The oEA stars QY Aql, BW Del, TZ Dra, BO Her and RR Lep: Photometric analysis, frequency search and evolutionary status

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Abstract New and complete multi-band light curves of the oEA stars QY Aql, BW Del, TZ Dra, BO Her and RR Lep were obtained and analysed with the Wilson-Devinney code. The light curves residuals were further analysed with the Fourier method in order to derive the pulsation characteristics of the oscillating components. All the reliable observed times of minimum light were used to examine orbital period irregularities. The orbital period analyses revealed secular changes for QY Aql and BW Del, while the Light-Time Effect seems to be the best explanation for the cyclic period changes in TZ Dra and BO Her. RR Lep has a rather steady orbital period. Light curve solutions provided the means to calculate the absolute parameters of the components of the systems, which subsequently were used to make an estimate of their present evolutionary status.

Keywords Methods: data analysis – Methods: observational – stars: binaries:eclipsing – stars: fundamental parameters – stars: variables: δ Scuti – Stars: evolution – stars:individual: QY Aql, BW Del, TZ Dra, BO Her, RR Lep

1 Introduction

Generally, eclipsing binary systems (hereafter EBs) offer unique information for the calculation of stellar absolute parameters and evolutionary status. Especially, the cases of binaries with δ Scuti components are extremely interesting, since they provide additional information (i.e. pulsation characteristics) for this part of the stellar lifetime. It has been shown that the δ Scuti stars in classical Algols (oEA stars) show difference in their pulsational characteristics from time to time due to mass gain (Mkrtichian et al. 2004, 2007). Therefore, the calculation of their absolute parameters and the identification of their oscillating characteristics help us to obtain useful conclusions for this ‘unstable’ part of stellar lifetime. Soydugan et al. (2006a) and Liakos et al. (2012) found a connection between orbital and pulsation periods in these systems and showed that binarity plays an essential role in the evolution of the components. Moreover, Liakos et al. (2012) reported an empirical relation between evolutionary stage and dominant pulsation frequency of the δ Scuti stars in binaries, which differs significantly from that for single ones. Seventy four binaries with δ Scuti components have been discovered so far (Liakos et al. 2012), but their number is increasing with a rapid rate. The present work is the continuation of the survey for candidate EBs with pulsating components (Liakos & Niarchos 2009, 2012; Liakos et al. 2012).

According to the Observed–Calculated times of minima variations (hereafter O–C) analysis, it is feasible to detect which physical mechanisms play a role in the period modulation (e.g. third body existence, mass transfer between the components) of a binary. On the other hand, from the light curve (hereafter LC) analysis it is possible to determine the Roche geometry of the EB (i.e. semi-detached, detached or contact configuration) or detect a third light. The solutions of these analyses are obviously qualitatively and in some cases also quantitatively (e.g. existence of a third body) connected, even though they are based on different methods.

Five eclipsing systems candidate to include a δ Sct component, namely V345 Cyg, BW Del, MX Her, TW Lac and AQ Tau, were selected from the lists of Soydugan et al. (2006b) in order to check them for any possible pulsational behaviour. The results showed that
only BW Del exhibits pulsations, therefore systematic observations were performed in order to obtain its complete LCs. Moreover, short-periodic pulsations in the system LT Her were suspected by Dr. Mkrtchian (private communication), based on his unpublished photometric observations, who kindly suggested us the system for further photometric observations. Our preliminary photometric analysis indeed confirmed the oscillating nature of the primary component and the results will be presented in a future work. Finally, the present work presents results for BW Del and for other four confirmed cases of oEA stars, namely QY Aql, TZ Dra, BO Her and RR Lep, for which systematic observations were also made. For these five cases of oEA stars, initially, we performed LC analysis in order to determine their geometric and absolute parameters. Subsequently, frequency analysis on their LC residuals was made with the aim to reveal their main pulsational properties. In addition, since all systems, except for RR Lep, present orbital period modulations, their O–C diagrams were also analysed. Finally, combining the derived information from the pre-mentioned analyses we obtained a more comprehensive view of these systems. The motivation for the present work was: (a) the lack of accurate and/or modern observations for these systems, especially in multiple bands, (b) their poor coverage of their LCs, (c) the lack of accurate pulsation characteristics and (d) the lack of interpretation of their orbital period changes.

