PHOTOMETRIC, SPECTROSCOPIC, AND ORBITAL PERIOD STUDY OF THREE EARLY-TYPE SEMI-DETACHED SYSTEMS: XZ AQL, UX HER, AND AT PEG

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ABSTRACT

In this paper, we present a combined photometric, spectroscopic, and orbital period study of three early-type eclipsing binary systems: XZ Aql, UX Her, and AT Peg. As a result, we have derived the absolute parameters of their components and, on that basis, we discuss their evolutionary states. Furthermore, we compare their parameters with those of other binary systems and with theoretical models. An analysis of all available up-to-date times of minima indicated that all three systems studied here show cyclic orbital changes; their origin is discussed in detail. Finally, we performed a frequency analysis for possible pulsational behavior, and as a result we suggest that XZ Aql hosts a δ Scuti component.

Key words: binaries: eclipsing -- stars: individual (XZ Aql, UX Her, AT Peg)

Supporting material: data behind figures

1. INTRODUCTION

Classification of eclipsing binaries is performed according to the physical and evolutionary characteristics of their components, in addition to the shapes of their light curves. The degree to which their inner critical equipotential surfaces (Roche lobes) have been filled is a critical parameter for their classification, which helps in the understanding of their physical nature. Semi-detached binaries constitute an important class of objects, with one component filling its Roche lobe. The shape of a typical semi-detached binary light curve is an Algol-type light variation. These objects are important in understanding this stage of evolution when the mass transfer starts to take place and alters the evolution of the components as single stars. Whether or not one or both of the components are in contact with their Roche lobes or very close to filling them is very important in understanding the evolution of interacting binary systems. In order to achieve this goal, light and radial velocity observations are analyzed to determine their absolute parameters (temperatures, masses, radii, and surface potentials, in particular). If the mass transfer has begun in these systems at some point during their evolution, it also manifests itself as orbital period changes because a transfer of mass would alter a system’s moment of inertia.

In this study, we present the results of light curve and period change analyses of three Algol-type binary systems: XZ Aql, UX Her, and AT Peg. We derive their absolute parameters from the analysis of their light and radial velocity curves that we obtained at two different observatories. We analyze the differences between the observed (O) and the calculated (C) eclipse timings, occurring due to the changes in their orbital period, by constructing O–C diagrams. We also perform a frequency analysis to investigate the potential pulsation signals in the data of the studied systems. Finally, we discuss the evolutionary states of the components of these systems on Hertzsprung–Russell, mass–luminosity, and mass–radius diagrams (hereafter HRD, MLD, and MRD, respectively). Such thorough analyses for these systems are performed for the first time in this study.

2. SYSTEMS

2.1. XZ Aql

XZ Aql (HD 193740, BD−07° 5271, GSC 5174-108, SAO 144345) is an Algol-type eclipsing binary. It was discovered by Cannon (1922). The first detailed description of the light curve (without a plot) was presented by Witkowski (1925). Erlekosova (1959) was the first (and, so far, the only one) to present the graphical light curve and give the first discussion of the O–C diagram. She proposed two alternative models of the period variation: first, as an abrupt change between JD 2430000 and 2433000, and second as an increase at a constant rate. Pokorný & Zlataška (1976) discussed the same subject, using a larger number of eclipse timings. Wood & Forbes (1963) and Samolyk (1996) noted a quadratic term in the ephemeris. A detailed discussion of the shape of the O–C diagram was given by Soydugan et al. (2006). They modeled the variation with a sinusoidal superimposed on a secular parabolic change. They attributed the sinusoid variation to the light time effect caused by an unseen third body, and the secular term to a conservative mass transfer from the less massive component to the more massive one, which had already been noted by previous studies. The orbital period of the hypothetical third body was $P_3 = 36.7 ± 0.6$ year. The spectral type of XZ Aql is A2, as found by Cannon (1922) when the star was discovered. Neither the mass ratio, based on radial velocity observations, nor any light curve solution have been published until now.


