-zero value of the third light was also detected during the light curve solution.

One system is a giant star, namely CD-33 2771, which merits special attention for future investigation. It has also the longest orbital period of about 200 days. Because this star has such a long period it would not be expected to show wide eclipses when it is not a giant star. According to our modelling, the primary component is probably of luminosity class III, while the secondary of subgiant class IV.

Also remarkable are systems where some possible additional variation in the $O-C$ diagram appears after subtraction of the apsidal motion term. These are mainly: V1137 Cas, KO Nor, V883 Sco, and V1301 Sco. These should be suitable for further observations to detect these changes, and to confirm the third-body hypothesis or other phenomena. See Fig. 2 for their $O-C$ diagrams after subtraction of the apsidal motion.

Amongst all of the studied systems, we have chosen those with given some spectral type estimates and derived the relativistic contribution to the total apsidal motion. This is viable only when we know the masses, in cases when the temperatures were only derived using the photometric indices the masses are

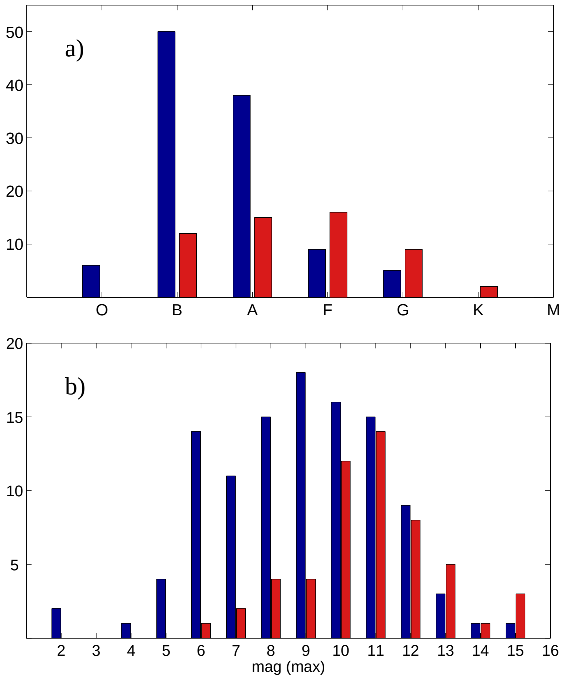

Fig. 3. Comparison of our sample of eccentric binaries (red) with the catalogue of eccentric systems by Bulut & Demircan (2007) in blue. Upper plot: Distribution of spectral types. Lower plot: Apparent magnitudes of the systems.

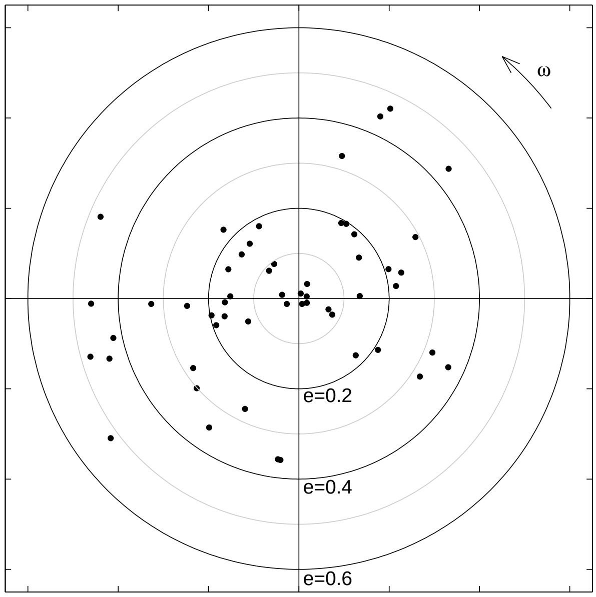

Fig. 4. Distribution of omega angles with respect to the eccentricity.

too uncertain for any such analysis. Following the method by Giménez (1985) we derived the relativistic apsidal advance and for those systems with the largest contribution we gave their values in Table A.1. As one can see, these values are affected by large errors due to the fact that the apsidal advance is very slow and only small fraction of the whole apsidal period is covered with data nowadays. These systems also deserve detailed study in the future.

Eccentric eclipsing binaries which have been studied quite frequently, and the known systems were also included in various catalogues of EEBs. The first one is for example, by Hegedüs (1988), later updated by Petrova & Orlov (1999), while the most recent compilation of those stars is presented in Bulut & Demircan (2007). Their catalogue contains a total of 108 systems with known eccentricities and apsidal motion periods. Therefore, our set of 54 new EEBs presents a significant contribution to the topic.

One can compare these two sets of stars and plot several interesting statistics. As can be seen in Fig. 3, our new systems have slightly later spectral types, and are also rather fainter than the original sample by Bulut & Demircan (2007). This is caused by the fact that we mainly used the photometry from the various databases and automatic surveys, which are typically focused on stars fainter than 10 mag. On the other hand, the catalogue by Bulut & Demircan (2007) presented all the well-known systems that have been studied for up to decades or even more, and that are sometimes as bright as naked-eye stars. The distribution of spectral types is a little more complicated to describe due to the fact that we do not know the interstellar reddening for most of these stars, and that the assumed spectral types were only derived on the basis of their photometric indices (i.e. a kind of lower limit). However, the stars having early spectral types have mostly been studied during the last century, and it is only during the last decades with the use of large telescopes did the focus of stellar astronomers shift to the more late and fainter systems. We also have more systems with longer orbital periods (> 30 d) than appear in Bulut & Demircan (2007).

We can also address the issue of selection effects for our sample of stars. These "serendipitous" discoveries should be more likely detected as eccentric when the two minima are displaced from their positions 0.0 and 0.5 in phase diagram, but the binaries which have ω close to 90° or 270° should be only rarely detected. This can more easily be done when the photometry is sufficiently precise and also when the eccentricity is higher (i.e. the durations of both eclipses are significantly different). Hence, we tried to test this distribution of ω versus eccentricity in our Fig. 4. One can see that the diagram is almost uniformly covered with data points, but the number of systems with higher eccentricity is still rather low (see Sect. 4 below).

Table 1. Relevant information for the analysed systems.

