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New Apsidal Motion in Four Eccentric Eclipsing Binaries: V610 Car, V944 Cep, V2815 Ori and V1260 Tau

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Abstract

This paper presents an apsidal motion analysis. The apsidal motion analysis of the eccentric eclipsing binaries V610 Car ($P = 4.84$ days), V944 Cep ($P = 6.56$ days), V2815 Ori ($P = 2.13$ days), and V1260 Tau ($P = 5.43$ days) was performed using minima times from the $O-C$ Gateway database, ASAS-3, ASAS-SN, and TESS, following Lacy's approach. The rates of change of periastron longitude were found to be 0.0253 ± 0.0041, 0.0347 ± 0.0015, 0.0288 ± 0.0010 and $0.0294 \pm 0^{\circ}\!.0079$ cycle^{-1}, respectively. From the light curve study, the first photometric mass ratio of V944 Cep was found to be $q = 1.4994 \pm 0.0012$. A new light curve of V944 Cep was obtained using TESS data. The first absolute dimensions of V944 Cep were $M_1 = 1.10 \pm 0.01\ M_{\odot}$, $M_2 = 1.64 \pm 0.02\ M_{\odot}$, $R_1 = 2.04 \pm 0.37\ R_{\odot}$, $R_2 = 3.77 \pm 0.67\ R_{\odot}$ for the hotter primary component ($T_1 = 4925$ K), and $M_1 = 1.04 \pm 0.01\ M_{\odot}$, $M_2 = 1.57 \pm 0.02\ M_{\odot}$, $R_1 = 2.26 \pm 0.36\ R_{\odot}$, $R_2 = 3.74 \pm 0.59\ R_{\odot}$ for the cooler primary component ($T_1 = 4475$ K). For V610 Car, V944 Cep, V2815 Ori and V1260 Tau, the apsidal motion periods were found to be 188 ± 26 yr, 186 ± 8 yr, 73 ± 3 yr and 182 ± 38 yr, respectively. For V944 Cep, the internal structural constants of the component stars $\log_{k2,\mathrm{obs}} = -2.05 \pm 0.01$ and $\log_{k2,\mathrm{theo}} = -1.83$ for hotter primary component and $\log_{k2,\mathrm{obs}} = -1.97 \pm 0.01$ and $\log_{k2,\mathrm{theo}} = -1.89$ for cooler primary component were calculated.

Key words: (stars:) binaries: eclipsing – stars: fundamental parameters – techniques: photometric

1. Introduction

For decades, apsidal motion in eccentric eclipsing binaries has been employed to test stellar structure and evolution hypotheses. The rotation of the major axis in the orbital plane is known as apsidal motion in eccentric binary systems. Because this phenomenon depends on the density distributions within each component, and observations of such motion can be valuable independent checks on the density distributions derived from stellar interior theory. Thus, the studies of apsidal motion on eclipsing binaries enable the determination of the observational internal constants of stars as well as observational tests of the general theory of relativity (Gimenez 1985; Claret & Gimenez 1993).

Working with eclipsing binaries teaches the research community a great deal about stellar astrophysics. Eclipsing binaries with apsidal motion have long been recognized as a significant source of stellar interior structure. Several binary systems for which the apsidal motion characteristics are well understood indicate the importance of these works. The $O-C$ diagrams with apsidal motion, which illustrate eclipsing binaries with eccentric orbits produced by the primary and secondary eclipse minima times, show sinusoidal oscillations with the same period and a 180° phase shift. Apsidal motion periods are typically decades long, necessitating extremely lengthy observation runs.

This paper reports the apsidal motion analysis of four eclipsing binaries: V610 Car, V944 Cep, V2815 Ori and V1260 Tau. These systems are included in Bulut & Demircan (2007)'s database of eclipsing binaries with eccentric orbits. All of them have orbital eccentricities that are less than 0.3.

2. Apsidal Motion Analysis

An $O-C$ diagram analysis was used to investigate apsidal motion in binary systems examined in this study. Gimenez & Garcia-Pelayo (1983) and Lacy (1992) developed suitable numerical methods for apsidal motion analysis. Giménez & Bastero (1995) also proposed improved expressions for predicting eclipse periods implementing an iterative weighted least squares approach that includes eccentricity terms up to the fifth order. In addition, Wolf & Sarounova (1995) provided a relationship for time predictions of minima, which is employed in the least squares approach of minimization. Without relying on approximations, this method could solve the ephemeris-curve equations. The apsidal motion in these four eccentric eclipsing binaries was studied utilizing a computer program developed by Zasche et al. (2009) based on the mathematical theory presented by Giménez & Bastero (1995).

In the apsidal motion study of the four eclipsing binary systems considered, the minimum times were acquired from the

Table 1
New and Recalculated V Minima Times of V610 Car

HJD +2,400,000	E	$(O-C)$ (days)	Type	Reference
51873.7554	−311.5	−0.4005	S	1
51902.8380	−305.5	−0.3874	S	1
52700.6939	−141.0	0.4783	P	2
52729.7882	−135.0	0.5031	P	2
52731.2998	−134.5	−0.4078	S	2
53383.8500	0.0	0.5000	P	2
54357.6729	201.0	0.4930	P	2
54359.2250	201.5	−0.3774	S	2
54822.7831	297.0	0.4904	P	3
55975.8336	535.0	0.4487	P	2
57729.6959	897.0	0.4482	P	3
57750.7306	901.5	−0.3193	S	3

Note. 1: Asas-3 (2001), 2: Paschke & Brat (2006), 3: Asas-sn (2003).

contemporary database of the $(O - C)$ Gateway, ASAS-3, ASAS-SN and TESS. In addition, ASAS-3, ASAS-SN and TESS provided new minimum times. Tables 1–3 and 6–7 contain this information.