### 2. UX Her

The UX Her (HD 163175, BD+16° 3311, HIP 87643, SAO 103195, GSC 01557-01268) system was discovered by Cannon (Pickering 1908), who found its spectral type as B9 or A. Zinner (1913) confirmed the discovery and determined the correct period of the system. Later, Tsesevich (1944, 1954), Kaho (1952), Kurzemnetse (1952), Ashbrook (1952), and Koch & Koch (1962) revised the elements. Gordon & Kron (1963, 1965) published the first light curve solution based on the spectroscopic orbit determined by Sanford (1937) and their own photometric observations. They proposed that the secondary was an evolved, low-mass, late-type star. Hill et al. (1975) estimated the primary component’s spectral type as A0V–A3V for different orbital phases. Following the light curve studies of Cester et al. (1979), Mardirossian et al. (1980), and Giuricin & Mardirossian (1981), Lazaro et al. (1997) analyzed the first infrared light curves of the system in the J, H, and K bands, together with published B and V band light curves of Gordon & Kron (1965). They determined the parameters of the system and found that none of the components of the binary filled their Roche lobes. Although UX Her is a short-period system, they assigned it to a category of slightly detached systems, most of which, as they pointed out, were long-period systems. Djurašević et al. (2006) computed the mass ratio \( q = m_2/m_1 = 0.248 \) as the result of the \( q \)-search method. When combined with the results of their \( B \) and \( V \) band light curve analysis, this mass ratio value suggests a semi-detached configuration of UX Her.

Kurzemnetse (1952) noted for the first time that the period was variable. Tremko et al. (2004) first published a period variation study of the system, which excluded a mass transfer between the components as the cause of the observed variations in the orbital period of the system, since neither of the stars filled their Roche lobes according to their interpretation. They proposed that a low-mass (0.3 \( M_\odot \)) unseen companion, bound to the system, was causing the period to change periodically.

### 2.3. AT Peg

Cannon (Cannon & Pickering 1924) published the first spectroscopic observation of AT Peg (HD 210892, BD+07° 4824, SAO 127380, GSC 1137-185), and determined its spectral type as A0. The variability of the system was first announced by Schneller (1931), who identified it as an Algol-type binary. Guthnick & Prager (1931), Rügemer (1934), Lassovszky (1935), Cristaldi & Walter (1963), Wood & Forbes (1963), Obůrka (1964a, 1964b, 1965), and Cristaldi & Walter (1965) published their photometric observations and revised the light elements. Hill & Barnes (1972) published the orbital elements of the system based on the first detailed spectroscopic observations and determined the spectral type as A7 V. They found the mass ratio \( m_1/m_2 \) to be 2.4 and the orbital inclination to be 76°7. Gülmen et al. (1993) found that AT Peg was a semi-detached binary with a later type subgiant secondary component filling its Roche lobe. Maxted et al. (1994) obtained spectra of the system and determined a spectroscopic mass ratio of 2.115 \( (m_1/m_2) \), smaller than the one determined by Hill & Barnes (1972) from photographic plates. They determined absolute parameters of the system using the photometric observations of Cristaldi & Walter (1963). They also classified the spectral type of the primary component (A4 V) from a combined spectrum of their data, which was consistent with the temperature estimates obtained from the Strömgren photometry by Hilditch & Hill (1975). The configuration of the system as a semi-detached eclipsing binary has been widely accepted since this study and that of Giuricin et al. (1981).

Svedoff (1951) was the first to notice that the orbital period was variable. Although the secular change in the eclipse timing variations has been noted by recent studies (Margrave 1981; Gudur et al. 1987; Hanna 2012; Liakos et al. 2012a), Liakos et al. (2012a) also noticed the discrepancy between the configuration and the direction of the mass transfer. They suggested either mass loss via stellar winds or system angular momentum loss via magnetic braking as possible explanations. Periodic variations in the O–C diagram have also been noted and attributed to unseen third bodies with parameters differing from one study to another (Borkovits & Hegedus 1995, 1996; Liakos et al. 2012a), or to magnetic activity with single (Sarna et al. 1997) or multiple cycles (Hanna 2012). However, there is no firm evidence for strong magnetic activity other than enhanced X-ray emission (Hanna 2012).

### 3. OBSERVATIONS

Between 2012 and 2013, we performed photometric observations of XZ Aql, UX Her, and AT Peg using the 40 cm Cassegrain telescope (f/5 using a focal reducer) of the Gerostathopoulion Observatory of the University of Athens (UoA Observatory). This setup results in a field of view (FOV) of \( 17 \times 26 \) arcmin. The telescope was equipped with with an SBIG ST-10 XME CCD detector and a set of \( BVRI \) filters (Bessell specifications) in order to perform multi-band photometry. We present a log of our observations in Table 1.