**QY Aql:** The system has an orbital period of \( \sim 7.22956^d \). The radial velocities of its primary component and the mass function of the system were calculated by Struve (1946) and recalculated by Lucy & Sweeney (1971) who found \( K_1 = 36 \text{ km/s} \) and \( f(m) = 0.035 \text{ M}_\odot \), respectively. Giuricin & Mardirossian (1981), based on the photographic LCs of Whitney (1945, 1948), published revised photometric elements of the system but they disputed the past results of \( K_1 \) and \( f(m) \), since both members turned out to be extremely massive. The spectral type of the system is F0 (cf. Budding et al. 2004; Malkov et al. 2006). Modern measurements of the system are given by the ASAS project (Pojmanski et al. 2005), but they contain only a few points which do not cover the whole LCs. Finally, the pulsational behaviour of its primary was reported by Liakos et al. (2012).

**BW Del:** This EB (\( P \sim 2.42313^d \)) was generally neglected. The only available measurement concerns its F2 spectral type (cf. Hanson et al. 2004; Skiff 2010).

**TZ Dra:** The spectral type of this system is A7V (Herbig 1960) and its period has a value \( P \sim 0.86603^d \). Rovithis-Livaniou & Rovithis (1990) reported for the first time that the period of the system is changing. Rovithis-Livaniou et al. (2003) noticed that small light variations, that can be connected either with spot activity or pulsations, occur in the system. A few years later, Rovithis-Livaniou et al. (2005), Mkrtchian et al. (2003) and Mkrtchian et al. (2004) found \( \delta \text{ Sct-type} \) pulsations in the primary component with a pulsation period of \( \sim 28^\text{min} \).

**BO Her:** The orbital period of this eclipsing pair is \( \sim 4.27283^d \) and its spectral type is A7V (Halbedel 1984). The primary’s component oscillating nature was reported by Sumter & Beaky (2007), who found a dominant pulsation period of 1.7871\( ^{hr} \).

**RR Lep:** The system has a period of \( \sim 0.91543^d \). Photoelectric LCs were given by Bookmyer et al. (1986), Abhyankar & Vyas (1989), Vyas & Abhyankar (1989) and Samec et al. (1989). Samec et al. (1989) detected a light variation of \( \sim 45 \text{ min} \), but they did not interpret it as a possible pulsation. A CCD LC of the system in V-filter was published by the ASAS project (Pojmanski et al. 2005), but it is of low quality (i.e. small number of points, large photometric error and incomplete LC). Dvorak (2009), based on his CCD observations, found that pulsations occur in the system with a dominant frequency of 31.87 c/d (\( \sim 45 \text{ min} \)). The spectral type of the system has not been defined so far and ranges between A0-A7 in several catalogues and works (cf. Payne-Gaposchkin 1952; Malkov et al. 2006; Fabricius et al. 2002; Wright et al. 2003; Surkova & Svechnikov 2004).

The absolute parameters of all systems were calculated by Brancewicz & Dworak (1981) (except for QY Aql), based on the photometric parallax method, and Svechnikov & Kuznetsova (1990), who used statistic relations (e.g. mass-radius, mass-luminosity).

## 2 Observations and data reduction

The observations were carried out at the Gerostathopoulos Observatory of the University of Athens (\( At \),

| System | \( m_{\text{min}} \) (mag) | S.T. | \( F \) | \( N \) hrs | \( f_{\text{dom}} \) (c/d) | Inst |
|--------|----------------------|------|-----|---------|-----------------|-----|
| QY Aql | 11.4                 | F0a  | B   | 36      | 211             | K&At |
| V345 Cyg | 11.3               | A1b  | B   | 2       | 9               | K   |
| BW Del | 11.4                 | F2b  | BV  | 18      | 86              | K&At |
| TZ Dra | 9.6                  | A7b  | BV  | 6       | 33              | 50.993 |
| BO Her | 10.7                 | A7d  | BVI | 25      | 125             | 13.430 |
| LT Her | 10.7                 | A2b  | BV  | 5       | 20              | 30.521 |
| MX Her | 11.4                 | F5b  | B   | 2       | 12              | K&At |
| TW Lac | 11.5                 | A2b  | B   | 2       | 10              | At   |
| RR Lep | 10.2                 | A7b  | BV  | 9       | 30              | 33.280 |
| AQ Tau | 12.0                 | A5b  | B   | 1       | 4.5             | At   |

\(^a\text{Watson et al. (2006).} \(^b\text{Malkov et al. (2006).} \(^c\text{Samus et al. (2011).} \(^d\text{Halbedel (1984).} \)
using the 0.4 m Cassegrain telescope equipped with various CCD cameras and the BVRI (Bessell specification; Bessell 1990) photometric filters. In particular, all systems were observed with the ST-10XME CCD, except for TZ Dra for which the ST-8XEI CCD was used. Additional observations were also made at the Kryonerion Astronomical Station (K) of the Astronomical Institute of the National Observatory of Athens located at Mt. Kyllini, Corinthia, and the 1.2 m Cassegrain telescope equipped with the Ap47p CCD and the Bessell BVRI filters set.