This approach was utilized to determine five independent variables: the zero epoch-initial epoch T_0, the sidereal period P_s, the eccentricity of the orbit e, the rate of periastron progress $\dot{\omega}$ and the position of periastron ω_0. The relationship between the sidereal period P_s and anomalistic period P_a is given by $P_s = P_a\ (1 - \dot{\omega}/360)$ and the period of apsidal motion U is defined as $U = 360\ P_a/\dot{\omega}$.

3. V610 Car

V610 Car (NSV 04476, HD 304625, 2MASS J09225976-5944560, TYC 8596-1398-1, Gaia DR2 5299559807255661696, CPD-59 1371, UCAC2 5520852, Gaia EDR3 52995 59807258653440, GSC 08596-01398, TIC 436715053, Gaia DR1 5299559802940310912; R.A. = $09^h22^m59^s.77$, decl. = $-59°\ 44'56''.15$, $V_{\rm Max} = 10.22$ mag; SpT = B8) is an early-type binary. Its binary nature was discovered by Pojmanski (2002). In the ASAS catalog of variable stars, V610 Car is designated as ASAS 092300-5944.9. The first magnitude (10.20–10.75 mag), epoch (2453383.850) and period (4.84493 days) were determined by Otero & Wils (2005), who found this system's spectral type to be B8.

This system is included in Bulut & Demircan (2007)'s database of eclipsing binaries with eccentric orbits. Kazarovets et al. (2008) published the Name-List of Variable Stars, which contains data on 1270 variable stars, most of which are previous, suspected variables from the NSV catalog. Additionally, Kim et al. (2018) determined the orbital elements of an eccentric orbit, such as the orbital period (4.844955 days) and the secondary minimum occurring at phase (0.316). The

Table 2
New and Recalculated V Minima Times of V944 Cep

HJD +2,400,000	E	$(O-C)$ (days)	Type	Reference
51429.5541	−6.5	−6.4607	S	1
51462.3592	−1.5	−6.4557	S	1
51478.5730	0.0	−0.0819	P	1
51482.0367	1.5	−6.4582	S	1
55434.2968	603.0	−0.0465	P	1
55506.4540	614.0	−0.0495	P	1
56372.3872	746.0	−0.0381	P	1
57222.0098	876.5	−6.4974	S	2
57238.3224	878.0	−0.0248	P	1
57297.3502	887.0	−0.0371	P	1
57579.4547	930.0	−0.0132	P	1
57540.0703	924.0	−0.0375	P	2
57989.5029	993.5	−6.5259	S	1
58353.5224	1048.0	−0.0272	P	1
58409.3467	1057.5	−6.5230	S	1
58766.8073	1111.0	−0.0232	P	3
58770.1371	1112.5	−6.5334	S	3
58773.3675	1112.0	−0.0230	P	3
58779.9275	1113.0	−0.0230	P	3
58783.2573	1114.5	−6.5332	S	3
58786.4875	1114.0	−0.0230	P	3
58793.0477	1115.0	−0.0228	P	3
58796.3765	1116.5	−6.5340	S	3
58799.6078	1116.0	−0.0227	P	3
58806.1676	1117.0	−0.0229	P	3
58809.4964	1118.5	−6.5342	S	3
58812.7278	1118.0	−0.0228	P	3

Note.1: Paschke & Brat (2006), 2: Asas-sn (2003), 3: TESS (2021).

Table 3
Photometric Indices and Estimated Mean Effective Temperature of V944 Cep

Photometric Index	Value	T (K)	Reference
Johnson V	10.940 ± 0.070	...	1
2MASS J	8.874 ± 0.018	...	2
2MASS H	8.643 ± 0.028	...	2
2MASS Ks	8.527 ± 0.025	...	2
Johnson $B-V$	0.840 ± 0.060	5216 ± 373	3
Johnson $V-R$	1.110 ± 0.060	3695 ± 200	3
Johnson/2MASS $V-J$	2.066 ± 0.044	4529 ± 96	1, 2
Johnson/2MASS $V-H$	2.297 ± 0.049	4806 ± 103	1, 2
Johnson/2MASS $V-Ks$	2.413 ± 0.048	4809 ± 95	1, 2
2MASS $J-Ks$	0.347 ± 0.025	5846 ± 413	1, 2

Note. 1: Høg et al. (2000), 2: Cutri et al. (2003).

following linear ephemeris was discovered by Kreiner (2004)

$$\text{Pri.Min} = 2{,}452{,}502.0847(5) + 4^d8448424(5) \times E. \quad (1)$$

All photoelectric times from Pojmanski (2002), Otero & Wils (2005), and Paschke & Brat (2006) and the minimum times obtained from the ASAS and ASAS-SN light curves were included in the calculations. Table 1 shows the minimum