The ephemerides of all systems (see Table 2) were calculated using the least squares method on the minima timings derived from our observations and the most recent ones taken from the literature. The photometric data sets were reduced with dark and flat frames which were gathered before or after each observing run, while image reduction as well as differential aperture photometry were performed using either C-munipack.
Table 2

| System | Epoch ($T_0$) (HJD+2400000) | Period (days) | $m_v$ (mag) | $(B-V)$ (mag) | Comparison | Check |
|--------|-----------------------------|--------------|-------------|---------------|------------|-------|
| XZ Aql | 52501.0881                  | 2.139207     | 10.18       | 0.25          | 5175-0726  | 10.48  |
|        |                             |              |             |               | 5174-0186  | 10.87  |
| UX Her | 52501.5262                  | 1.548869     | 8.97        | 0.15          | 1557-1029  | 9.21   |
|        |                             |              |             |               | 1557-1196  | 9.73   |
| AT Peg | 52500.9285                  | 1.146065     | 9.02        | 0.19          | 1137-0492  | 9.78   |
|        |                             |              |             |               | 1137-10134 | 10.58  |

(Ephemerides, Magnitudes of the System, and the Comparison and Check Stars)

(42x131)

We acquired radial velocity measurements of our targets at the Dominion Astrophysical Observatory (DAO) in Victoria, British Columbia, Canada using the Cassegrain spectrograph attached on the 1.85 m Plaskett telescope. A grating (#21181) with 1800 lines mm$^{-1}$, blazed at 5000 Å giving a reciprocal linear dispersion of 10 Å mm$^{-1}$ in the first order and covering a wavelength region from approximately 5000 to 5260 Å was used. A log of all spectroscopic observations is presented in Table 2 together with their properties.

In order to investigate the effect of the differing spectral types of the standard stars on the resulting radial velocities, we split the standard stars into two groups: one with F-types, and the other with G-types. Looking at the mean radial velocities derived from each group, we noted negligible differences between corresponding values—certainly less than the estimated errors. Therefore, we did not deem it necessary to use different standard stars for primary and secondary spectra or to restrict the standard star choices in any other way.

AT Peg has previous radial velocity measurements using the 1.2 m telescope at the DAO, which were reported in Maxted et al. (1994). Their determinations used an older technique involving a reticon detector and cross-correlations. We made use of their measurements in our analysis but did not combine both radial velocity data sets together because the $V_γ$ values differ from one data set to another.

4. ANALYSIS

4.1. Light Curve Modeling

In order to obtain initial parameters of the systems studied in this paper, we used the Wilson–Devinney program augmented with the Monte Carlo search algorithm to ensure that the global minimum was found within the set ranges of free parameters. We followed the procedure outlined in Zola et al. (2014), which is keeping the values constant for systems’ mass ratios, as derived from sine fitting to the radial velocities. In the search for solutions, we adjusted inclination ($i$), the temperature of the secondary ($T_2$), potentials ($Ω_{1,2}$), and the luminosity of the primary star ($L_1$). Neither a spot nor a third light was required for the three targets analyzed in this work. In addition to the mass ratios, we also kept the temperatures of the primary components ($T_1$) constant following from the spectral type of a system. In order to determine $T_1$, we used the spectral type versus temperature calibration published by Harmanec (1988). Furthermore, the albedo and gravity darkening coefficients were set at their theoretical values for either a radiative or a convective envelope. The limb darkening coefficients were built into the code and were chosen as a function of a star temperature and the wavelength of the observations from the tables by Claret & Bloemen (2011) and Claret et al. (2012, 2013) based on square root law. Due to the large number of observed single points, we calculated about 150 mean points for every binary and in each filter. These were calculated in such a way that they evenly covered the observed light curve and used ephemerides listed in Table 2. This procedure speeded up computations and also provided error estimates for each mean point. The convergence was achieved for all three systems and the resulting configurations (not assumed a priori) were all semi-detached with the secondaries filling the Roche lobe. In the next step, we used the resulting parameters as the starting ones in the simultaneous solution of light and radial velocity curves using the latest version, the 2015 release (WD2015), of the Wilson–Devinney code (Wilson & Devinney 1971; Wilson 1979, 1990, 2008, 2012; Van Hamme & Wilson 2007; Wilson et al. 2010). We made use of Mode-5 for the configuration, the usual mode for Algol-type binaries with a secondary component filling its Roche lobe in parallel with our findings for the configurations in the previous step. The list of free parameters was similar to those of the Monte Carlo search, however, the mass ratio was also adjusted as well as two further parameters describing the orbit: the semimajor axis of the binary system relative orbit and the systemic velocity. We assumed that the orbits are circular due to strong tidal forces in the case of semi-detached systems. These computations were done with all individual points and, setting the control parameter KSD = 1, we made use of the program feature to let the program compute the curve weights. Several iterations were required to derive the final combined RV and LC solutions.
For AT Peg, we determined two separate solutions, one using RV data from Maxted et al. (1994), and the other, our own RV results. All the radial velocity observations and their fits obtained with the WD2015 code are given in Figures 1 and 2. The results of the light curve analyses, as derived in the second step, are listed in Table 4 together with the formal error for each parameter in parentheses as computed by the Wilson–Devinney code. The fits and their residuals are shown in Figures 3–6. Finally, the computed absolute parameters are given in Table 5.