System name	Other ID	RA	DE	$V_{\rm max}^{A}$ [mag]	$(J-H)^{B}$ [mag]	$(B-V)^{A}$ [mag]	Sp.Type^{C}
V1137 Cas	GSC 04297-01664	$01^h34^m53^s.930$	$+67°38'15''.00$	$11^{\rm m}.81$	0.255	0.80	
CR Per	AN 16.1940	$02^h09^m52^s.170$	$+57°54'32''.28$	$12^{\rm m}.02$	0.100	0.47	
CzeV 662	GSC 03691-00735	$02^h36^m48^s.615$	$+56°04'11''.92$	$12^{\rm m}.96$	0.077	0.36	
CzeV 701	TYC 3700-608-1	$02^h40^m23^s.897$	$+54°14'34''.92$	$10^{\rm m}.81$	0.254	0.52	
CzeV 688	GSC 03708-01145	$02^h47^m20^s.119$	$+56°15'05''.63$	$13^{\rm m}.12$	0.254	1.01	
V1018 Cas	GSC 04048-00934	$03^h01^m19^s.374$	$+60°34'20''.24$	$10^{\rm m}.24$	0.099	0.72	B2III [1]
V1268 Tau	HIP 17168	$03^h40^m38^s.770$	$+28°46'24''.00$	$7^{\rm m}.38$	0.050	0.15	A0 [2]
NO Per	SV* SON 8551	$04^h15^m41^s.820$	$+48°40'42''.10$	$12^{\rm m}.21$	0.216	0.89	
CzeV 1279	UCAC4 093-005674	$04^h50^m58^s.786$	$-71°31'49''.35$	$11^{\rm m}.07$	0.285	0.38	
DT Cam	HIP 24390	$05^h13^m57^s.689$	$+56°30'28''.63$	$8^{\rm m}.19$	0.054	0.20	A2 [2]
UCAC4 609-022916	2MASS J05455225+3142200	$05^h45^m52^s.250$	$+31°42'20''.00$	$14^{\rm m}.83$	0.162	0.52	
V409 Cam	TYC 4524-1856-1	$05^h46^m43^s.904$	$+75°20'56''.51$	$10^{\rm m}.73$	0.136	0.42	
CzeV 1144	UCAC4 602-024605	$05^h48^m07^s.920$	$+30°13'19''.10$	$14^{\rm m}.59$	0.158	0.46	
V437 Aur	HIP 27469	$05^h49^m03^s.060$	$+54°01'57''.03$	$8^{\rm m}.47$	-0.016	0.03	B9 [3]
CzeV 364	GSC 02405-01470	$05^h49^m40^s.700$	$+30°25'00''.70$	$13^{\rm m}.95$	0.236	0.59	
CzeV 464	USNO-A2.0 1200-03882057	$05^h50^m11^s.541$	$+31°19'40''.34$	$15^{\rm m}.12$	0.103		
TYC 3750-599-1	GSC 03750-00599	$05^h50^m52^s.961$	$+53°58'23''.60$	$10^{\rm m}.60$	-0.072	0.08	
TYC 729-1545-1	GSC 00729-01545	$06^h07^m18^s.601$	$+13°31'45''.93$	$9^{\rm m}.26$	0.105	0.29	
CD-33 2771	TYC 7076-1598-1	$06^h10^m16^s.479$	$-33°21'20''.88$	$9^{\rm m}.78$	0.724	1.47	K5III+K5V [4]
HD 44093	GSC 00140-01064	$06^h20^m04^s.841$	$+04°54'44''.60$	$9^{\rm m}.25$	-0.043	0.09	B8/9V [5]
TYC 5378-1590-1	GSC 05378-01590	$06^h45^m43^s.953$	$-08°50'35''.50$	$10^{\rm m}.93$	-0.029	-0.02	
HD 55338	TYC 4823-2213-1	$07^h12^m20^s.843$	$-05°25'53''.94$	$9^{\rm m}.54$	0.034	0.11	A1IV/V [5]
RW CMi	AN 128.1929	$07^h22^m22^s.590$	$+02°26'22''.30$	$12^{\rm m}.87$	0.139	0.39	
V611 Pup	HD 62589	$07^h44^m06^s.063$	$-16°55'57''.95$	$8^{\rm m}.09$	-0.140	-0.09	B3III [6]
CzeV 1283	HD 68304	$08^h09^m51^s.160$	$-45°37'50''.69$	$10^{\rm m}.00$	0.146	0.40	F0IV/V [11]
TYC 7126-2416-1	GSC 07126-02416	$08^h16^m30^s.996$	$-33°14'38''.31$	$10^{\rm m}.37$	0.483	0.93	
CzeV 1183	2MASS 08283756-4351041	$08^h28^m37^s.562$	$-43°51'04''.11$	$12^{\rm m}.43$	0.251	0.77	
DK Pyx	HIP 41980	$08^h33^m24^s.062$	$-34°38'55''.31$	$7^{\rm m}.84$	-0.114	-0.10	B3III [7]
PS UMa	TYC 4375-1733-1	$08^h56^m46^s.479$	$+69°40'32''.12$	$12^{\rm m}.45$	0.311	0.54	
HD 87803	HIP 49354	$10^h04^m31^s.513$	$-69°21'20''.27$	$9^{\rm m}.51$	0.013	0.06	B9.5V [8]
TYC 8603-723-1	GSC 08603-00723	$10^h06^m25^s.330$	$-55°00'44''.60$	$11^{\rm m}.38$	-0.027	0.08	
HD 306001	GSC 08958-03048	$11^h06^m07^s.882$	$-61°09'09''.25$	$9^{\rm m}.58$	-0.071	-0.09	B5 [9]
TYC 8217-789-1	GSC 08217-00789	$11^h15^m06^s.983$	$-48°15'33''.44$	$11^{\rm m}.28$	0.186	0.65	
TYC 9432-1633-1	2MASS J14444107-7721530	$14^h44^m41^s.077$	$-77°21'53''.02$	$11^{\rm m}.70$	0.290	0.69	
SS TrA	GSC 09022-01335	$15^h39^m21^s.650$	$-60°53'38''.30$	$11^{\rm m}.02$	0.106	0.27	
KO Nor	TYC 8719-163-1	$16^h25^m59^s.508$	$-56°55'03''.97$	$10^{\rm m}.85$	0.082	0.62	
V883 Sco	HD 152901	$16^h57^m52^s.443$	$-37°59'47''.57$	$7^{\rm m}.04$	0.013	0.05	B2V [10]
V1301 Sco	GSC 07368-01457	$17^h05^m18^s.635$	$-34°56'00''.71$	$13^{\rm m}.03$	0.228	0.68	
HD 158801	TYC 7896-1604-1	$17^h33^m19^s.034$	$-43°15'01''.40$	$9^{\rm m}.54$	0.060	0.27	A5/7II [11]
TYC 6258-1011-1	2MASS J17533294-2031094	$17^h53^m32^s.945$	$-20°31'09''.53$	$12^{\rm m}.08$	0.182	0.48	
HD 163735	TYC 5095-296-1	$17^h57^m54^s.027$	$-05°41'10''.15$	$9^{\rm m}.62$	0.251	0.54	F3V [5]
HD 313631	TYC 6842-1455-1	$18^h00^m10^s.195$	$-23°53'46''.10$	$10^{\rm m}.41$	0.170	0.58	OB [12]
HD 164610	GSC 07899-00130	$18^h03^m39^s.099$	$-37°43'47''.68$	$8^{\rm m}.64$	0.052	0.22	A1mA8-A8 [7]
V1344 Her	HD 348698	$18^h27^m18^s.443$	$+19°08'33''.32$	$11^{\rm m}.69$	0.228	0.27	G0 [9]
HD 170749	TYC 7398-2681-1	$18^h32^m34^s.765$	$-33°14'40''.85$	$9^{\rm m}.94$	0.060	0.17	A0/1V [7]
TYC 8378-252-1	GSC 08378-00252	$18^h59^m51^s.282$	$-47°11'47''.75$	$11^{\rm m}.03$	0.168	0.58	
TYC 6303-308-1	2MASS J19393409-1739553	$19^h39^m34^s.096$	$-17°39'55''.45$	$11^{\rm m}.31$	0.110	0.37	
PS Vul	HIP 9709	$19^h43^m55^s.974$	$+27°08'07''.43$	$6^{\rm m}.46$	0.768	1.02	K3II+B6 [13]
V839 Cep	TYC 3964-741-1	$21^h03^m31^s.714$	$+59°25'50''.41$	$9^{\rm m}.73$	0.055	0.36	B8 [14]
TYC 5195-11-1	2MASS J21264316-0031104	$21^h26^m43^s.166$	$-00°31'10''.53$	$11^{\rm m}.32$	0.233	0.49	
TYC 2712-1201-1	GSC 2712-1201	$21^h34^m57^s.620$	$+35°12'51''.46$	$10^{\rm m}.70$	-0.015	-0.01	
UCAC4 585-123180	NSVS 8774343	$21^h39^m21^s.030$	$+26°52'36''.70$	$12^{\rm m}.88$	0.264	0.57	
V922 Cep	TYC 4481-230-1	$23^h01^m39^s.222$	$+69°42'44''.96$	$11^{\rm m}.39$	0.137	0.29	
V389 And	HIP 116153	$23^h32^m01^s.312$	$+43°49'20''.49$	$8^{\rm m}.56$	-0.031	0.19	A0 [15]

Note: [A] - value based on APASS (Henden et al. 2015) or Tycho catalogue Høg et al. (2000), [B] - 2MASS catalogue, Skrutskie et al. (2006), [C] - Various published papers: [1] - Rydström (1978), [2] - Tucker et al. (1983), [3] - Morgan (1933), [4] - Parihar et al. (2009), [5] - Houk & Swift (1999), [6] - Houk & Smith-Moore (1988), [7] - Houk (1982), [8] - Houk & Cowley (1975), [9] - Nesterov et al. (1995), [10] - Garrison et al. (1977), [11] - Houk (1978), [12] - Stephenson & Sanduleak (1971), [13] - Ginestet & Carquillat (2002), [14] - Alknis (1958), [15] - Dyson (1935).