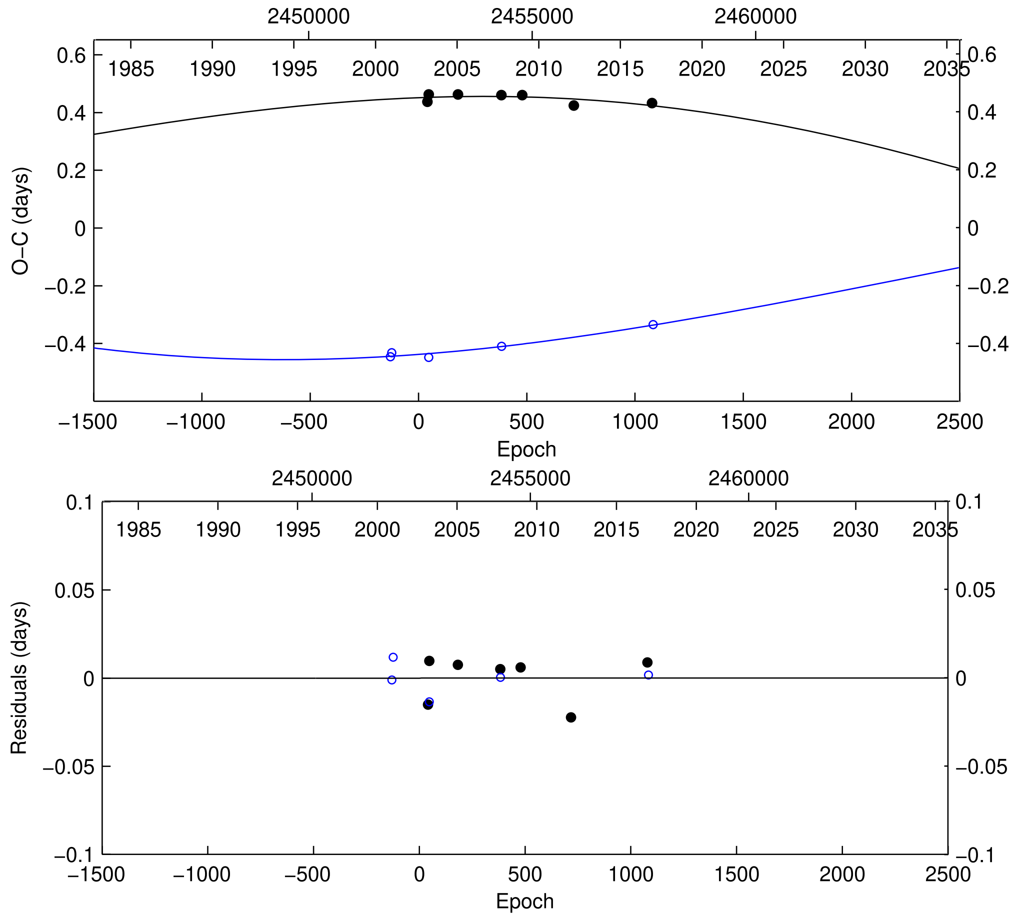

Figure 1. $O-C$ diagram (upper panel) and residuals (lower panel) for V610 Car showing apsidal motion. The filled black and empty blue circles represent the primary and secondary minima, respectively.

times used for V610 Car. A total of 12 times of minima (seven primary and five secondary) were collected for V610 Car from the literature. Table 8 displays the computed apsidal motion elements and their least squares fit internal errors. The apsidal motion period of the system was estimated to be $U = 188$ yr. Figure 1 demonstrates the $O-C$ changing graph and residuals at all periods of minimum with respect to the linear portion of the apsidal motion equation.

4. V944 Cep

The detached eclipsing binary V944 Cep (TYC 4292-745-1, TIC 427767269, Gaia DR2 2210381249327114624, GSC 04292-00745, USNO-A2.0 1500-09818583, Gaia EDR3 2210381249327114624, 2MASS J23303493+6633457, Gaia DR1 2210381245028591616; R.A. $= 23^h30^m34^s.9$, decl. $= +66°33'45''.64$, $V_{\rm Max} = 10.94$ mag), a dim early-type binary with a lengthy orbital period of 6.56 days, has similarly received little attention. Otero et al. (2006) discovered variables consisting of 50 new eccentric eclipsing binaries in the ASAS, Hipparcos and NSVS Databases, as well as the magnitude range (10.86–11.21 mag) of the system and the phase (0.528) of the secondary minimum. This system was included in Bulut & Demircan (2007)'s database of eclipsing binaries with eccentric orbits. Kim et al. (2018) obtained the first magnitude (10.9 mag), epoch (HJD 2451478.670), period (6.5600625 days) and secondary minimum at phase (0.528). The orbital durations and phases of secondary minima (0.528) were determined by Kozyreva et al. (2019). The following linear ephemeris was obtained by Kreiner (2004)

$$\text{Pri.Min} = 2{,}452{,}501.9500(4) + 6^d560066(5) \times E. \quad (2)$$

ASAS-SN and TESS light curves provided new minimum times. Table 2 lists the minimum times used. A total of 27 times of minima (17 primary and ten secondary) were collected for V944 Cep from the literature. Table 8 contains the apsidal motion elements and their errors, and Figure 2 demonstrates the appropriate $O-C$ diagram and residuals. The system's apsidal motion period was calculated using a period of $U = 186$ yr.