Aperture photometry was applied to the raw data and differential magnitudes were obtained using the software MuniWin v.1.1.29 (Hroch 1998). For the cases of BW Del, TZ Dra and BO Her, where field stars exist close to the variables, we chose the photometry apertures with high caution in order to avoid any photometric contribution to the background measurements. The adopted observational strategy in this survey regarding the candidate oscillating binaries was the same as that described in detail in the first paper (Liakos & Niarchos 2000). Briefly, the observational guidelines were: i) the time span should be greater than 3 hr, ii) the filter B and/or V should be used, iii) the comparison star should be of similar magnitude and spectral type to the variable, iv) appropriate exposure times and binning modes must be used for the highest possible photometric S/N (signal-to-noise ratio), and v) the observations should be made outside the primary eclipse.

The log of observations for all systems is listed in Table 1 which contains: their brightest apparent magnitude $m_{\text{min}}$, their spectral type ST, the filters F used, the number of nights N and the total hours hrs spent, the dominant pulsation frequency $f_{\text{dom}}$ found (for details see Section 5) and the instrumentation used Inst. Table 2 includes information only for the systems which were observed systematically and pulsations were detected. Particularly, we list: the number of nights spent, the date range and the time span T.S. of the observations, the number of points collected per filter and their mean photometric error sd, and the comparison C and check stars K used in the photometry.

### 3 Light curve analysis

Complete LCs of each system were analysed simultaneously, using all individual observations, with the PHOEBE v.0.29d software (Prša & Zwitter 2005) that is based on the Wilson-Devinney (W-D) code (Wilson & Devinney 1971, 1973, 1990). In the absence of spectroscopic mass ratios, the ‘q-search’ method (cf. Liakos & Niarchos 2012) was applied in modes 2 (detached system), 4 (semi-detached binary with its primary component filling its Roche lobe) and 5 (conventional semi-detached binary) to find feasible (‘photometric’) estimates for the mass ratio. This value of q was set as adjustable parameter in the subsequent analysis. The temperatures of the primaries $T_1$ of all systems, except for RR Lep, were assigned values according to the spectral class-temperature correlation (Cox 2000) and were kept fixed during the analysis, while the temperatures of secondaries $T_2$ were adjusted. The values of bolometric albedos $A$ and gravity darkening coefficients $g$ were given standard theoretical values according to the adopted type of stellar atmosphere, namely $A=1$ and $g=1$ for radiative (Rucinski 1969; von Zeipel 1924), and $A=0.5$ and $g=0.32$ for convective atmospheres (Rucinski 1969, Lucy 1967). The (linear) limb darkening coefficients $x_1$ and $x_2$, were taken from van Hamme (1993); the dimensionless potentials $\Omega_1$ and $\Omega_2$, the fractional luminosity of the primary component $L_1$ and the system’s orbital inclination $i$ were set as adjustable parameters.

Since the spectral type of RR Lep ranges between A0-A7, the above analysis’ steps were made for different values of $T_1$ and the final solution was selected according to the least value of squared residuals.

### Table 2: Detailed observations log of systems with a pulsating component.

| System | Nights spent | Obs. dates T.S. | Number of points/sd | Comparison stars | m$_V$ (mag) |
|--------|--------------|----------------|---------------------|-----------------|-------------|
|        |              |               | B      | V      | I      |                     |                     |
| QY Aql | 36           | 28/06-15/09   | 97     | 3255/3.8 | 3136/3.4 | 3159/3.2 | C: TYC 1618-1286-1 | 11.3$^a$ |
|        |              | of 2011       |        |        |        |                     |                     |
| BW Del | 18           | 01/09-26/10   | 55     | 1791/3.8 | 1760/4.5 | –          | C: TYC 1635-1273-1 | 11.4$^a$ |
|        |              | of 2011       |        |        |        |                     |                     |
| TZ Dra | 6            | 02/07-20/07   | 19     | 2108/4.3 | 2107/3.5 | –          | C: TYC 3529-0198-1 | 9.51$^a$ |
|        |              | of 2008       |        |        |        |                     |                     |
| BO Her | 25           | 28/05-06/07   | 39     | 1992/3.8 | 1920/3.5 | 1881/3.3 | C: TYC 2111-0124-1 | 11.3$^a$ |
|        |              | of 2011       |        |        |        |                     |                     |
| RR Lep | 9            | 17/01-16/03   | 59     | 1035/2.8 | 991/2.7  | –          | C: TYC 5342-0022-1 | 9.6$^a$  |
|        |              | of 2012       |        |        |        |                     |                     |