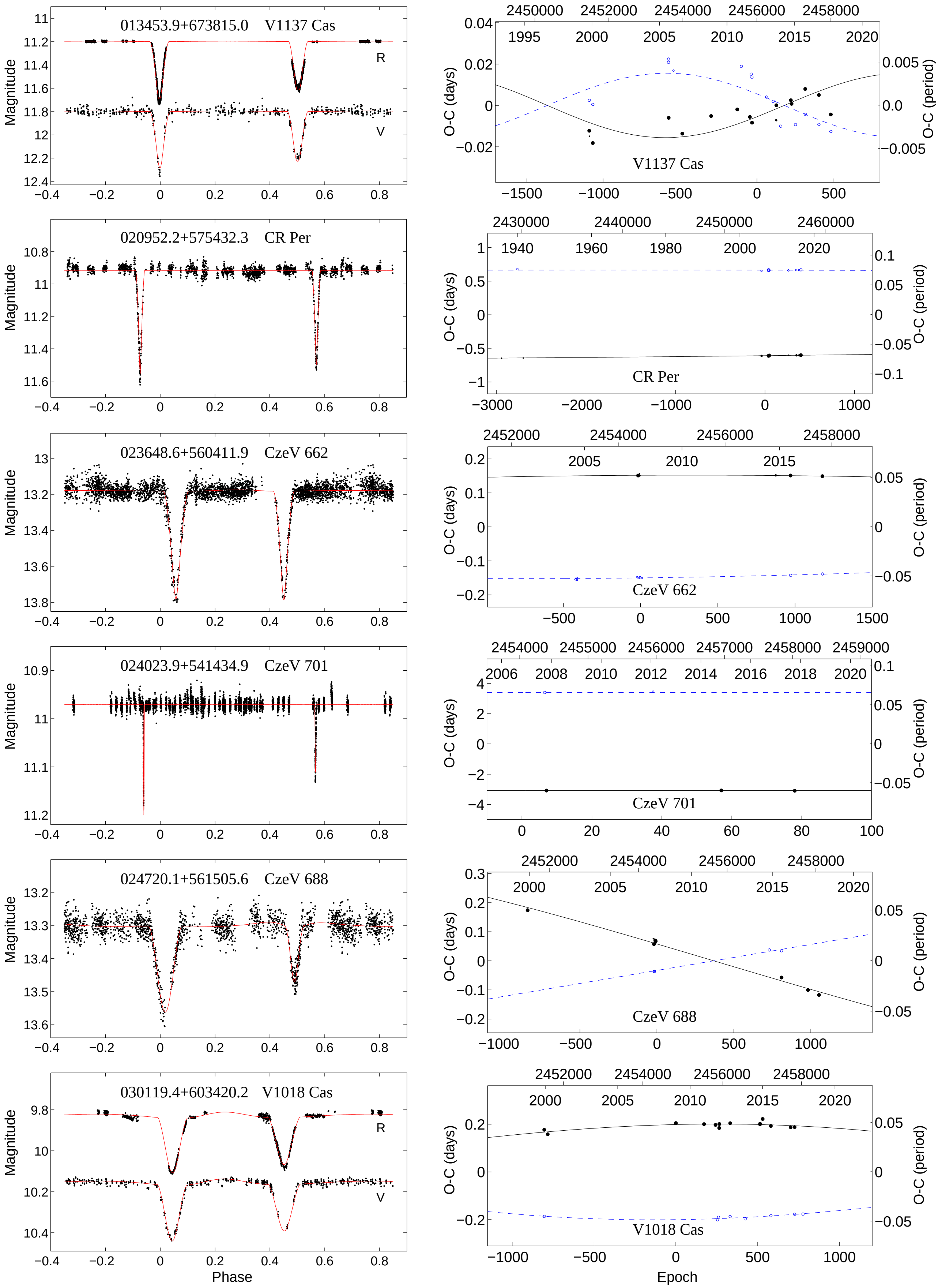

Fig. 1. Plot of the light curves and $O-C$ diagrams of the analysed systems. The small letters denote the individual filters for the particular light curve (standard notation, while "C" stands for unfiltered data and "S" indicates the special SuperWASP filter). For the $O-C$ diagrams the full dots stand for the primary minima (as well as the solid line), while the open circles represent the secondary minima (and the dashed curve).

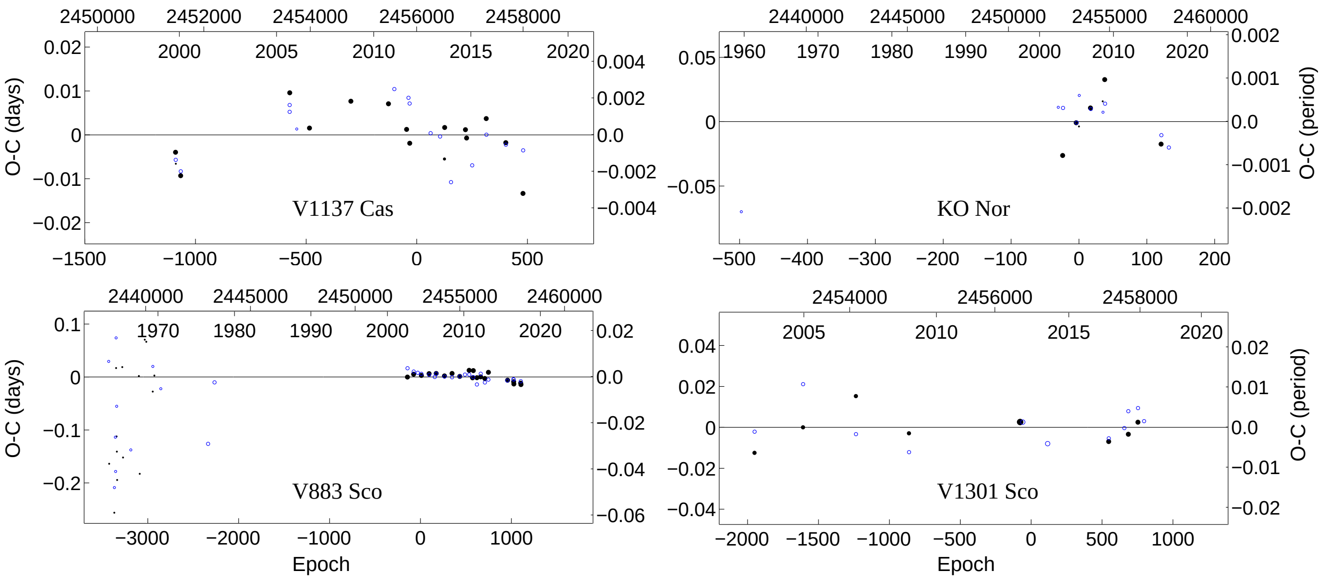

Fig. 2. O-C diagrams after subtraction of the apsidal motion term. These four systems are suspected for some additional variation of their minima times, hence deserve a special attention.

Table 3. The parameters of the light curve fits and the apsidal motion.