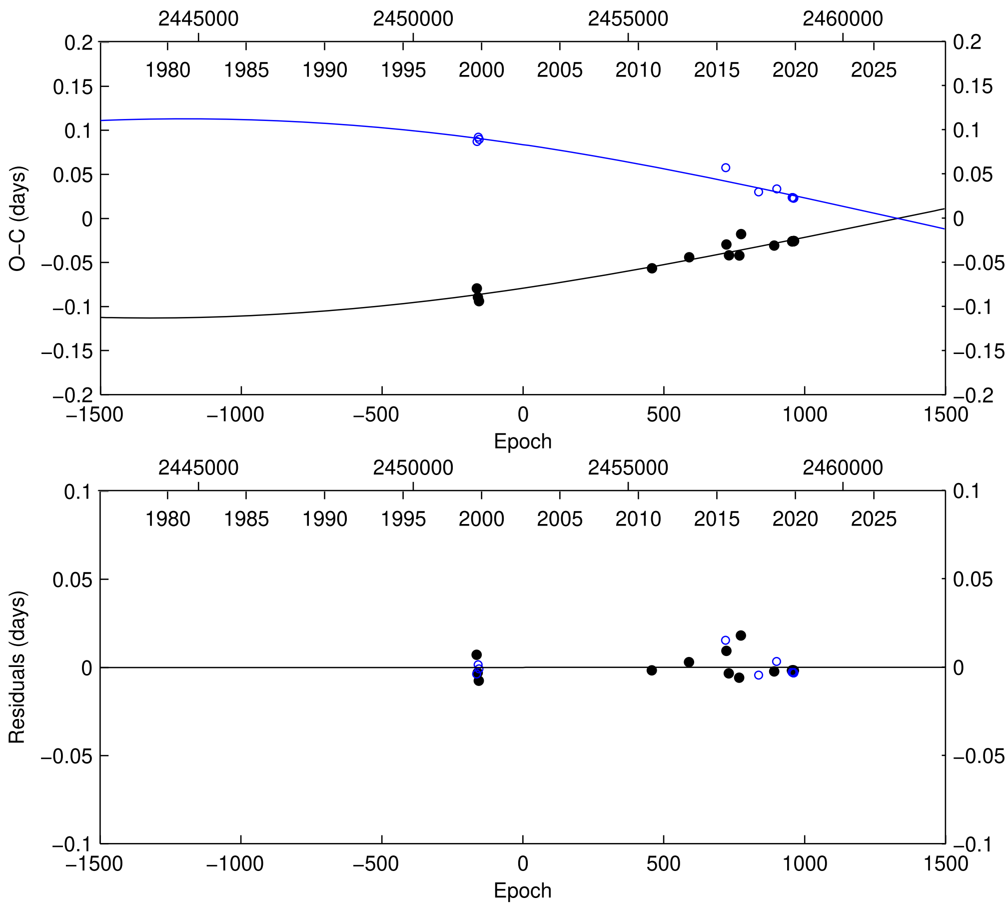

Figure 2. The $O-C$ (upper) and residuals (lower) graphs of V944 Cep. The labels are the same as in Figure 1.

4.1. New Light Curve of V944 Cep and Light Curve Modeling

In the TESS catalog of variable stars, V944 Cep is designated as TIC 427767269. The *V* photometric data of V944 Cep obtained between 2019 and 2020 from the TESS data were considered. During the survey, 16,945 observations of the system were made, with 5534 of them being of excellent photometric quality, such that they could be used to form the new light curve. Minimum times were obtained by the method of Kwee & van Woerden (1956). Figure 3 plots the system's light curve.

The software PHOEBE (version 0.31a) developed by Prša & Zwitter (2005) was used to analyze the light curve of V944 Cep. This software incorporates the Wilson-Devinney (W-D) program (Wilson & Devinney 1971). The light curve was calculated as a function of the following parameters: the orbital eccentricity e, the periastron longitude ω, the orbital inclination i, the surface temperature $T_{1,2}$, the dimensionless surface potentials $\Omega_{1,2}$, the mass ratio q, the relative luminosities $L_{1,2}$, the gravity darkening exponents $g_{1,2}$, the limb darkening coefficients $x_{1,2}$ and the bolometric albedos $A_{1,2}$.

With certain assumptions, the detached binary mode (in W-D mode 2) was utilized. During the light curve modeling, some component parameters had to be fixed. For the square root law, the associated linear limb-darkening coefficients were interpolated from van Hamme's tables (van Hamme 1993). The bolometric albedo coefficients ($A_{1,2} = 1.0$) and gravity-darkening exponents ($g_{1,2} = 1.0$) were fixed to their specified values for radiative atmospheres (Lucy 1968). The literature's magnitudes and color indices could be applied when calculating the system's mean effective temperature for the combined light. Table 3 summarizes the findings. For dwarf stars, the color/temperature calibrations were taken from Casagrande et al. (2010) and Ramírez & Meléndez (2005). The average temperature value given in the Gaia-DR2 survey is 4704.34 K. In this analysis, two different solutions were carried out by considering the hotter primary component (4925 K) and cooler primary component (4475 K).

The q-search approach with a step of 0.1 was applied to obtain reasonable photometric estimations for the mass ratio

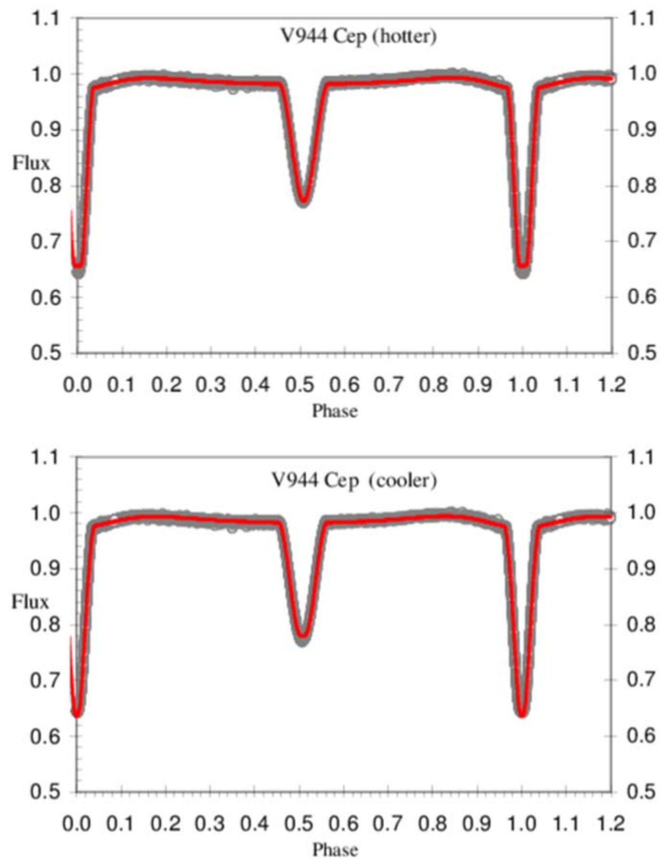

Figure 3. The light curve obtained in the Johnson V filter of V944 Cep. The upper and lower panels represent the hotter and cooler primary component's solution, respectively.

because the spectroscopic value was unknown. Figure 4 features the variation of the weighted sum of squared residuals, $\Sigma W(O-C)^2$, for the corresponding mass ratios q. As seen from the figure, the smallest value of the residuals occurs at about $q = 1.50$. This value was used as the initial value of the mass ratio in the differential correction procedure. The theoretical light curve and observations given in Figure 3 depict the solution with a hotter primary component and a cooler primary component. The final photometric mass ratios of V944 Cep determined from the light curve analysis are $q = 1.4979 \pm 0.0023$ for the hotter primary component and $q = 1.5058 \pm 0.0013$ for the cooler primary component. Since the chi-square value of the cooler primary component's solution given in Table 4 is lower than those of the other solutions, it can be concluded that the cooler primary component's solution is more suitable for this binary system. Table 4 contains the findings of the light curve solution. As a result of the light curve solution, the system's absolute parameters were determined and are expressed in Table 5. To the author's knowledge, V944 Cep has never been the subject of photometric or spectroscopic research until now.