$^a$Høg et al. (2000), $^b$Høg et al. (1998)
Table 3  Light curve (upper part) and absolute parameters (lower part) for all systems. Formal errors are indicated in parentheses alongside adopted values.

| Parameter            | QY Aql | BW Del | TZ Dra | BO Her | RR Lep |
|----------------------|--------|--------|--------|--------|--------|
| Light curve parameters |        |        |        |        |        |
| $i$ (°)              | 88.6 (5) | 78.6 (4) | 77.6 (1) | 85.4 (4) | 80.3 (9) |
| $q$ ($m_2/m_1$)      | 0.25 (2) | 0.16 (2) | 0.31 (3) | 0.22 (2) | 0.23 (2) |
| Component            | P      | S      | P      | S      | P      |
| $T$ (K)              | 7300$^a$ | 4244 (122) | 7000$^a$ | 4061 (30) | 7800$^a$ |
| $\Omega$             | 5.19 (6) | 2.34$^b$ | 4.61 (6) | 2.14$^b$ | 3.46 (1) |
| $x_V$                | 0.569 | 0.856 | 0.493 | 0.823 | 0.523 |
| $x_I$                | 0.385 | 0.584 | – | – | – |
| $(L/L_T)_B$          | 0.942 (1) | 0.058 (1) | 0.963 (1) | 0.037 (2) | 0.924 (1) |
| $(L/L_T)_V$          | 0.896 (1) | 0.104 (1) | 0.932 (1) | 0.068 (1) | 0.889 (1) |
| $(L/L_T)_I$          | 0.773 (1) | 0.227 (1) | – | – | 0.730 (3) |
| Absolute parameters  |        |        |        |        |        |
| $M$ ($M_\odot$)      | 1.6 (2)$^a$ | 0.4 (1) | 1.5 (2)$^a$ | 0.3 (1) | 1.8 (2)$^a$ |
| $R$ ($R_\odot$)      | 4.1 (2) | 5.4 (2) | 2.1 (1) | 2.2 (1) | 1.7 (1) |
| $L$ ($L_\odot$)      | 43 (3) | 8 (1) | 10 (1) | 1.2 (1) | 9 (1) |
| $\log g$ (cm/s$^2$)  | 3.4 (1) | 2.6 (1) | 4.0 (1) | 3.1 (1) | 4.2 (1) |
| $\alpha$ ($R_\odot$) | 4.0 (2) | 16.3 (7) | 1.3 (1) | 8.0 (4) | 1.2 (1) |

*assumed, $^a$fixed, $^bL_T = L_1 + L_2$, P=Primary, S=Secondary

Fig. 1  Synthetic (solid lines) and observed (points) light curves of (a) QY Aql, (b) BW Del, (c) TZ Dra.

Fig. 2  Synthetic (solid lines) and observed (points) light curves of (a) BO Her and (b) RR Lep.

All primaries were adopted as radiative and all secondaries as convective stars according to their temperature values, therefore we set $A_1=1$, $A_2=0.5$, $g_1=1$ and $g_2=0.32$. In the cases of TZ Dra and BO Her the relative luminosity contribution $l_3$ of a possible third light was left free due to possible existence of tertiary components (see Section [6]). Nevertheless, it resulted in unrealistic values for both systems, therefore it was excluded from the final solutions. Finally, all systems were found to be in semi-detached configurations with their cooler and less massive components filling their
Fig. 3 Positions of the systems' components (P=Primary, S=Secondary) in the $M-R$ diagram.

Roche lobes. Observed LCs and their modelling are illustrated in Figs 1-2 with corresponding parameters listed in Table 3.