### 4.2. Orbital Period Analysis

In order to better understand the nature of the systems studied, we constructed the O–C diagrams (Figures 7 and 8) by using all minima times available in the literature together with those derived from our own observations, and weighting them according to the observation method (photographic: 0.3, visual: 0.5, photoelectric: 0.8, CCD: 1). We made use of the Kwee-van Woerden method (Kwee & van Woerden 1956) to derive the times of minimum light levels in our own light curves (Table 6).

Out of the three systems, XZ Aql and AT Peg show secular period changes, either a period increase or decrease. The former may be an indication of mass transfer from the less massive to the more massive component or mass loss from the system while the latter, mass transfer in the opposite direction. We fitted the trends in period changes with parabolae under the assumption of conservative mass transfer between components. Furthermore, we analyzed the residuals from the parabolic fit for two systems: XZ Aql and AT Peg. Cyclic variations were noted that could be attributed to the light time effect (LiTE) due to unseen additional components to these systems. For UX Her, we found only cyclic variations that may be caused by a companion that is dynamically bound to the binary system. The parameters corresponding to companions of the three systems were derived using equations based on the formulation of Irwin.
and also shifted as arbitrarily as the light curves. The data used to create this theoretical light curves corresponding to the best fits are plotted in solid lines. Residuals from the fits are given at the right of the light curves using the same symbols, and also shifted as arbitrarily as the light curves. The data used to create this figure are available.

![Observed light curves of XZ Aql. Data in the BVRI filters from top to bottom were shifted arbitrarily by the amounts shown in the figures for clarity.](image)

**Figure 3.** Observed light curves of XZ Aql. Data in the BVRI filters (from top to bottom) were shifted arbitrarily by the amounts shown in the figures for clarity. Theoretical light curves corresponding to the best fits are plotted in solid lines. Residuals from the fits are given at the right of the light curves using the same symbols, and also shifted as arbitrarily as the light curves. The data used to create this figure are available.

| Stellar Parameters | XZ Aql | UX Her | AT Peg |
|--------------------|--------|--------|--------|
| \( i (\degree) \) | 85.88(3) | 82.28(2) | 76.30(4) |
| \( T_1 (\text{K}) \) | 8770 | 8770 | 8360 |
| \( T_2 (\text{K}) \) | 4744(5) | 4478(5) | 5057(6) |
| \( \Omega_1 \) | 4.26(1) | 4.55(1) | 4.20(1) |
| \( \Omega_2 \) | 2.19(1) | 2.19(1) | 2.85(1) |
| \( V_c (\text{km s}^{-1}) \) | 17.6(9) | −67.6(11) | 10.0(19) |
| \( q = m_2/m_1 \) | 0.184(4) | 0.184(21) | 0.484(3) |

**Table 4**
Results from the Light Curve Analysis\(^a,b\)

\(^a\) Formal errors from the WD-code are in parentheses.

\(^b\) Column RV\(_1\) shows the results from the analysis using our own RV measurements, and RV\(_2\) shows the same but using RVs from Maxted et al. (1994).

(1952, 1959). We checked the dynamical stability of the configurations by using the stability condition given by Harrington (1977) when an unseen third body was assumed to explain the periodic changes in the O–C diagrams. In each case, the orbit of the third bodies has been assumed to be coplanar with that of the eclipsing pair. Errors have been estimated using a specific IDL code written by us. The results from the O–C analysis, including estimated mass transfer rate, are given in Table 7. The errors were computed by propagating the observational errors on the results in a formal manner. Before the results, in this table we also give the initial light elements that we used in the computation of the orbital phases for each of the systems.