System	i [deg]	T_1 [K]	T_2 [K]	L_1 [%]	L_2 [%]	L_3 [%]	R_1/a	R_2/a	HJD_0 [2400000+]	P [d]	e	ω [deg]	U [yr]
V1137 Cas	88.19(0.45)	6000	5938(80)	68.5(0.9)	31.5(0.6)	0.0	0.130(6)	0.090(7)	56002.7216	4.1589888	0.012(0.017)	69.2 (12.8)	35.1 (7.3)
CR Per	89.25(0.22)	20000	18995(427)	52.0(1.9)	48.0(2.0)	0.0	0.051(3)	0.051(2)	54005.9671	8.8096975	0.234(0.016)	14.2 (8.2)	> 1000
CzeV 662	87.68(0.24)	7500	7474(110)	51.9(0.8)	48.1(0.7)	0.0	0.135(3)	0.131(2)	54417.7801	2.8943665	0.164(0.033)	182.9 (3.7)	232.7 (59)
CzeV 701	89.27(0.11)	6500	6258(72)	53.8(0.7)	46.2(0.9)	0.0	0.011(2)	0.011(2)	54032.0336	51.2568523	0.209(0.012)	18.2 (0.5)	> 1000
CzeV 688	81.77(0.28)	6000	4652(126)	84.0(0.6)	16.0(0.5)	0.0	0.168(3)	0.154(3)	54417.3197	3.4676851	0.360(0.032)	263.5 (0.7)	193.3 (12)
V1018 Cas	79.69(0.21)	20000	17912(260)	50.8(0.5)	49.2(0.5)	0.0	0.234(2)	0.163(8)	54833.4983	4.1277539	0.152(0.021)	178.1 (7.9)	126.1 (5)
V1268 Tau	86.99(0.06)	10000	7166(20)	78.3(0.3)	19.5(0.3)	2.2(0.6)	0.069(2)	0.063(2)	56205.8772	8.1612083	0.301(0.002)	221.3 (0.5)	> 1000
NO Per	89.93(0.23)	6200	6169(95)	53.2(1.8)	23.7(0.7)	23.1(2.2)	0.169(2)	0.115(2)	57048.6114	5.6923047	0.280(0.007)	213.4 (0.8)	> 1000
CzeV 1279	89.29(0.17)	5750	5815(117)	18.8(1.7)	81.2(2.6)	0.0	0.015(3)	0.030(2)	57017.4806	28.8680283	0.420(0.008)	192.0 (0.9)	> 1000
DT Cam	87.69(0.19)	8800	7382(75)	66.4(0.7)	33.6(0.6)	0.0	0.068(3)	0.064(2)	56203.8349	7.0662440	0.188(0.010)	49.2 (1.3)	> 1000
UCAC4 609-022916	81.58(0.22)	6600	6535(59)	59.9(2.1)	40.1(2.3)	0.0	0.213(6)	0.177(6)	57775.5551	1.6736231	0.161(0.016)	34.3 (1.2)	64.6 (19)
V409 Cam	84.40(0.32)	6500	6585(128)	51.4(1.1)	47.1(1.5)	1.5(0.6)	0.099(2)	0.094(2)	53123.6893	6.6764702	0.038(0.022)	167.6 (18.5)	158.9 (37)
CzeV 1144	78.14(0.17)	6600	6321(73)	58.3(0.6)	41.7(0.6)	0.0	0.173(3)	0.163(2)	57752.3849	2.0833922	0.192(0.015)	60.7 (0.8)	298.5 (99)
V437 Aur	88.16(0.34)	11000	10981(48)	62.4(0.8)	37.6(0.8)	0.0	0.090(4)	0.065(3)	56338.8586	11.7938027	0.226(0.007)	137.6 (4.2)	> 1000
CzeV 364	79.37(0.30)	6000	5186(81)	55.5(0.7)	40.6(2.2)	3.9(1.8)	0.137(5)	0.158(4)	51522.9781	2.5522095	0.364(0.008)	335.3 (1.7)	> 1000
CzeV 464	88.20(0.21)	7200	7075(69)	52.1(0.4)	47.9(0.4)	0.0	0.050(4)	0.050(4)	56408.9827	10.4774146	0.018(0.014)	14.6 (25.2)	835.8 (690)
TYC 3750-599-1	77.80(0.17)	13000	12730(78)	53.2(0.6)	46.1(1.0)	0.7(0.5)	0.210(4)	0.202(3)	56280.6576	2.0597637	0.090(0.011)	137.0 (2.1)	68.6 (4.7)
TYC 729-1545-1	74.92(0.38)	10000	10940(212)	37.7(1.3)	62.3(1.0)	0.0	0.183(5)	0.216(5)	53504.8365	5.0778902	0.217(0.031)	7.3 (12.5)	143.7 (120)
CD-33 2771	89.43(0.82)	4400	3943(99)	86.2(1.8)	11.3(0.7)	2.5(1.9)	0.191(8)	0.105(7)	52327.9925	199.9666008	0.123(0.079)	204.3 (18.7)	> 1000
HD 44093	85.27(0.32)	11000	11434(157)	39.7(2.1)	60.3(1.9)	0.0	0.133(7)	0.149(8)	52637.0168	5.9414804	0.442(0.078)	65.9 (11.0)	> 1000
TYC 5378-1590-1	89.85(0.16)	10000	9380(201)	64.1(0.8)	35.9(0.8)	0.0	0.123(2)	0.098(3)	53946.4904	3.7323527	0.319(0.023)	338.0 (6.8)	> 1000
HD 55338	87.20(2.45)	9200	8591(49)	15.7(2.0)	11.1(1.1)	73.2(2.3)	0.264(9)	0.245(15)	53023.7640	1.2114599	0.014(0.007)	300.6 (2.3)	31.3 (3.1)
RW CMi	86.74(0.27)	6700	6870(96)	38.8(0.9)	61.2(0.9)	0.0	0.076(3)	0.090(2)	57046.9677	6.0838012	0.479(0.065)	195.6 (22.3)	> 1000
V611 Pup	80.96(0.24)	17000	19859(179)	39.6(0.7)	60.4(0.7)	0.0	0.142(2)	0.153(2)	53500.8872	6.3178011	0.160(0.009)	142.3 (11.4)	> 1000
CzeV 1283	89.50(0.29)	7200	7199(88)	40.9(1.0)	45.0(1.1)	14.1(5.2)	0.032(4)	0.034(3)	57040.2488	39.9810718	0.460(0.007)	181.4 (8.7)	> 1000
TYC 7126-2416-1	87.17(0.30)	4800	4280(132)	66.8(2.7)	33.2(2.6)	0.0	0.048(2)	0.048(3)	53531.8932	189.2707501	0.192(0.009)	197.9 (9.2)	> 1000
CzeV 1183	87.43(0.21)	6000	5799(77)	55.6(3.2)	31.3(2.8)	13.1(2.4)	0.210(9)	0.172(8)	53497.1451	2.5814597	0.209(0.014)	327.0 (3.3)	83.8 (12)
DK Pyx	78.41(0.66)	17000	14549(190)	81.4(2.3)	17.1(1.6)	1.5(1.4)	0.159(5)	0.085(7)	53123.0475	6.1784209	0.327(0.011)	182.1 (6.9)	400.7 (97)
PS UMa	85.39(0.38)	6500	6535(205)	53.4(6.8)	46.6(5.2)	0.0	0.094(4)	0.086(8)	51507.9642	9.2716673	0.094(0.022)	125.6 (13.7)	> 1000
HD 87803	87.25(0.09)	10400	10386(72)	50.2(1.3)	45.9(1.0)	3.9(1.2)	0.053(3)	0.051(2)	53511.1799	11.5105711	0.475(0.010)	157.6 (10.0)	> 1000
TYC 8603-723-1	84.78(0.40)	9500	8032(111)	68.1(1.7)	26.3(5.0)	5.6(3.9)	0.121(5)	0.101(4)	53511.7334	4.4111698	0.439(0.031)	40.9 (8.4)	> 1000
HD 306001	78.65(0.78)	15000	13852(215)	54.2(4.0)	39.9(6.3)	5.9(3.1)	0.127(5)	0.126(4)	52007.3924	6.1015690	0.440(0.017)	197.6 (11.8)	> 1000
TYC 8217-789-1	87.38(0.44)	6000	5874(139)	58.8(2.3)	41.2(2.1)	0.0	0.105(4)	0.092(3)	53452.8919	6.7867621	0.178(0.020)	315.0 (7.2)	> 1000
TYC 9432-1633-1	88.27(0.50)	5500	5770(227)	35.2(4.1)	64.8(5.4)	0.0	0.054(5)	0.065(6)	53512.0943	10.0220862	0.319(0.095)	327.2 (17.0)	> 1000
SS TrA	89.43(0.72)	7500	7424(156)	63.4(1.9)	36.6(1.6)	0.0	0.077(2)	0.060(2)	53509.9548	8.6012129	0.519(0.029)	216.6 (8.3)	> 1000
KO Nor	89.65(0.18)	7300	6964(87)	57.1(7.0)	42.9(6.7)	0.0	0.053(6)	0.050(5)	53485.9247	33.5618767	0.359(0.030)	262.6 (1.9)	> 1000
V883 Sco	82.11(1.10)	17000	15537(92)	59.7(0.8)	26.4(3.1)	13.9(4.2)	0.268(4)	0.196(9)	53120.8310	4.3411841	0.082(0.007)	334.3 (1.0)	90.1 (2.3)
V1301 Sco	83.65(0.15)	6100	6340(36)	29.5(0.6)	70.5(0.6)	0.0	0.123(2)	0.177(3)	56500.2186	1.9540710	0.183(0.003)	118.8 (2.3)	435.3 (210)
HD 158801	88.01(0.23)	8000	8281(130)	37.4(0.9)	62.6(0.8)	0.0	0.053(3)	0.065(3)	53505.6755	12.7764409	0.197(0.004)	190.9 (21.5)	> 1000
TYC 6258-1011-1	87.78(0.61)	9000	9533(108)	44.5(1.2)	55.5(0.9)	0.0	0.153(3)	0.159(5)	53644.0728	3.3156733	0.292(0.005)	27.8 (18.3)	273.2 (180)
HD 163735	87.24(0.17)	6700	6566(44)	71.1(0.7)	28.9(0.5)	0.0	0.129(2)	0.086(2)	52002.7823	4.0501532	0.163(0.017)	131.8 (22.7)	> 1000
HD 313631	87.14(0.59)	24000	20592(780)	68.8(5.3)	31.2(4.8)	0.0	0.100(2)	0.079(4)	53545.4322	9.9214123	0.330(0.005)	73.2 (1.0)	> 1000
HD 164610	86.98(0.36)	8000	7496(100)	57.1(2.6)	40.3(1.4)	2.6(1.8)	0.064(3)	0.062(6)	52006.7671	7.8961010	0.029(0.010)	204.1 (12.8)	206.2 (112)
V1344 Her	88.63(0.41)	6000	5998(107)	58.5(7.4)	41.5(6.2)	0.0	0.121(4)	0.102(3)	55501.8489	7.1461026	0.070(0.006)	340.0 (19.4)	> 1000
HD 170749	83.26(0.30)	9500	11599(226)	25.9(1.5)	50.0(1.0)	24.1(1.2)	0.103(3)	0.116(4)	53501.2998	3.6898553	0.467(0.028)	64.3 (10.6)	791.4 (520)
TYC 8378-252-1	87.65(0.92)	6000	6077(144)	53.4(1.6)	46.6(1.2)	0.0	0.153(6)	0.134(5)	51981.7745	2.8776861	0.169(0.018)	157.4 (11.9)	557.7 (341)
TYC 6303-308-1	87.67(0.17)	7000	6815(92)	60.4(1.3)	39.6(2.0)	0.0	0.076(2)	0.066(2)	53499.4058	10.7037742	0.348(0.006)	235.2 (7.8)	> 1000
PS Vul	79.51(1.48)	14000	13005(493)	22.2(3.1)	7.8(2.7)	70.0(10.3)	0.231(5)	0.145(4)	48504.8122	3.8173592	0.169(0.020)	193.5 (18.0)	280.0 (127)
V839 Cep	86.59(0.39)	12000	11445(157)	52.1(2.0)	47.7(1.6)	0.2(0.2)	0.067(3)	0.066(3)	51448.7078	9.9633587	0.037(0.019)	60.5 (22.5)	> 1000
TYC 5195-11-1	89.25(0.51)	6500	6346(87)	50.8(1.7)	47.5(0.9)	1.7(0.8)	0.085(3)	0.085(3)	53508.2286	8.3587149	0.272(0.020)	244.0 (8.7)	> 1000
TYC 2712-1201-1	80.71(0.16)	10000	10296(110)	29.7(0.4)	43.7(0.6)	26.6(3.0)	0.167(2)	0.195(2)	51430.5593	1.8779673	0.196(0.009)	57.6 (1.0)	86.8 (6.3)
UCAC4 585-123180	86.11(0.14)	5900	5565(132)	62.9(1.8)	37.0(2.0)	0.0	0.067(2)	0.060(2)	57045.7780	7.9515013	0.248(0.012)	183.8 (12.3)	> 1000
V922 Cep	86.86(0.09	6800	6838(77)	48.9(2.0)	49.6(1.8)	1.5(1.2)	0.098(2)	0.098(2)	51606.7539	3.5749727	0.135(0.005)	2.3 (11.6)	609.2 (450)
V389 And	88.76(0.57)	10000	9431(220)	54.2(0.9)	43.9(2.0)	1.9(1.5)	0.033(2)	0.032(2)	56203.7313	25.7783229	0.020(0.002)	331.8 (1.8)	> 1000

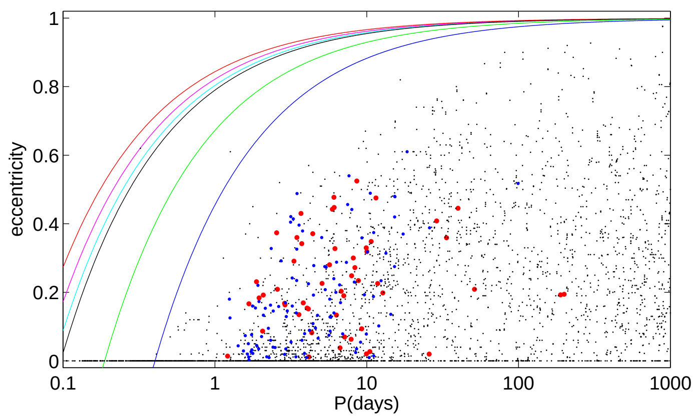

Fig. 5. Distribution of known eccentric systems in the period-eccentricity diagram. New data are plotted in red, systems from the catalogue by Bulut & Demircan (2007) in blue, and spectroscopic binaries from the SB9 catalogue (Pourbaix et al. 2004) as small black points. See the text for detailed description of the solid lines.