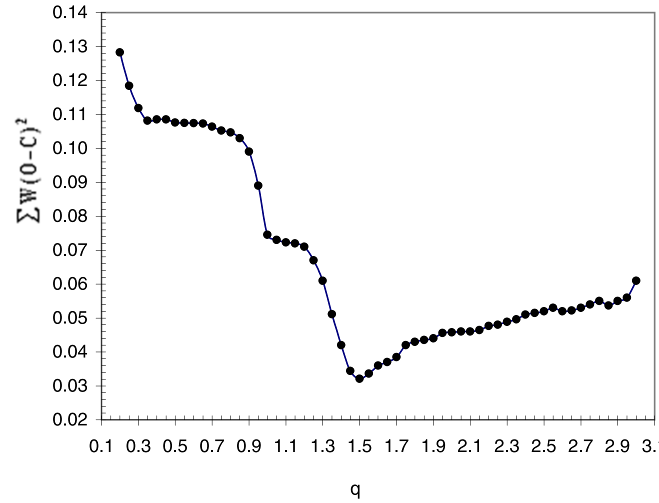

Figure 4. The q-search diagram of V944 Cep.

Table 4
The Results Obtained from the Light Curve Analysis of V944 Cep

Parameter	Hotter Primary Component	Cooler Primary Component
T_0 (HJD)	2,451,478.670	2,451,478.670
P (days)	6.5600625	6.5600625
i (deg)	86.35 ± 0.01	86.47 ± 0.01
e	0.241487 ± 0.00129	0.161058 ± 0.00079
ω (deg)	87.38 ± 0.03	265.86 ± 0.03
T_1 (K)	4925	4475
T_2 (K)	4553 ± 100	4733 ± 100
T_1/T_2	1.08	0.94
Ω_1	12.721 ± 0.012	10.826 ± 0.003
Ω_2	9.331 ± 0.011	9.243 ± 0.005
q	1.4979 ± 0.0023	1.5058 ± 0.0013
x_1	0.802	0.808
x_2	0.809	0.803
$A_1 = A_2$	1.00	1.00
$g_1 = g_2$	1.00	1.00
$L_1/(L_1+L_2)$	0.303 ± 0.004	0.199 ± 0.002
$L_2/(L_1+L_2)$	0.697	0.801
$r_{1,\mathrm{mean}}$	0.099122 ± 0.000104	0.111151 ± 0.000052
$r_{2,\mathrm{mean}}$	0.182825 ± 0.000254	0.184127 ± 0.000136
χ^2	0.153	0.076

Note. T_0, P and T_1 are fixed during the light curve solution of the hotter and cooler primary component.

5. V2815 Ori

The eclipsing binary V2815 Ori (TYC 127-719-1, 2MASS J05432252+0701209, UCAC2 34233393, Gaia DR2 3333362051577320192, ATO J085.8438+07.0224, NSVS 9649804, UCAC3 195-29882, Gaia EDR3 3333362051577320192, GSC 00127-00719, TIC 200613553, Gaia DR1 3333362051577320192; R.A. $= 05^{\mathrm{h}}43^{\mathrm{m}}22^{\mathrm{s}}.5$, decl. $= +07°\ 01'20''.75$, $V_{\mathrm{Max}} = 11.83$ mag) is an early-type detached binary

Table 5
Absolute Parameters of V944 Cep

Parameter	Hotter Primary Component	Cooler Primary Component
M_1 ($M_\odot$)	1.10 ± 0.01	1.04 ± 0.01
M_2 ($M_\odot$)	1.64 ± 0.02	1.57 ± 0.02
R_1 ($R_\odot$)	2.04 ± 0.37	2.26 ± 0.36
R_2 ($R_\odot$)	3.77 ± 0.67	3.74 ± 0.59
log g_1 (cgs)	3.86 ± 0.10	3.75 ± 0.10
log g_2 (cgs)	3.50 ± 0.10	3.49 ± 0.10
T_1 (K)	4925	4475
T_2 (K)	4553 ± 100	4733 ± 100
T_1/T_2	1.08	0.94
log L_1 ($L_\odot$)	0.34 ± 0.16	0.26 ± 0.14
log L_2 ($L_\odot$)	0.73 ± 0.16	0.79 ± 0.14
$M_{1,\mathrm{bol}}$	3.91 ± 0.52	4.11 ± 0.55
$M_{2,\mathrm{bol}}$	2.92 ± 0.23	2.77 ± 0.19
a ($R_\odot$)	20.61 ± 3.56	20.30 ± 3.09
log $k_{2,\mathrm{obs}}$	-2.05 ± 0.01	-1.97 ± 0.01
log $k_{2,\mathrm{theo}}$	−1.83	−1.89

with phase Min II (0.481), and a period of 2.13 days. Pojmanski (2002) discovered it to be a variable star. The first magnitude (11.8 mag), epoch (HJD 2453059.622), period (2.1310132 days) and phase (0.481) of the secondary minimum were all derived by Kim et al. (2018). In the ASAS catalog of variable stars, V2815 Ori is designated as ASAS 054323 +0701.3. The following light elements were reported by Kreiner (2004)

$$\mathrm{Pri.Min} = 2{,}452{,}501.3176(4) + 2^{\mathrm{d}}1310188(5) \times E. \quad (3)$$

A total of 22 times of minima (12 primary and ten secondary) were collected for V2815 Ori from the literature. Minimum timings were compiled for 20 yr, from 1999 to 2019. All photoelectric times from Paschke & Brat (2006) were included in the calculations; the new minimum times were obtained from the ASAS and ASAS-SN light curves. Table 6 shows the minimum times used for V2815 Ori. Figure 5 displays the $O-C$ changing and residuals graph of V2815 Ori. Table 8 features the results obtained from the $O-C$ analysis of V2815 Ori.