### 4.3. Frequency Analysis

In order to search for potential pulsations in the data of the systems studied, we subtracted the theoretical light curves of the binary model from the corresponding observed ones and performed frequency analyses on the out-of-eclipse phases of the residuals with the software PERIOD04 v.1.2 (Lenz & Breger 2005; for further details, see Liakos et al. 2012b; Liakos & Niarhos 2013). We searched for frequencies up to 80 cycles per day (c/d). After the first frequency computation, the residuals were subsequently pre-whitened for the next one until the detected frequency had a signal-to-noise ratio \( S/N < 4 \), which is the programme’s critical trustable limit. The \( P^\alpha \) of the pulsation modes were identified with the software FAMIAS v.1.01 (Zima 2008) using theoretical \( \delta \) Scuti models (MAD; Montalban & Dupret 2007).

UX Her and AT Peg did not show any evidence of pulsating behavior. For XZ Aql we found two frequencies in the range 30–36 c/d. By taking into account the temperature of the primary component (8770 K), the frequency range (3–80 c/d—Breger 2000), and the spectral types of the \( \delta \) Sct stars (A–F), it can be plausibly suggested that this component is a \( \delta \) Sct-type pulsator. The pulsation signal is present in all filters, and its amplitude decreases from \( B \) to \( I \). Frequency analysis includes \( \sim 1300 \) points per filter coming from 19 nights of observations in a time span of 73 days. The data of the first 17 nights were obtained in a time span of 28 days, which is sufficient to detect...
quick pulsation modes. Finally, given that the system is a conventional semi-detached system (i.e., the more massive component, the pulsator in this case, is the mass gainer), it can also be categorized as a typical oEA system (Mkrtichian et al. 2002). Furthermore, two more frequencies were found (0.50 and 0.93 c/d), but they were also detected with approximately the same values in the comparison check light curves. So, we conclude that their origin is not connected with the true pulsations, and they can be considered as artifacts (e.g., observational drift). Table 8 includes the frequency values (f), the amplitudes (A), the phases (Φ), the S/N, and the f². In Figure 9 the periodogram and the Fourier fit on the data of an individual night are presented. Although the observed amplitude is rather low to reach a firm conclusion, there is more than one frequency with sufficient S/N in the range where δ Scuti stars pulsate and the beating seems to be obvious. More precise
Note.

Table 5 Absolute Parameters

| Parameter   | XZ Aql | UX Her | AT Peg |
|-------------|--------|--------|--------|
| $a (R_\odot)$ | 9.94(21) | 8.00(9) | 6.86(8) | 6.91(7) |
| $M_1 (M_\odot)$ | 2.42(14) | 2.42(12) | 2.22(8) | 2.26(7) |
| $M_2 (M_\odot)$ | 0.45(6) | 0.44(6) | 1.08(6) | 1.11(5) |
| $R_1 (R_\odot)$ | 2.45(7) | 1.84(5) | 1.86(3) | 1.87(3) |
| $R_2 (R_\odot)$ | 2.43(6) | 1.96(5) | 2.18(3) | 2.20(3) |
| $M_{\text{bol,1}}$ (mag) | 0.99(21) | 1.61(11) | 1.80(10) | 1.78(9) |
| $M_{\text{bol,2}}$ (mag) | 3.68(21) | 4.40(11) | 3.64(10) | 3.62(9) |
| log $g_1$ (cgs) | 4.04(6) | 4.29(5) | 4.24(3) | 4.25(3) |
| log $g_2$ (cgs) | 3.32(6) | 3.50(5) | 3.79(3) | 3.80(3) |

Note.

* Column RV$_1$ shows the results from the analysis using our own RV measurements, and RV$_2$ shows the same but using RVs from Maxted et al. (1994).

future observations will provide further evidence for the existence of heat-driven pulsations in this system.