4. Period eccentricity relation

The diagram which should be discussed in more detail is the period-eccentricity distribution of our systems. We plotted our results together with those already published before by Bulut & Demircan (2007) and also with the spectroscopic binaries from the SB9 catalogue by (Pourbaix et al. 2004) in the Fig. 5. As can be seen, orbital circularization plays a role in binaries with shorter periods (Raghavan et al. 2010, Duchêne & Kraus 2013), while practically all systems that have periods below one day are already circular. Besides the plotted observed data we have also plotted several solid lines representing the limits of very close periastron approaches of both components (i.e. $1.5\times R_\star$) when these likely collide with each other. These periastron distances were computed for different spectral types (B to M) according to their typical radii and masses (see Zombeck 1990) with the assumption that both components are similar to each other (same masses and radii). As we can see, the sample of eclipsing apsidal motion systems has increased significantly with our new data set and should be very helpful in future when analysing the P-e diagram in detail.

However, we still have to be very careful when interpreting these results with our new data. For some systems a significant change of eccentricity could appear for the case when the star still has poor data coverage of both light curve and the $O-C$ diagram. The P-e diagram still lacks of such systems which have significant eccentricity close to its upper limit for a particular period. The system with the highest eccentricity from the catalogue by Bulut & Demircan (2007) is LV Her (P=18.44d, e=0.61), while some more eccentric eclipsing systems definitely exist in the catalogue of OGLE (Zasche, in prep.), and Kepler (Prša, priv.comm.).

5. Discussion and conclusions

We have derived the preliminary apsidal motion and light curve parameters for 54 Algol-type binaries. This is the first time any such analysis of such a large sample of eccentric eclipsing binaries has been studied in our Galaxy using different sources of photometry. Bringing together data from various databases and surveys has facilitated estimation of the long-term evolution of the orbit and the apsidal precession of our sample. Hong et al. (2016) is the only similar study of such a large sample of stars. The authors present 90 eclipsing binaries with apsidal motion. However, their study only used the OGLE III database (Graczyk et al. 2011) covering eight seasons. The advantage of our approach for the galactic targets is the fact that we also used archival photometry and the already published data reach back even to the 1930s in one case (SS TrA), hence the detected slow apsidal motion should be more conclusive.

We should also mention the difference between our sample and the one already published earlier by Bulut & Demircan (2007) – both in magnitude ranges as well as spectral types. The assumed spectral type and the distribution of both periods (orbital and apsidal motion) can also be studied as noted for example, by Hong et al. (2016). They presented a diagram showing that there is a possible relation between both periods and the masses of the components. However, they concluded that a much larger sample is needed for the final verdict, especially the longer-periodic binaries (P > 6 d) that also have longer apsidal motions. In our contribution to the topic more than 50% of our studied systems have periods longer than six days.

The sample of 54 systems presented in this study provides a good starting point for future dedicated observations and analyses of several more interesting systems, for example, these showing some suspicious additional variability of their orbital periods, these with rapid apsidal motion, or those containing close components. As good spectroscopic data (i.e. knowing the individual masses) is also available for them, one should be able to derive the internal structure constants or compute the relativistic contribution to the total apsidal motion rate.

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Note added in proof: A new study on eccentric eclipsing binaries by Kim et al. (2018) was published while this manuscript was in the final stages of publication. For five of the systems in common between Kim et al. (2018) and our paper, the results are slightly different. This is likely to be due to different methodologies and possibly also the different weightings used for the times of minima.

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Table A.1. Apsidal rotators with significant relativistic contribution.

Star	$\dot{\omega}_{rel}/\dot{\omega}_{total}$
V1268 Tau	59.9 ± 35.0 %
V437 Aur	37.5 ± 14.7 %
HD 44093	52.8 ± 18.4 %
V611 Pup	73.2 ± 40.8 %
HD 163735	22.3 ± 15.7 %
HD 313631	57.1 ± 23.5 %
V1344 Her	55.0 ± 42.8 %

Appendix A: Appendix

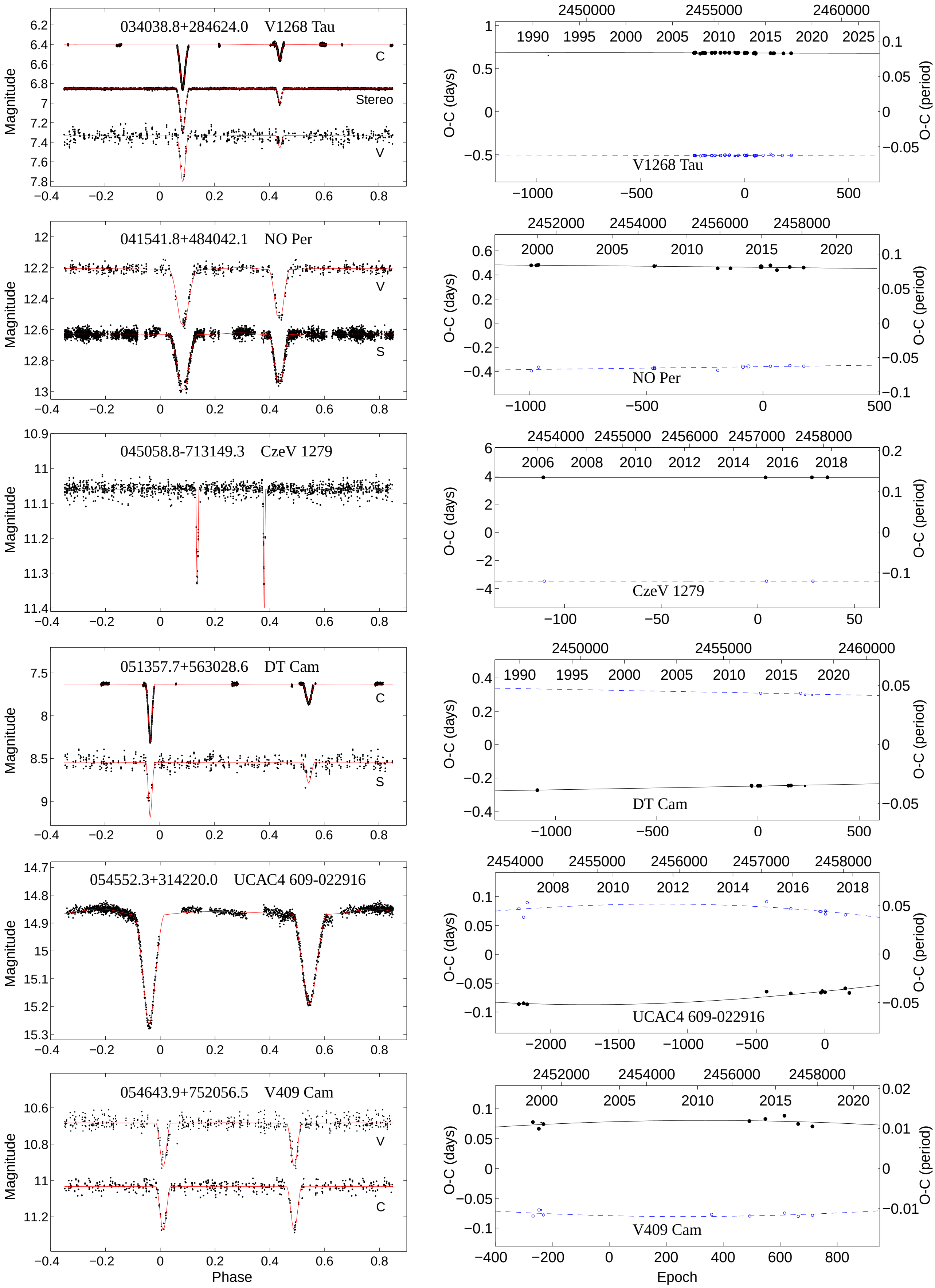

Fig. A.1. Plot of the light curves and $O - C$ diagrams of the analysed systems, cont.