6. V1260 Tau

Kharadze & Chargeishvili (1990) discovered the eclipsing binary V1260 Tau (HD 245819, 2MASS J05390391+2536104, TIC 75164365, Gaia DR2 3440914049918649984, AAO+25 99, NSV 2503, TYC 1865-2657-1, Gaia EDR3 3440914049921640320, BD+25 896, Renson 10016, UCAC2 40818435, Gaia DR1 3440914045624158080, GSC 01865-02657; R.A. = $05^{\mathrm{h}}39^{\mathrm{m}}03^{\mathrm{s}}.9$, decl. = $+25°36'10''.37$, V_{Max} = 10.10 mag, Sp = A3m) as an early-type detached binary, having a period of 5.430 days. Additionally, Otero & Wils (2005) determined it to be a variable system found in the ASAS-3 (Pojmanski 2002), Hipparcos (Perryman et al. 1997) and NSVS (Wozniak et al. 2004) databases, with the initial magnitude range (10.15–10.75 mag), epoch (HJD 2453347.724) and period (5.43077 days).

Table 6
New and Recalculated *V* Minima Times of V2815 Ori

HJD +2,400,000	E	$(O-C)$ (days)	Type	Reference
51516.7832	−409.0	0.0061	P	1
51545.5200	−395.5	−0.0259	S	1
52388.3600	0.0	−0.0047	P	1
52526.8863	65.0	0.0052	P	2
52846.5392	215.0	0.0050	P	1
52943.4624	260.5	−0.0333	S	1
53274.8700	416.0	0.0006	P	2
53448.4999	497.5	−0.0477	S	2
53773.5469	650.0	0.0186	P	1
53812.9133	668.5	−0.0389	S	1
54492.6987	987.5	−0.0492	S	2
54554.5050	1016.5	−0.0425	S	2
54726.1022	1097.0	0.0075	P	1
54761.2104	1113.5	−0.0462	S	1
54849.7013	1155.0	0.0073	P	1
54865.6315	1162.5	−0.0451	S	1
55582.7753	1499.0	0.0101	P	1
55893.8977	1645.0	0.0035	P	1
56313.7054	1842.0	0.0000	P	1
56625.8497	1988.5	−0.0503	S	3
57031.8660	2179.0	0.0065	P	3
57606.1172	2448.5	−0.0524	S	3

Note. 1: Paschke & Brat (2006), 2: Asas-3 (2001), 3: Asas-sn (2003).

This system is included in Bulut & Demircan (2007)'s database of eclipsing binaries with eccentric orbits. The current 79th Name-List of Variable Stars includes information needed to identify new variables finally declared in 2008 (Kazarovets et al. 2008). Furthermore, Smalley et al. (2014) presented the light curve solution parameters of the V1260 Tau eclipsing binary system in the SuperWASP survey ($i = 86°.98$, $e = 0.25$, $P = 5.4309$ days, $T_{\mathrm{eff}} = 7557$ K, $R_1 = 2.11\ R_\odot$, $R_2 = 2.81\ R_\odot$ and $q = 1.11$). Kreiner (2004) measured the first magnitude (10.2 mag), epoch (HJD 2453347.880), period (5.4308176 days) and phase (0.555) of secondary minimum. The following linear light elements were obtained by Kreiner (2004)

$$\mathrm{Pri.Min} = 2{,}452{,}500.5160(4) + 5^{\mathrm{d}}430830(5) \times E. \quad (4)$$

A total of 17 times of minima (ten primary and seven secondary) were collected for V1260 Tau from the literature. Minimum times were compiled for 20 yr, from 1999 to 2019. All photoelectric times from Paschke & Brat (2006) were included in the calculations; the new minimum times were obtained from the ASAS-SN light curves. Table 7 shows the minimum times used for V1260 Tau. Figure 6 displays the $(O-C)$ changing and residuals graph of the V1260 Tau binary system. Table 8 lists the resulting apsidal motion parameters.