4.4. Evolutionary Status

We used the Geneva stellar models (Ekström et al. 2012) to investigate the evolutionary states of the components of all the systems studied. We generated a grid of evolutionary tracks for a suitable range of fixed masses spanning the measured values by making use of interactive tools provided by a web interface. We fixed metallicity at solar composition ($Z = 0.014$) and generated non-rotating models. In order to populate the HRD with observed stars in detached, semi-detached, and near-contact eclipsing binaries, we collected the parameters of components in detached systems from Torres et al. (2010) and those in semi-detached binaries from Surkova & Svechnikov (2004). From both catalogs we have selected only the binaries with spectroscopically determined mass ratios. In Figure 10 we show the computed Geneva evolutionary tracks, parameters of components of selected detached binaries (primaries are indicated with filled triangles while secondaries with unfilled triangles), semi-detached and near-contact binaries (primaries are indicated with filled circles and secondaries with unfilled circles), and our program stars (indicated with marks selected according to their nature and component type and in red) on the HRD. We also present the mass–luminosity (MLD) and mass–radius (MRD) diagrams in Figure 11 following the same symbols used in Figure 10. It should be borne in mind that the stellar models are valid only for single stars, or stars in binaries that do not interact strongly, while the stars in our sample cannot be assumed to be free from stellar interactions in a binary system. The implications of this fact are clear when the positions of the evolved secondary components in these systems are compared with the evolutionary tracks given for their masses because they transfer material to their more massive and rather unevolved counterparts. The lines indicating the positions of the zero age main sequence (ZAMS) and the terminal age main sequence (TAMS) are shown in these figures. ZAMS is defined as the time when the hydrogen mass fraction in the center ($X_*$) has decreased by 0.25% for a newborn star with the solar composition, while TAMS is set at the time when $X_*$ will be of the value $10^{-5}$ for a star starting its life with solar composition. Following the above definition, a star will be on the ZAMS when thermal equilibrium is achieved and the star has burnt 0.25% of its hydrogen in the core (Ekström et al. 2012; Mowlavi et al. 2012).

5. RESULTS AND DISCUSSION

In this study we have performed thorough analyses of the light curves and period variations of three close binary systems.
Table 6

| System  | Time of Min. (HJD +2400000) | Error | Filter | Type |
|---------|-----------------------------|-------|--------|------|
| XZ Aql  | 56486.4291                  | 0.0001| BVRI   | primary |
|         | 56487.4975                  | 0.0004| BVRI   | secondary |
| UX Her  | 56089.4797                  | 0.0003| BVRI   | primary\(^a\) |
|         | 56093.3568                  | 0.0001| BVRI   | secondary\(^a\) |
| AT Peg  | 56146.5608                  | 0.0001| BVRI   | primary |
|         | 56153.4397                  | 0.0016| BVRI   | primary |
|         | 56157.4471                  | 0.0005| BVRI   | secondary |
|         | 55436.5775                  | 0.0005| BR     | secondary\(^b\) |
|         | 55439.4392                  | 0.0004| BR     | primary\(^b\) |
|         | 55442.2968                  | 0.0008| BR     | secondary\(^b\) |
|         | 55447.4616                  | 0.0001| BR     | primary\(^b\) |

Notes.
\(^a\) Liakos & Niarchos (2010).
\(^b\) Liakos et al. (2014).

Table 7

| System | \(T_e\) (HJD) | \(P\) (days) | \(dM/dt\) (\(M_e\) yr\(^{-1}\)) | \(dp/dE\) (days/cycle) | \(P_s\) (years) | \(A\) (days) | \(\omega\) (\(^\circ\)) | \(e\) | \(a_{12}\sin(i)\) (au) | \(f(\Phi)\) (\(M_e\)) | \(M_{\odot\,\text{min}}\) (\(M_e\)) |
|--------|---------------|--------------|-------------------------------|-------------------------|----------------|-------------|------------------|------|-----------------|-----------------|----------------------|
| XZ Aql | 2441903.4610\(^a\) | 2.139181 | 6.37(13) \times 10^{-8} | 4.33(5) \times 10^{-9} | 37.97(96) | 0.015(1) | 316(18)       | 0.21(10) | 2.62(150) | 0.01(2) | 0.52(8) |
| UX Her | 2439672.3760\(^a\) | 1.548853 | ... | ... | 37.97(96) | 0.037(2) | 181(1)       | 0.41(7)  | 6.99(16) | 0.045(3) | 0.87(7) |
| AT Peg | 2445219.8512\(^a\) | 1.1460764 | ... | ... | 37.97(96) | 0.016(1) | 86(11)        | 0.53(8)  | 2.72(90) | 0.02(2) | 0.68(5) |

Notes.
\(^a\) Samus et al. (2012).
\(^b\) Tremko et al. (2004).