4 Absolute parameters and evolutionary status of the components

Although no radial velocity measurements exist for the systems studied, we can form fair estimates of their absolute parameters. Since there is no trustworthy information in the literature (see Section 4) regarding the methods used for the determination of their absolute parameters, the masses of the primaries were assumed according to their spectral types using the correlations of (Cox 2000). A fair error of $\sim 10\%$ of the mass value was also assumed in order to obtain more realistic conclusions. The secondary masses follow from the determined mass ratios (see Table 3) and the semi-major axes $a$ are then derived from Kepler’s third law. The errors were calculated using the error propagation method. The parameters are listed in Table 3 and the positions of the systems’ components in the $M-R$ diagram are given in Fig. 3. The theoretical lines for Zero Age Main Sequence (ZAMS) and Terminal Age Main Sequence (TAMS) were taken from Niarchos & Manimanis (2003).

The primary of TZ Dra is located closer to the ZAMS, while the primary of RR Lep closer to the TAMS. The primary of BO Her was found to be exactly on the TAMS, while the primaries of BW Del and QY Aql have left the MS. All secondaries are evolved stars lying far beyond the TAMS limits.

5 Frequency analysis

The pulsating components of the systems are the primaries, since their temperatures are well inside the range of $\delta$ Scuti type stars (A-F spectral types). For the frequency search, the theoretical LCs of the eclipsing binary model were subtracted from the respective observed data. Frequency analysis was performed on the LC residuals on the out of primary eclipse data with the software PERIOD04 v.1.2 (Lenz & Breger 2005), that is based on classical Fourier analysis. Given that typical frequencies for $\delta$ Scuti stars range between 3-80 c/d (Breger 2000, Sovdzhan et al. 2006), the analysis was made for this range. Frequencies in the range 0-3 c/d were considered as non-physical, and they were excluded from the final model. After the first frequency computation the residuals were subsequently pre-whitened for the next one, until the detected frequency had $S/N < 4$, which is the programme’s critical trustable limit. The errors were calculated using analytical simulations. The $l$-degrees of the pulsation modes were identified with the software FAMIAS v.1.01 (Zima 2003) that is based on theoretical $\delta$ Scuti models (MAD - Montalban & Dupret 2007). However, the $l$-degrees determination, using only photometric data, is strongly based on the information from various wavelength bands. Since we used only two or three filters for these systems, the $l$-degrees calculations can be considered as preliminary. Frequency analysis results are given in Table 4 where we list: frequency values $f$, $l$-degrees, semi-amplitudes $A$, phases $\Phi$ and $S/N$. Amplitude spectra, spectral window plots and Fourier fits on the longest data sets are given in Fig. 4.

For QY Aql one pulsation frequency ($\sim 10.656$ c/d) was detected. For its adopted mass value, there is no theoretical $\delta$ Scuti model for determining the $l$-degree, therefore, we tested another slightly higher mass values. We found that the $l$-degree can be calculated using a mass of $1.9 M_{\odot}$.

TZ Dra is found to oscillate in a mono-periodic mode with a frequency value $\sim 50.994$ c/d, while its $l$-degree was calculated using the adopted mass value.

Three oscillation frequencies were found for BW Del with the most dominant one at $\sim 25.100$ c/d. The $l$-degrees were determined using a mass value of $1.6 M_{\odot}$, which is inside the limits of the adopted error. Two pulsation frequencies were identified for BO Her and RR Lep. However, for BO Her the frequencies $f_2$ and $f_4$ are the first and second harmonics of $f_1$, respectively, while $f_2$ and $f_4$ were found below the significance limit in $I$-filter data and they are excluded from the final solution. The $l$-degrees for both systems were calculated using the mass values given in Table 3.

6 Orbital period analysis

Since all systems, except for RR Lep, show interesting period changes, $O-C$ diagram analysis was per-
Fig. 4 Amplitude spectra (left panels) where the detected frequencies, the significance level (4σ) and spectral window plots (internal panels) are indicated, and Fourier fits on the longest data sets (right panels) for: (a) QY Aql, (b) BW Del, (c) TZ Dra, (d) BO Her and (e) RR Lep.
formed in order to find the mechanisms forming their orbital periods. TZ Dra and BO Her show cyclic period modulations, therefore the Light–Time Effect (hereafter LITE) (Woltjer 1922; Irwin 1959) and the Applegate’s mechanism (Applegate 1992) were tested. On the other hand, QY Aql and BW Del present secular period changes, so the mechanisms of mass transfer and mass loss due to possible magnetic braking effect were examined for implications in their orbital period.