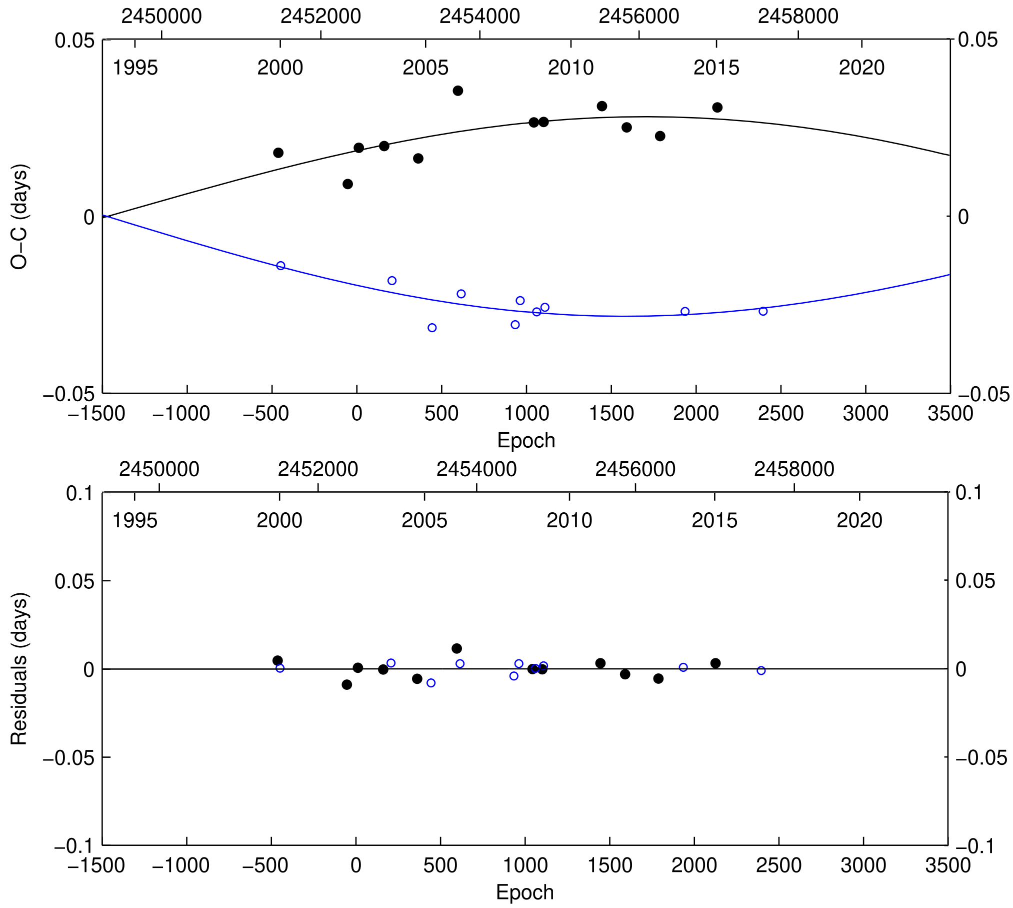

Figure 5. The $O - C$ changing diagram (upper) and residuals (lower) graph of V2815 Ori. The labels are as in Figure 1.

Table 7
New and Recalculated *V* Minima Times of V1260 Tau

HJD +2,400,000	*E*	($O - C$) (days)	Type	Reference
53347.7240	0.0	−0.0983	P	1
53575.8212	42.0	−0.0954	P	1
53578.8459	43.5	−5.2169	S	1
54067.6224	133.5	−5.2138	S	1
54124.3286	143.0	−0.1004	P	1
54409.7555	196.5	−5.2221	S	2
55139.9050	330.0	−0.0866	P	1
55883.9247	467.0	−0.0887	P	1
55946.6788	479.5	−5.2198	S	1
56239.9422	533.5	−5.2204	S	1
56269.5117	538.0	−0.0896	S	1
56964.6589	666.0	−0.0869	P	1
57388.2578	744.0	−0.0916	P	1
57391.2628	745.5	−5.2328	S	1
57385.8155	744.5	−5.2493	S	2
57420.8534	750.0	−0.0809	S	2
57730.4051	807.0	−0.0857	P	1

Note. 1: 1: Paschke & Brat (2006), 2: Asas-sn (2003).

The $O-C$ diagrams for V610 Car, V944 Cep, V2815 Ori and V1260 Tau and the theoretical curves correspond to the apsidal motion parameters in Table 8. The solid and open circles represent individual primary and secondary minima, respectively.

7. Conclusions and Discussion

Considering all available minima times, the $O-C$ analyses of four eclipsing binaries (V610 Car, V944 Cep, V2815 Ori and V1260 Tau) were carried out. First, the minimum times of the systems available in the literature were collected, and the new minimum times obtained from ASAS-3, ASAS-SN and TESS satellite observations were added. The apsidal motion parameters of the systems have been determined by the $O-C$ analyses. This type of analysis for these systems was done for the first time in this study.

V610 Car, V944 Cep, V2815 Ori and V1260 Tau have apsidal motion periods of 188 ± 26 yr, 186 ± 8 yr, 73 ± 3 yr and 182 ± 38 yr, respectively. The rates of change of periastron longitude

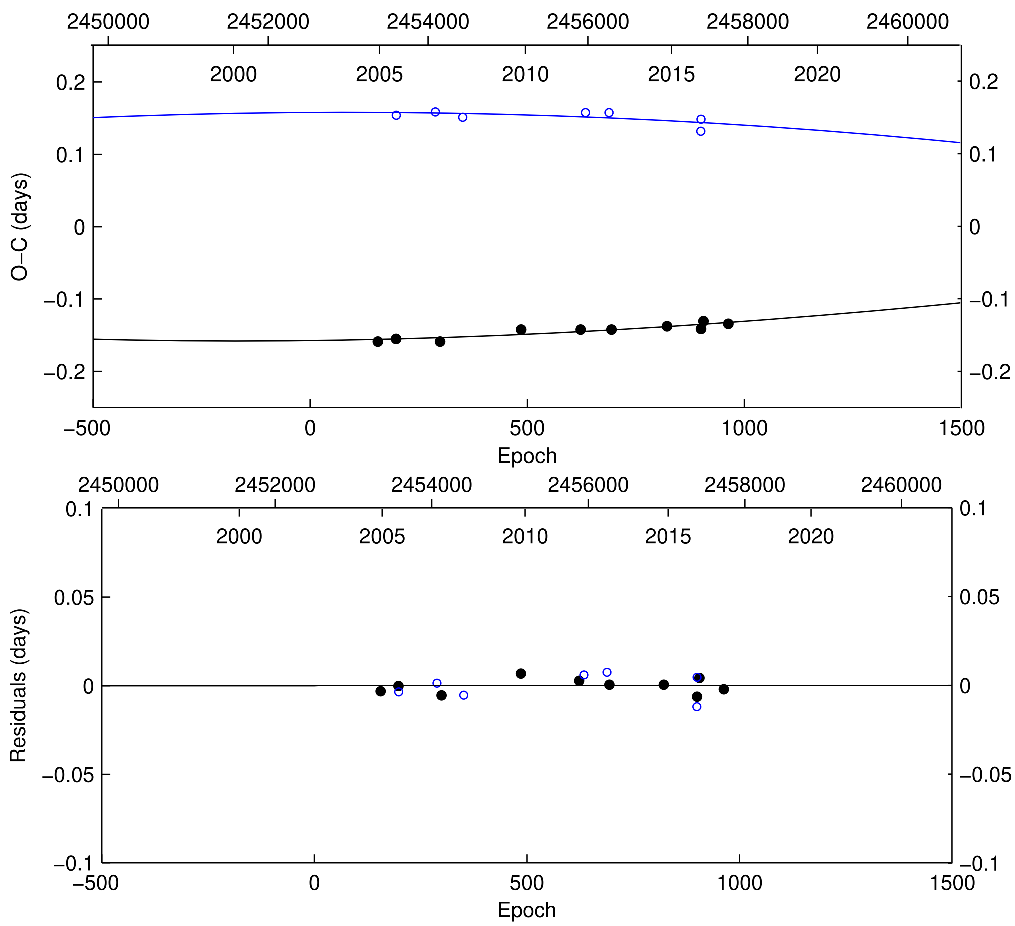

Figure 6. The $O-C$ diagram (upper) and residuals (lower) of V1260 Tau. The labels are as in Figure 1.