Table 8

| \(F'\) | Filter | \(f\) (c/d) | \(A\) (mmag) | \(\Phi\) (\(2 \pi\) rad) | S/N |
|--------|--------|-------------|--------------|--------------------------|-----|
| 3      | B      | 30.631(1)   | 5.4(4)       | 0.51(1)                  | 7.8 |
|        | V      | 30.633(1)   | 4.4(4)       | 0.46(1)                  | 8.1 |
|        | R      | 30.632(1)   | 3.2(4)       | 0.48(2)                  | 5.3 |
|        | I      | 30.635(1)   | 2.6(3)       | 0.44(2)                  | 7.9 |
| 0      | B      | 35.247(1)   | 3.2(4)       | 0.64(2)                  | 4.0 |
|        | V      | 35.250(1)   | 2.4(3)       | 0.57(2)                  | 4.2 |
|        | R      | 35.289(1)   | 1.9(4)       | 0.73(3)                  | 4.3 |
|        | I      | 35.240(1)   | 1.9(3)       | 0.81(2)                  | 3.9 |

Analysis of our light curves was based on combined photometric and spectroscopic data. The mass ratios of the systems studied were determined from our own spectroscopic observations. We made use of the Wilson–Devinney algorithm to derive the best fits to new, multicolor light curves, and based on the results obtained we calculated the absolute parameters of components. The complementary information about the systems has been derived by analyzing their period behavior.
5.1. XZ Aql

The light curve of XZ Aql has equal levels of light maxima, and we were able to obtain its solution, which required neither a spot nor a third light. This is a high inclination ($i = 86^\circ$), semi-detached binary with a less massive secondary filling its Roche lobe, while the primary component is well inside its Roche lobe. The frequency analysis performed after having removed the binarity effects from its light curves hints that this A-type primary is a $\delta$ Scuti-type pulsator. Due to a significant temperature difference between components, the contribution of the secondary star to the total system light is small: it is only 2% in the $B$ filter and about 13% in the $I$ filter.

From the O–C analysis we found a parabolic change in the eclipse timings combined with a periodic variation that could be due to an unseen third body, as previously suggested by Soydugan et al. (2006). We made trial computations with a third light; however, its resulting intensity was negligible, reaching only 1% in the $I$ filter. Assuming that this third body is in coplanar orbit with the binary and that it is an MS star, its luminosity contribution to the total light would only be 0.2%. We found that the orbit of this third companion would be stable according to Harrington’s criterion (Harrington 1977). We have found a parabolic relation in the residuals that may be due to mass transfer from the less massive component to the more massive one. When the corresponding orbital period changes are removed, one might argue that there is a possibility of a second periodicity in the O–C points, but the number of data points is not sufficient to prove it. Alternatively, the periodic variation of the orbital period could also be explained with the quadrupole moment variation of the secondary.

Our results from the orbital period variation analysis also support the finding that the secondary component fills its Roche lobe and transfers mass to the more massive primary conservatively. The positions of its component on the HRD, MLD, and MRD based on the absolute parameters computed for each of the components as a result of the light curve modeling support this finding. Both the computed masses and the effective temperatures from our fit are qualitatively consistent with evolutionary tracks, which also point to a main sequence primary halfway between the ZAMS and TAMS with $\sim 2.42 M_\odot$, and an evolved red giant secondary, somewhat more massive ($\sim 0.65 M_\odot$) than our computed value ($\sim 0.45 M_\odot$). This discrepancy can be explained by the mass transfer from the secondary to the primary star, the timescale of which should be less than 10 Myr assuming a constant rate for the mass transfer. The fact that the main sequence primary has not gained all the mass of the secondary transfers can only be explained by a non-conservative mass loss.

5.2. UX Her

Our light curve modeling for UX Her used the new value for the spectroscopic mass ratio resulting from our DAO data $q_{sp} = 0.184$. It is significantly smaller than the previous
determination from photometry alone as a result of the $q$-search by (Djurašević et al. 2006). We obtained a semi-detached configuration for this system with the less massive component filling its Roche lobe while the primary is well within it. Therefore, mainly due to the lower $q$ value, the derived secondary mass is also smaller than that previously found (Lazaro et al. 1997; Djurašević et al. 2006). Both considered this system as a detached one based on either photometrically or spectroscopically determined mass ratios from photographic plates. The evolutionary state of UX Her components deduced from their positions on the HRD, MLD, and MRD diagrams point to the interpretation that the primary star is still on the main sequence, while the secondary is the more evolved star.

