The First Light Curve Solution of GW Leo and Refined Ephemeris of Two Contact Binary Systems

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Abstract—We performed the first light curve analysis of GW Leo and a new ephemeris is obtained for QT Boo. The light curve investigation also yields that the system GW Leo is a contact W UMa eclipsing binary with a photometric mass ratio of \(q = 0.44 \pm 0.03\), a fillout factor of \(f = 59.6\%\), and an inclination of \(50.77^\circ \pm 0.09^\circ\). Due to the O’Connell effect which is known as asymmetries in the light curves’ maxima, a cold spot is employed along with the solution. The photometric and physical parameters of GW Leo were determined (e.g., \(M_v = 1.373 \pm 0.024\), \(M_c = 0.604 \pm 0.027\), \(R_v = 1.261 \pm 0.041\), \(R_c = 0.909 \pm 0.039\), and \(a(R_v) = 2.553 \pm 0.004\)). According to the light curve solution results, we suggest that GW Leo is an A-type W UMa binary system. We also calculate the distance of GW Leo from the distance modulus formula as \(483.5 \pm 41\) pc, which is in a good agreement to the quantity measured by the Gaia EDR3 using the binary systems’ parallax. Moreover, the positions of their components on the H–R diagram are represented.

Keywords: photometry, ephemeris, individual: GW Leo and QT Boo
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1. INTRODUCTION

EW-type eclipsing variables are considered a subclass of W Ursae Majoris-type eclipsing binaries and have periods of less than a day. EW eclipsing binaries may form through magnetic braking in which detached binary stars with short periods lose angular momentum [1]. It is also discussed that components in W Uma type binary systems have close temperatures because of their proximity [2].

We present photometric observations of GW Leo and QT Boo as W UMa binary systems. The study includes the first light curve analysis of GW Leo and the determination of a new ephemeris for both systems. We find that systems selected in terms of magnitude and period are very suitable for investigation. GW Leo (GSC 00843-00262), which is located in the Leo constellation, has a magnitude of 12.33 and a period of 0.336157 days [3]; and QT Boo (GSC 03486-01026), which is located in the Booties constellation has a magnitude 11.77 and a period of 0.319065 days [4], respectively.

2. OBSERVATION AND DATA REDUCTION

GW Leo was observed with a 10-inch Schmidt Cassegrain telescope at the Bkaran Observatory of Kerman, Iran (Long. 57°01′13″ E, Lat. 30°16′55″ N, Alt. 1764 m) in May 2020. During two nights, a total of 404 photometric data were obtained in the V filter with an exposure time of 30 seconds for every single image. We used a Nikon D5300 DSLR Camera attached to the telescope.

QT Boo was another candidate in this study, and it was observed in September 2020 at the Payame Noor University Observatory of Ardabil, Iran (Long. 48°17′42″ E, Lat. 38°12′55″ N, Alt. 1380 m). For two nights, a total of 159 images were taken in the standard V filter. An 11-inch Schmidt Cassegrain telescope along with a Canon 600D DSLR Camera was employed to collect data. The exposure time for two times of minima was 30 seconds.

We selected one reference star and one comparison star for each of the binary systems to perform differential photometry. The magnitude of the variable, comparison, and reference stars, as well as their right ascension and declination, are available in Table 1.

Using the Digital Single Lens Reflex camera (DSLR) has been currently a common method of photometry in small observatories. The skill of the observer and the stage of data reduction are two main
factors that determine the quality of data in this method [5].

Bias, dark, and flat-field frames were used to do data subtraction and correction. We employed Astro-ImageJ (AIJ) software to calibrate and perform differential aperture photometry [6]. The minimum times were found through fitting the models to the light curves and existing minima based on Gaussian and Cauchy distributions. We then employed the Monte Carlo Markov Chain (MCMC) method to measure the amount of uncertainty related to each value [7]. We also benefited from Python along with its PyMC3 package to execute the lines of code [8]. Figure 1 shows the observed and synthetic light curves in the V filter for GW Leo, and Fig. 2 shows the observed light curve of QT Boo.

3. NEW EPHEMERIS

Based on our observation, we determined two minimum times for each binary system and also collected 16 and 11 more minima for GW Leo and QT Boo, respectively, from the literature. They are all listed in the first column of Tables 2 and 3 in the Barycentric Julian Date in the Barycentric Dynamical Time (BJD\text{\tiny TDB}) format, and their uncertainties appear in column 2. Epochs of these minima times and O–C values are in columns 3 and 4, respectively, and the references of mid-eclipse times are shown in the last column.