Table 8
Apsidal Motion Elements of V610 Car, V944 Cep, V2815 Ori and V1260 Tau

Parameter	V610 Car Value	V944 Cep Value	V2815 Ori Value	V1260 Tau Value
T_0 (HJD)	2,452,501.6153 ± 0.1759	2,452,502.0277 ± 0.0176	2,452,501.2946± 0.0082	2,452,500.6779 ± 0.0884
P_s (days)	4.844900 5 ± 0.0003346	6.560005 9 ± 0.0000226	2.1310162 ± 0.0000071	5.4308012 ± 0.0001355
P_a (days)	4.8452415 ± 0.0003346	6.5606387 ± 0.0000227	2.1311871 ± 0.0000071	5.4312444 ± 0.0001355
e	0.2890 ± 0.0742	0.0541 ± 0.0077	0.0417 ± 0.0064	0.0909 ± 0.0215
$\dot{\omega}$ (deg/cycle)	0.0253 ± 0.0041	0.0347 ± 0.0015	0.0289 ± 0.0010	0.0294 ± 0.0079
ω_0 (deg)	184.1 ± 6.3	43.8 ± 0.7	132.5 ± 0.4	0.9 ± 2.2
U (yr)	188 ± 26	186 ± 8	73 ± 3	182 ± 38

were found to be $0.^{\circ}0253 \pm 0.^{\circ}0041$ cycle^{-1}, $0.^{\circ}0347 \pm 0.^{\circ}0015$ cycle^{-1}, $0.^{\circ}0289 \pm 0.^{\circ}0010$ cycle^{-1} and $0.^{\circ}0294 \pm 0.^{\circ}0079$ cycle^{-1}, respectively. The $O-C$ diagrams and residuals of the systems show no change or indication of a third object. Therefore, future minimum time observations of all systems analyzed in this study are essential in terms of more sensitive determination of apsidal motion periods. Additionally, the first light curve analysis of the system V944 Cep was carried out. The photometric elements were used to estimate first absolute dimensions of the system. The new light curve was modeled with the W-D approach.

Because no spectroscopic measurements were available, the system's absolute properties could not be calculated directly. However, the absolute dimensions of V944 Cep could be calculated using empirical temperature-mass relationships. The main sequence masses of the primary component would be

$M_1 = 1.10 \pm 0.01$ $M_\odot$ for the hotter primary solution and $M_1 = 1.04 \pm 0.01$ $M_\odot$ for the cooler primary solution, based on its temperature (Eker et al. 2015). Using the mass ratios, $q = 1.4979 \pm 0.0023$ for the hotter primary component's solution and $q = 1.5058 \pm 0.0013$ for the cooler primary component's solution, and as given in Table 4, the masses of the secondary component should be $M_2 = 1.64 \pm 0.02$ $M_\odot$ for the hotter primary solution and $M_2 = 1.57 \pm 0.02$ $M_\odot$ for the cooler primary solution. Using Kepler's Third Law and the orbital period ($P = 6.560062$ days), the semimajor axis of the relative orbit can be estimated as $a = 20.61 \pm 3.56$ $R_\odot$ for the hotter primary solution and $a = 20.30 \pm 3.09$ $R_\odot$ for the cooler primary solution. The radii of the primary and secondary components, $R_1 = 2.04 \pm 0.37$ $R_\odot$ and $R_2 = 3.77 \pm 0.67$ $R_\odot$ for the hotter primary solution and $R_1 = 2.26 \pm 0.36$ $R_\odot$ and $R_2 = 3.74 \pm 0.59$ $R_\odot$ for the cooler primary solution, are calculated using the definition of fractional radii as $R_{1,2} = R_{1,2}/a$, and the mean fractional radii from Table 4 are $R_1 = 0.099122 \pm 0.000104$, $R_2 = 0.182825 \pm 0.000254$ for the hotter primary solution and $R_1 = 0.111151 \pm 0.000052$, $R_2 = 0.184127 \pm 0.000136$ for the cooler primary solution.

Table 5 shows the absolute measurements of V944 Cep. Using the values given in Tables 5 and 8 for V944 Cep the observed averaged internal structure constant of the system ($\log_{k2,\mathrm{obs}}$) is derived as $\log_{k2,\mathrm{obs}} = -2.05 \pm 0.01$ for the hotter primary solution and $\log_{k2,\mathrm{obs}} = -1.97 \pm 0.01$ for the cooler primary solution, and the theoretical internal structural constant is expected as $\log_{k2,\mathrm{theo}} = -1.83$ for the hotter primary solution and $\log_{k2,\mathrm{theo}} = -1.89$ for the cooler primary solution (Claret 2006). According to Table 4, since the chi-square value obtained from the light curve solution for the cooler primary component is 0.076, the cooler primary component's solution can be accepted as a more appropriate solution. To confirm the apsidal motion parameters presented above, new times of minima observations for all of the systems are required. The spectroscopic analyses of V610 Car, V944 Cep, V2815 Ori and V1260 Tau can, on the other hand, be extremely useful in determining the internal structural constants.

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