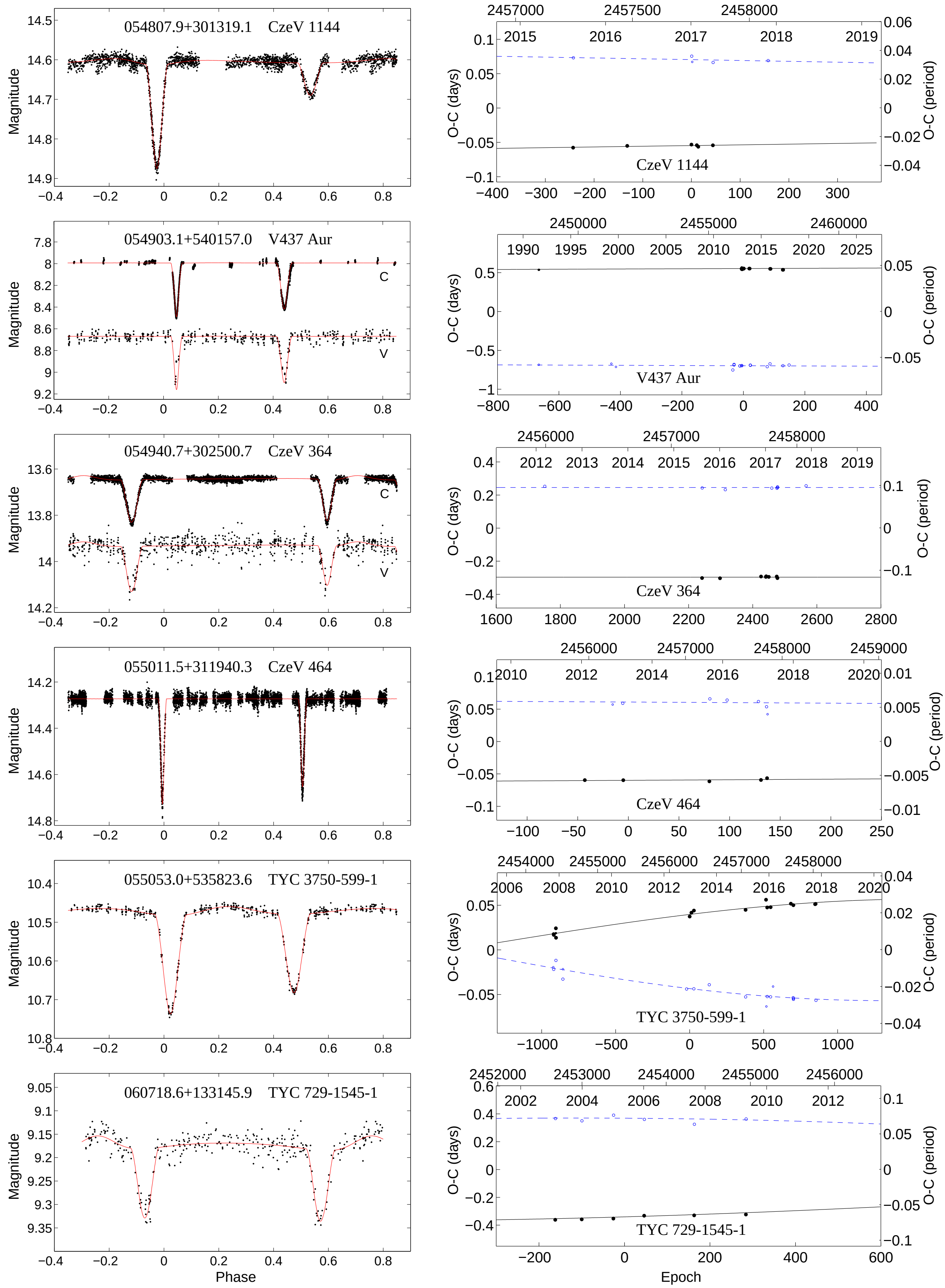

Fig. A.2. Plot of the light curves and $O-C$ diagrams of the analysed systems, cont.

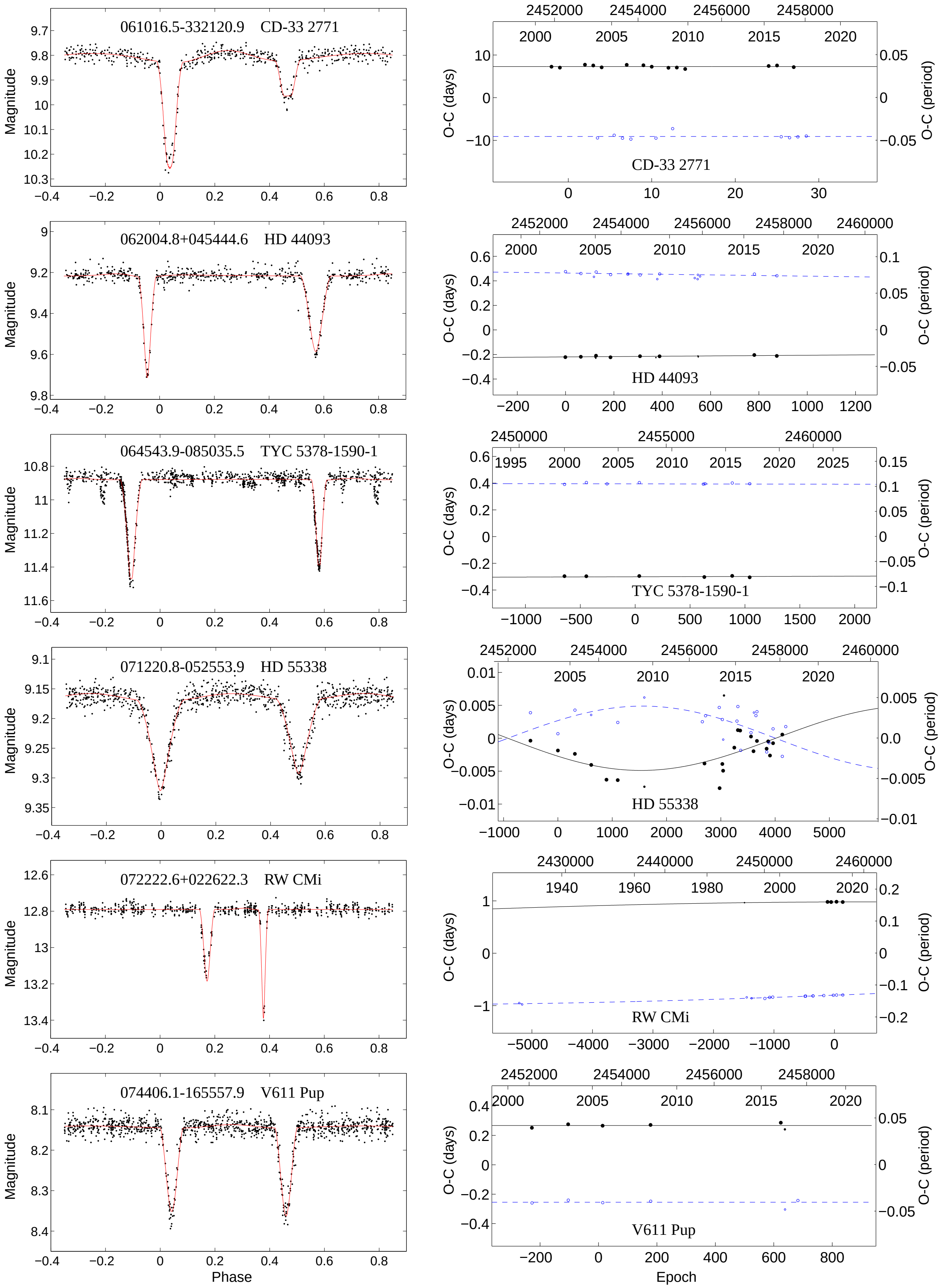

Fig. A.3. Plot of the light curves and $O - C$ diagrams of the analysed systems, cont.