Computation of the LITE parameters is a classical inverse problem for several derivable parameters; namely, period $P_3$ and eccentricity $e_3$ of the third body’s wide orbit, HDJ of the periastron passage $T_0$, semi-amplitude $A$ of the LITE and argument of periastron $\omega_3$. The ephemeris parameters ($JD_0$ and $P$ for the linear form and $C_2$ for the quadratic) were calculated together with those of the LITE. The LITE mass function $f(M_3)$ (cf. Liao & Qian 2009):

$$ f(M_3) = \frac{1}{P_3^3} \left[ \frac{173.145 A}{\sqrt{1 - e_3^2 \cos^2 \omega_3}} \right]^3 \frac{(M_3 \sin i_3)^3}{(M_1 + M_2 + M_3)^2} $$

(1)

with the wide orbit’s period $P_3$ in yr, and the LITE amplitude $A$ in days, therefore produces the minimal mass of the tertiary component $M_{3, \text{min}} = M_3 \sin i_3$ (with $i_3 = 90^\circ$). Late type components of EBs can be expected to present magnetic activity. The observed cyclic period changes may therefore come from variation of the magnetic quadrupole moment $\Delta Q$ (Applegate 1992). Applegate & Patterson (1985) and Rovithis-Livanio et al. (1994) suggested the following formulae, respectively, for the $\Delta Q$ calculation:

$$ \frac{\Delta P}{P} = -9 \frac{\Delta Q}{M a^2}, \quad (2) $$

$$ \Delta P = A \sqrt{2[1 - \cos(2\pi P/P_3)]}, \quad (3) $$

where $P$ and $a$ are the binary’s period and semi-major axis, respectively, $P_3$ and $A$ the period and the semi-amplitude of the variation, respectively, and $M$ the mass of the potential magnetically active star (i.e. the secondary components of the studied cases). According to Lanza & Rodon (2002), magnetic activity results in detectable period modulation when $\Delta Q$ ranges between $10^{55} - 10^{56}$ g cm$^2$.

Mass transfer as well as mass and angular momentum loss due to magnetic braking are mechanisms that produce secular orbital period changes (Hilditch 2001). The O–C analysis derives the quadratic term $C_2$ that can be used to calculate the orbital period change rate $\dot{P}$. Using the derived $\dot{P}$ and the parameters of the system’s components, the mass transfer $\dot{M}_{tr}$ ($> 0$ for classical Algols) and the mass loss $\dot{M}_{\text{loss}}$ ($< 0$) rates can follow using the following formulae of Hilditch (2001) (i.e. for conservative mass transfer) and Erdem et al. (2005) (i.e. for mass loss due to magnetic braking and mass transfer between the components), respectively:

$$ \dot{M}_{tr} = \frac{\dot{P}}{3P} \frac{M_1 M_2}{M_1 - M_2}, \quad (4) $$

$$ \frac{\dot{P}}{3P} = k^2 \left( \frac{r_A}{a} \right)^2 \frac{M_1 + M_2}{M_1 M_2} \dot{M}_{\text{loss}} + \frac{M_2 - M_1}{M_1 M_2} \dot{M}_{tr}, \quad (5) $$

where $k$ is the gyration constant of the mass looser, $r_A$ is the Alfvén radius, $a$ is the semi-major axis of the system’s orbit, and $M_1$, $M_2$ the masses of the components.
Table 5  O–C diagram analyses results. The errors are indicated in parentheses alongside adopted values.

| Parameters               | QY Aql        | BW Del        |
|--------------------------|---------------|---------------|
|                          |                |               |
| Eclipsing binary         | 37453.205 (1) | 37375.460 (1) |
| JD (HJD-2400000)         | 7.229560 (1)  | 2.423133 (3)  |
| P (d)                    | -191 (8)      | 40 (5)        |
| $C_2$ ($\times 10^{-10}$ d/cycle) | -19 (1) | 12 (2) |
| $\dot{M}_{tr}$ ($\times 10^{-8}$ $M_{\odot}$/yr) | 1$^a$ | 5.0 (6) |
| $\dot{M}_{loss}$ ($\times 10^{-8}$ $M_{\odot}$/yr) | -3.2 (1) | – |
|                          | TZ Dra        | BO Her        |
| LITE and third body      | 33852.346 (2) | 41884.620 (2) |
| $T_0$ (HJD-2400000)      | 0.8669033 (1) | 4.272834 (2)  |
| $\omega_3$ (°)           | 167 (10)      | 76 (40)       |
| $A$ (d)                  | 0.012 (1)     | 0.028 (2)     |
| $P_3$ (yr)               | 62 (3)        | 31.3 (7)      |
| $e_3$                    | 0.5 (1)       | 0.2 (1)       |
| $f(M_3)$ ($M_{\odot}$)  | 0.0036 (1)    | 0.111 (1)     |
| $M_{3,\text{min}}$ ($M_{\odot}$) | 0.29 (1) | 1.06 (1) |
| Quadrupole moment variation | $\Delta Q$ ($\times 10^{30}$ g cm$^2$) | 1.1 | 14 |