We did not find a significant quadratic component to the period variation, therefore, we conclude there is no evidence of mass transfer. The cyclic period variations can more plausibly be explained by a third body of mass $M_3 \approx 0.87 M_\odot$ orbiting the center of mass on a significantly eccentric orbit ($e = 0.41$). Tremko et al. (2004) found a smaller mass, less than half of the value that we found (0.30 $M_\odot$). As a test, we also performed computations adding a third light as a free parameter. It turned out that the contribution of this hypothetical tertiary to the total light is negligible: it reached about 1% only in the $I$ filter so therefore we present the solution without $l_3$ as the final one. If we assume that this body has a coplanar orbit with that of the eclipsing binary and that it is an M5 star, its luminosity contribution will be less than 1% (0.75% according to our calculations), which is below our detection limits with the photometry. Previously, Selam & Albayrak (2007) also found cyclic changes in the orbital period in UX Her. They attributed the variation to magnetic activity, which would also explain the observed asymmetries in the light curve. However, the latest CCD data have a very low scatter around our best fit. More scatter would be expected in the case of magnetic activity because it would complicate the measurement of the eclipse times from asymmetric minimum profiles due to the surface spots, therefore causing more errors. Further observations of the system covering a longer time will be needed to make sure that the period and the amplitude of the variation change from one cycle to another, which would be the case in the presence of strong magnetic activity. Otherwise, the variation could be argued to be caused by the gravitational pull of an unseen third body. In addition, the temperature of the primary is too high ($8770$ K) to expect cool surface spots. Though it would be somewhat reasonable to locate spots on the cooler secondary, our non-detected solution satisfactorily fits the observations. Therefore, we give here only the third body solution because we do not have further evidence (e.g., variations in magnetic activity indicators) supporting the magnetic activity argument. Moreover, the dynamical stability test according to Harrington’s criterion (Harrington 1977) points to a stable orbit for the suggested third body, thus supporting the second hypothesis.

5.3. AT Peg

Light curve modeling for AT Peg proceeded without difficulty for both radial velocity data sets (our own and that of Maxted et al. 1994). A convergence was quickly found for a model that required neither a third light nor a spot. Theoretical light curves fit the observed ones very well with just very small discrepancies visible around the primary minimum but only in the $B$ and $I$ filters. We arrived at the semi-detached solution with the less massive secondary filling the Roche lobe and the primary well within it. Absolute parameters and their errors differ only within a few percent between the two models obtained by using two different radial velocity data sets.

The O–C analysis shows a parabolic trend. A periodic relation for the residuals can also be asserted. The quadratic term cannot be interpreted as being due to conservative mass transfer between components as it would require the more massive star to be the mass loser, in contradiction with the results from light curve modeling. This discrepancy can be explained by non-conservative mass loss from the system or losing of angular momentum via magnetic breaking. Such systems with orbital period decrease may be the progenitors of contact binaries (Bradstreet & Guinan 1994; Qian 2000), because the fill-out factor of the primary may increase while the orbital period decreases, eventually causing the primary to fill its Roche lobe. We do not have evidence for strong magnetic activity such as light curve modulations and asymmetries in the light curves due to stellar spots. The spectral window of our
spectral observations is also limited to the 5000–5250 Å region, where we have not observed a signature of activity or stellar wind in the resolution our spectra were taken. The spectral type of the primary (A4) would not support this argument either, assuming it is a normal star without any kind of peculiarity. The positions of the components relative to the evolutionary tracks on the HRD indicate that the primary might have lost some mass. The evolutionary model value with no mass transfer is \( \sim 1.90 M_\odot \) for the primary component, while the computed mass from the light curve analysis is 2.22 \( M_\odot \) and the mass of the secondary is consistent in both models (\( \sim 1.08 M_\odot \)).

The residuals from the quadratic fit may be allowed to follow a periodic behavior, which can be attributed to an unseen body (\( M_{3,\text{min}} = 0.68 M_\odot \)) gravitationally bound to the system, orbiting its center of mass once every \( \sim 33 \) years on a significantly eccentric (\( e = 0.53 \)) orbit. The relatively low mass of the tertiary can explain its negligible contribution to the total light. Additional bodies have been plausibly argued to extract momentum from the binary, causing the orbit to shrink and hence the orbital period to decrease (Yang & Wei 2009). This could be at least a part of the reason for a period decrease, although the direction of the mass transfer is toward the more massive primary.

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