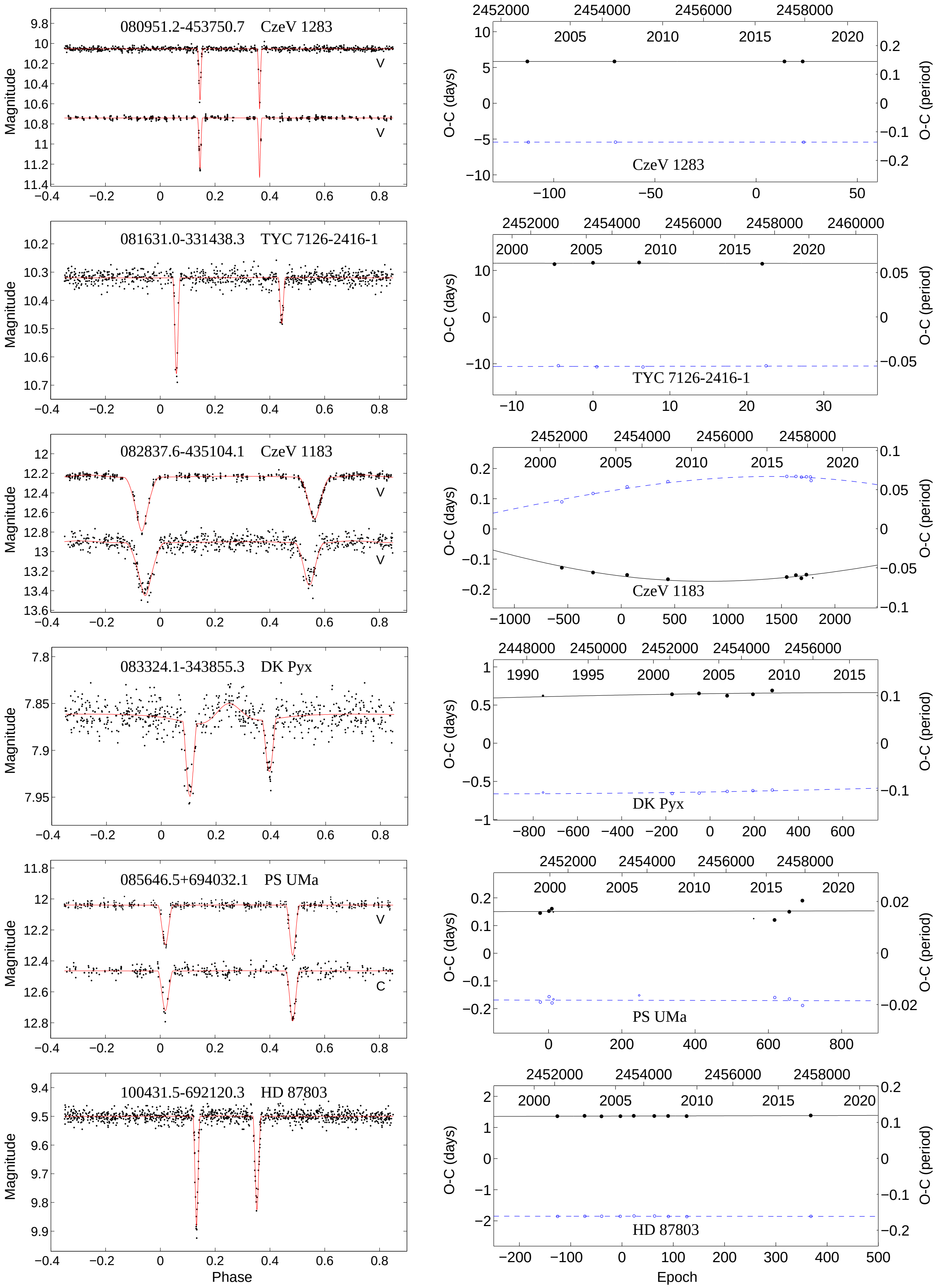

Fig. A.4. Plot of the light curves and $O-C$ diagrams of the analysed systems, cont.

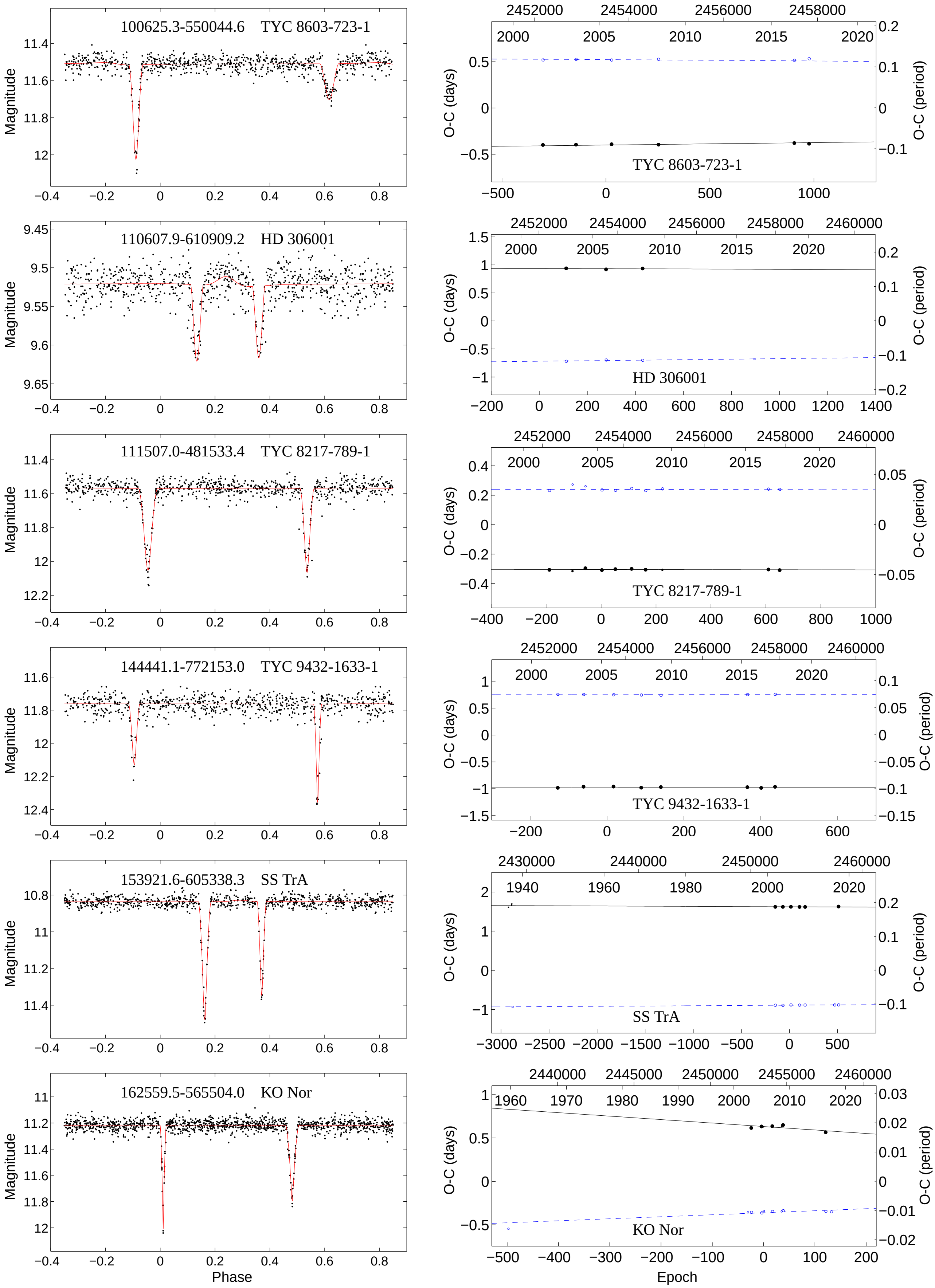

Fig. A.5. Plot of the light curves and $O-C$ diagrams of the analysed systems, cont.

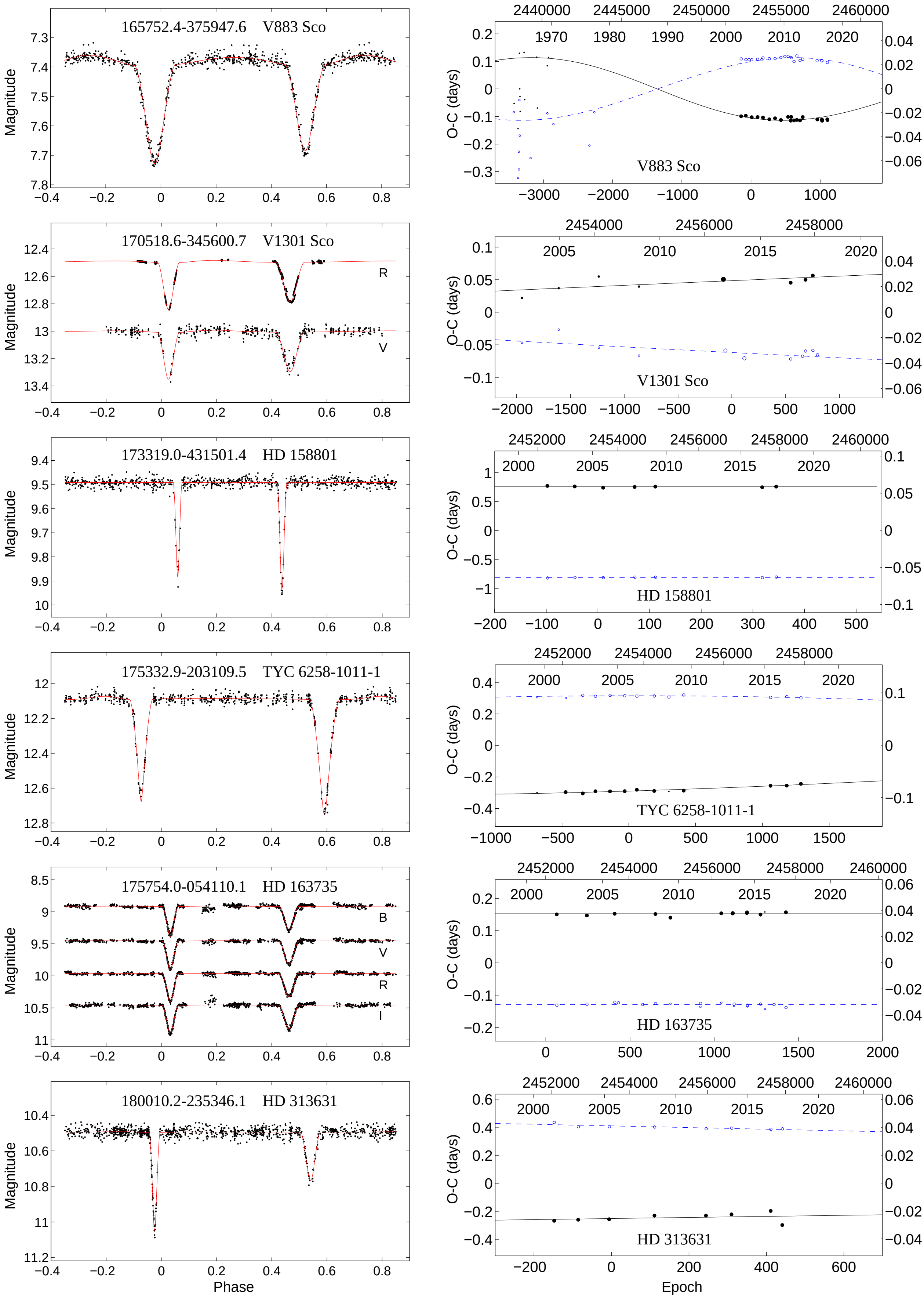

Fig. A.6. Light curves and $O-C$ diagrams of the analysed systems, cont.