The epochs and the O–C values were calculated according to the reference ephemeris for both binary systems (Table 4). We wrote a Python code based on the emcee package to fit all collected mid-eclipse times with a line shown in Figs. 3 and 4. We used the MCMC [18] to determine a new linear ephemeris for the primary minimum, and therefore we have obtained the posterior probabilities for these parameters (Fig. 5). Consequently, a new linear ephemeris related to the primary minimum for each system was determined and shown in Table 5. $E$ represents the number of cycles after the reference epoch, and the

| Star type  | Target   | Magnitude, V | RA (J2000), h m s | Dec. (J2000), °′″ |
|------------|----------|--------------|-------------------|------------------|
| Variable   | GW Leo   | 12.33        | 10 18 53.49       | +13 41 08.43     |
| Comparison | GSC 843-339 | 14.12      | 10 19 00.65       | +13 42 28.24     |
| Reference  | GSC 843-419 | 13.43      | 10 18 34.16       | +13 44 48.22     |
| Variable   | QT Boo   | 11.77        | 15 35 10.93       | +49 47 44.04     |
| Comparison | GSC 3486-1435 | 13.44      | 15 35 31.96       | +49 42 40.02     |
| Reference  | GSC 3486-1075 | 13.58      | 15 35 31.64       | +49 52 19.93     |

Fig. 1. The observed light curve of GW Leo and synthetic light curve in the V filter and residuals are plotted.
To perform a precise study of period variations, we need more observation in the future.

**4. LIGHT CURVE ANALYSIS OF GW LEO**

To determine the physical parameters of GW Leo, we analyzed the light curves using the binary star model of Wilson & Devinney (W–D) [19]. Since GW Leo is a W UMa type binary, “the overcontact binary not in thermal contact” mode was chosen for modeling. The parameters considered to be fixed in the W–D code are the gravity darkening exponents $g_c = g_h = 0.32$ [20], the bolometric albedo coefficients $A_c = A_h = 0.50$ [21], and linear limb darkening coefficients adopted from tables published by Van Hamme [22].

**Table 2. Available times of minima for GW Leo**

| BJD$_{TDB}$ | Error   | Epoch | O–C | References |
|-------------|---------|-------|-----|------------|
| 2452721.5287 | 0       | 0     | 0   | [3]        |
| 2455642.4396 | 0.0007  | 8689  | 0.0427 | [9]        |
| 2455642.4407 | 0.0006  | 8689  | 0.0438 | [9]        |
| 2455992.3524 | 0.0009  | 9730  | 0.0161 | [9]        |
| 2455992.3526 | 0.0005  | 9730  | 0.0163 | [9]        |
| 2456011.3361 | 0.0007  | 9786.5 | 0.0069 | [9]        |
| 2456011.3368 | 0.0004  | 9786.5 | 0.0076 | [9]        |
| 2456330.4993 | 0.0007  | 10736 | -0.0110 | [9]        |
| 2456330.5056 | 0.0007  | 10736 | -0.0047 | [9]        |
| 2456330.5098 | 0.0011  | 10736 | -0.0005 | [9]        |
| 2456670.6811 | 0.004   | 11748 | -0.0201 | [10]       |
| 2456670.6821 | 0.0010  | 11748 | -0.0191 | [10]       |
| 2456745.4366 | 0.0008  | 11970.5 | -0.0595 | [10]       |
| 2456745.4393 | 0.0005  | 11970.5 | -0.0568 | [10]       |
| 2457798.5414 | 0.0335  | 15103 | BRNO 41* |
| 2457798.5425 | 0.0346  | 15103 | BRNO 41 |
| 2458987.2919 | 0.0352  | 18639.5 | -0.0352 | This study |
| 2458987.4599 | 0.0353  | 18640 | -0.0353 | This study |

* [http://var2.astro.cz/brno/](http://var2.astro.cz/brno/)

**Table 3. Available times of minima for QT Boo**

| BJD$_{TDB}$ | Error   | Epoch | O–C | References |
|-------------|---------|-------|-----|------------|
| 2451402.5378 | 0       | 0     | 0   | [4]        |
| 2456368.4538 | 0.0008  | 15564 | -0.0117 | [9]        |
| 2456745.4298 | 0.0052  | 16745.5 | -0.0110 | [11]       |
| 2456745.5878 | 0.0027  | 16746 | -0.0125 | [11]       |
| 2457027.6388 | 0.0027  | 17630 | -0.0150 | [12]       |
| 2457100.3898 | 0.0022  | 17858 | -0.0108 | [13]       |
| 2457100.5368 | 0.0042  | 17858.5 | -0.0233 | [13]       |
| 2457124.7958 | 0.0022  | 17934.5 | -0.0132 | [14]       |
| 2457493.7888 | 0.0022  | 19091 | -0.0189 | [15]       |
| 2457807.9068 | 0.0030  | 20075.5 | -0.0204 | [16]       |
| 2457843.4818 | 0.0218  | 20187 | -0.0212 | [17]       |
| 2459104.4239 | 0.0040  | 24139 | -0.0239 | This study |
| 2459105.3807 | 0.0050  | 24142 | -0.0243 | This study |

Fig. 2. The observed light curve of QT Boo in the V filter.
According to the phase–flux light curve and minima placement, the light curve starts with the secondary minimum. As can be seen, the secondary minimum is deeper than the primary one in this system. The difference between the minima is 0.03 magnitude. This indicates that the cooler component is eclipsed by
the hotter one. So, we found that the primary star is hotter than the secondary.