$^a$assumed

62 times of minima for QY Aql, 48 for BW Del, 171 for TZ Dra, and 40 for BO Her, taken from literature and minima database, were used for the O–C analyses. The systems’ ephemerides of Kreiner et al. (2001) were used to compute, initially, the O–C points from all the compiled data. The analysis was based on least squares method with statistical weights on a MATLAB code (Zasche et al. 2009). Weights were set at $w = 1$ for visual, 5 for photographic and 10 for CCD and photoelectric data. In Fig. 5 full circles represent times of primary minima and open circles those of the secondary minima, where the bigger the symbol, the bigger the weight assigned. The corresponding parameters of the solutions are listed in Table 5.

The O–C points of TZ Dra and BO Her show cyclic distribution, therefore the LITE and the Applegate’s mechanisms were tested by fitting the respective periodic curves. Moreover, a parabolic term, in accordance with the potential mass transfer from the secondary to the primary (i.e. conventional semidetached configurations; see Section 3), was also tested in the fittings, but it resulted in unrealistic values, hence we excluded it. BO Her was found to have $\Delta Q$ value marginally outside the range that can produce cyclic period changes (Lanza & Rodon` o 2002), therefore, the LITE seems to be the most possible explanation for its orbital period modulations. On the contrary, both the LITE and the Applegate’s mechanism can explain the cyclic period changes of TZ Dra.

For BW Del and QY Aql a parabola was chosen for fitting their O–C points, since mass flow from the secondaries to the primaries is expected to occur in accordance with the secondaries’ Roche lobe filling (see

http://var.astro.cz/ocgate/
Section 3. BW Del indeed shows a secular period increase due to mass transfer from its less to its more massive component. Although we expected the same for QY Aql, it was found that its period decreases with a rapid rate. However, the observed period changes can be interpreted with a combination of two mechanisms, namely the magnetic braking effect of the secondary component, which causes mass loss from the system, and the mass transfer from the secondary to the primary. A similar case (BG Peg) regarding the geometrical shape, absolute parameters, evolutionary stage and orbital period modulations. These systems are confirmed as classical Algols with their primaries showing δ Sct type pulsations. Therefore, according to the definition given by Mkrtichian et al. (2004), they can also be considered as oEA systems. LT Her was also identified as an EB including a δ Sct type member, but the detailed results will be presented in the future. Four other EBs, candidates for including δ Sct components, namely V345 Cyg, MX Her, TW Lac and AQ Tau, were also checked for pulsations but the results were negative.

The primary component of QY Aql is located beyond the TAMS and pulsates with a frequency of ∼ 10.656 c/d. The decreasing orbital period rate of the system is well explained with the mass transfer process from the secondary to the primary component, which is supported by its conventional semi-detached geometrical status, and the mass loss due to magnetic braking of its secondary, which was found to be at the giant stage of evolution. A mass loss rate of 3.2 × 10^{-8} M_{⊙}/yr, typical for red giants (Hilditch 2001), was estimated.

Three pulsational frequencies were detected for the primary of BW Del, with the most dominant one at 25.1 c/d. Based on the adopted mass and the derived radius, the star is located beyond the TAMS, but very close to it. The secondary component was found to be very evolved and it transfers material to the primary with a rate of 5 × 10^{-8} M_{⊙}/yr.