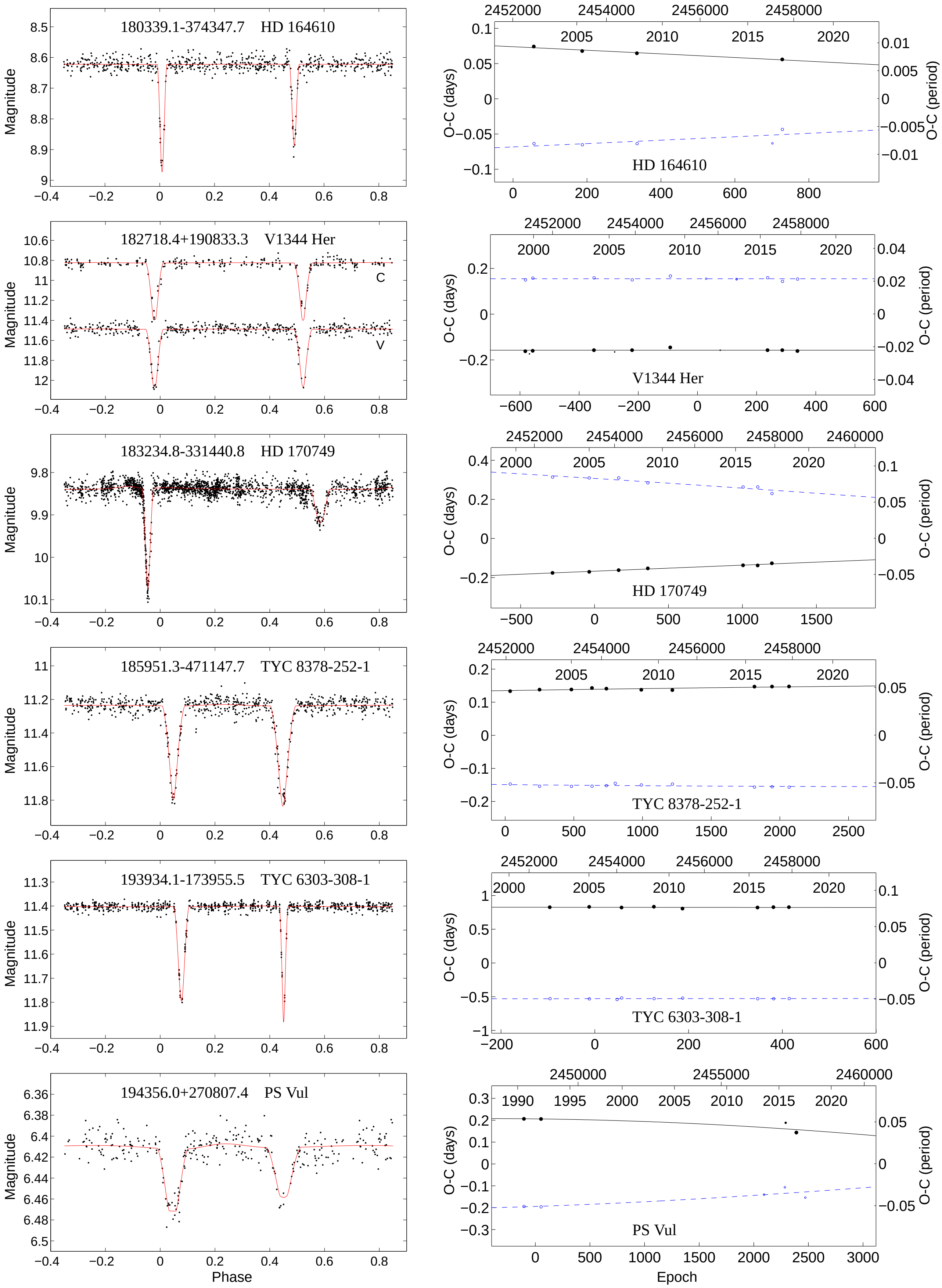

Fig. A.7. Light curves and $O - C$ diagrams of the analysed systems, cont.

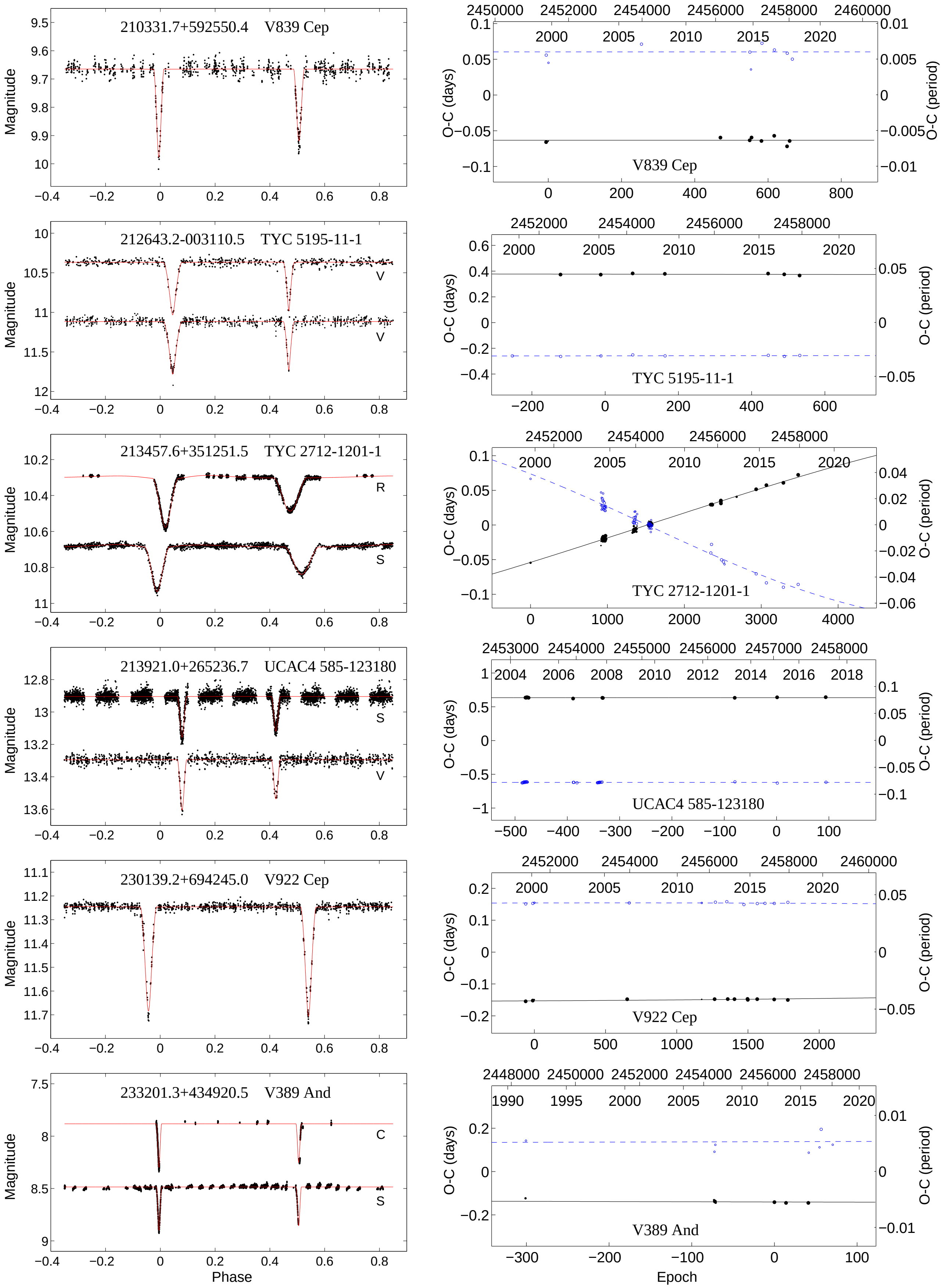

Fig. A.8. Light curves and $O-C$ diagrams of the analysed systems, cont.