The primary component of TZ Dra is a relatively fast pulsator with a frequency of ∼ 50.99 c/d and is located near the ZAMS. The frequency analysis results are in agreement with those of Mkrtichian et al. (2005). Based on its frequency value and its evolutionary status we conclude that its oscillating lifetime must have started recently, according to the evolutionary stage-pulsation period empirical relation for this kind of stars (Liakos et al. 2012). The secondary component of the system has filled its Roche lobe and is located beyond the TAMS. The cyclic changes of the system’s period are caused probably due to a tertiary component with a period of ∼ 62 yr and a minimal mass of ∼ 0.3 M_{⊙}. On the other hand, the LC analysis did not reveal any third light. However, assuming that the third body is a MS star, and based to the mass-luminosity relation for dwarfs (L ∼ M_{3.5}), we can calculate its luminosity and compare it with the absolute luminosity values of the binary’s members (see Table 3) by using the following formula:

\[ L_{3, O-C}(\%) = 100 \frac{M_{3, min}^{3.5}}{L_1 + L_2 + M_{3, min}^{3.5}} \]  

We found that the expected luminosity contribution of such a third star should be ∼0.14%, hence its light absence is plausible. However, according to the value of ΔQ (∼ 10^{50} g cm^2), it is possible that the period changes can be caused due to magnetic influence of the secondary component. Applegate’s mechanism predicts also brightness changes of the system, but this has not been verified so far. Therefore, future photometric observations covering several decades and/or astrometric observations are needed in order to conclude about the mechanism that forms the binary’s orbital period.

For the oscillating member of BO Her we traced two pulsation frequencies with the dominant one at 13.43 c/d. This results agrees with that of Sunter & Beaky (2007). Due to the relatively high amplitude of this mode, its first two harmonics of its pulsation frequency were also detected in the frequency spectrum. The primary (pulsating) component of the system is located on the TAMS edge. On the other hand, the secondary is located far beyond the TAMS, being at the giant stage of evolution. A third body with a minimal mass of ∼ 1.1 M_{⊙} and a period of ∼ 31 yr may exist around the EB, but we did not detect any additional luminosity in the LC analysis. Following the same method as for the case of TZ Dra, we found an expected luminosity contribution ∼5%, which is large enough to be
detected photometrically. The most possible explanation for this disagreement could be either the non-MS nature of the third body (e.g. exotic object) or that the third body is in fact a binary with two low-mass and low-temperature components, providing lower luminosity in total, instead of a single star. Future spectroscopic and/or astrometric observations are desirable in order to solve this mystery.

The primary component of RR Lep pulsates in two modes with the dominant frequency at $28.6$ c/d and it is located on the MS and very close to the TAMS. The present results regarding the frequency $f_1$ are in marginal agreement with those of Dvorak (2009), who found only one pulsation frequency of $31.87$ c/d. However, our results are based on two-filter data which were obtained with better equipment in comparison with that used by Dvorak (2009). The secondary of the system is a rather more evolved star located above the TAMS.

The O–C points distributions of TZ Dra, BO Her and RR Lep do not show any secular period changes that can be connected with mass transfer. Very probably, these systems are at slow mass-accretion stage (Mkrtichian et al. 2003) with a rate that cannot be detected with the current time coverage of minima timings.

Liakos et al. (2012), based on the pulsational and absolute parameters of the $\delta$ Sct components of all known oEA stars, derived empirical relations between the dominant pulsation period $P_{\text{puls}}$ and the gravity acceleration value $g$ and between the $P_{\text{puls}}$ and the orbital period $P_{\text{orb}}$ of the systems. Therefore, it is useful to check if the respective values of the pulsating components of the systems analysed herein follow these trends, and this is shown in Fig. 6.

The pulsating stars of all systems seem to follow well the $P_{\text{puls}} - P_{\text{orb}}$ and $g - P_{\text{puls}}$ trends, with the exception of the primary of QY Aql in the $g - P_{\text{puls}}$ diagram. This star is at the subgiant evolutionary stage. On the other hand, the sample, in which the empirical relation of $g - P_{\text{puls}}$ is based, consists mostly of MS stars. Therefore, QY Aql, with the longest orbital period and minimum $g$-value in the sample of Liakos et al. (2012), might have followed a different evolutionary track or another relation between $g - P_{\text{puls}}$ for the evolved oEA stars has to be examined.

Radial velocities measurements for all systems are needed in order to determine their absolute parameters and the $l$-degrees of their pulsation modes with higher certainty. Moreover, more precise photometric observations (e.g. space data) are expected to reveal additional pulsation frequencies that could not be detected with the present instrumentation setup. Future surveys aiming to new discoveries of this kind of systems and long-term monitoring of the already known ones are highly encouraged in order to enrich our knowledge about the mass transfer implication in the pulsation mechanisms and, in general, about the stellar evolution of binaries with A-F components.

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