The period–color relation given by Wang [23] for binary systems predicts that the intrinsic color index can be defined as

\[(B - V)_0 = 0.077 - 1.003 \log P,\]

(1)

where \(P\) is the orbital period. According to the period obtained in this study, the derived intrinsic color of the GW Leo is \((B - V)_0 = 0^m.552\). The interstellar reddening value, \(E(B - V) = 0^m.036\), was determined based on the distance of this binary system from Gaia EDR3 parallax, and \(A_V = 0.11\) comes from Schlafly and Finkbeiner [24]. Therefore, the calculated color index of GW Leo was found to be \((B - V)_{GW Leo} = 0^m.588\) with a known equation,

\[(B - V) = (B - V)_0 + E(B - V).\]

(2)

Thus, the primary component’s effective temperature in the light curve analysis was assumed from Allen’s table [25], as 5870 K.

Since there is no spectroscopically determined mass ratio \((q)\), we employed \(q\)-search to examine a series of values from 0.1 to 1.5. Orbital inclination \((i)\), the surface temperature of the hotter star \((T_c)\), relative monochromatic luminosity of the hotter star \((L_c)\), and omega-potentials of the components \((\Omega_c = \Omega_h)\) are considered as adjustable values through the W–D code’s evaluation. The sum of the squared residuals \(\sum W(O - C)^2\) for the tested mass ratios \((q)\) is plotted in Fig. 6. We selected \(q = 0.44 \pm 0.03\) with minimal residuals as the initial input in the differential-correction stage of the W–D code. Derived parameters from the light curve solution for GW Leo are listed in Table 6.

The mean fractional radii of components are 0.494 and 0.356 for the hotter and cooler components,

Table 4. The reference ephemeris of GW Leo and QT Boo

| Binary system | Reference ephemeris | Reference |
|---------------|---------------------|-----------|
| GW Leo        | Min I = BJD\_TDB 2452721.5287 + 0.336157E  | [3]       |
| QT Boo        | Min I = BJD\_TDB 2451402.5378 + 0.319065E  | [4]       |

Table 5. The New ephemeris of GW Leo and QT Boo

| Binary system | New ephemeris |
|---------------|---------------|
| GW Leo        | \(T_0 = BJD_{TDB} 2452721.55682^{+0.000010}_{-0.000010} + 0.33614880^{+0.00004296}_{-0.00000591}E\) days |
| QT Boo        | \(T_0 = BJD_{TDB} 2451402.54158^{+0.000213}_{-0.000319} + 0.31906397^{+0.00000015}_{-0.00000015}E\) days |
The fillout factor was calculated as 59.6% from the output parameters of the light curve solution via

\[ f = \frac{\Omega_{\text{in}} - \Omega}{\Omega_{\text{in}} - \Omega_{\text{out}}} \]  

respectively. These values were calculated from the equation

\[ r_{\text{mean}} = (r_{\text{pole}} r_{\text{side}} r_{\text{back}})^{1/3}. \]
where $\Omega_{\text{in}}$ and $\Omega_{\text{out}}$ are the inner and outer of critical Roche equipotential.

Generally, the asymmetric light curves of W UMa type systems may demonstrate starspot presence on one or both stars in the system. We produced starspot-free, symmetric model light curves fitted to the noticed brighter maximum of each epoch’s light curve. At first, the model did not fit the observed light curves, which are markedly asymmetric. Due to the deviations apparent on the light curves’ maximums known as the O’Connell effect [26], a starspot was placed on the hotter component.

Our observation and light curve solution indicate that GW Leo is an A-type W-UMa binary system with a high overcontact degree of 59.6% and a low mass ratio $q$. According to the following relation for A-type overcontact binaries [27],

$$M_1 = 0.761(\pm 0.150) + 1.82(\pm 0.28)P, \quad (5)$$

where $M_1$ is the mass of the primary component and $P$ is the orbital period. Therefore, the mass of the primary (hotter) component of GW Leo is $M_{\text{h}} = 1.373(24)M_\odot$. The mass of the secondary (cooler) component can be calculated via the mass ratio equation ($q = M_2/M_1$). We also apply Kepler’s third law to the calculated separation between two components of the GW Leo binary system. The absolute parameters of GW Leo are measured and given in Table 7. We provided an estimation of components mass through the photometry. For highly precise results and less amount uncertainties, spectral data are required.

Also, the radii of the components were computed using the formula $R = a_{\text{mean}}$ as 0.93 ($R_\odot$) and 0.90 ($R_\odot$) for the primary and secondary, respectively. As a result, the binary system is in a marginal contact state [28] since the sum of the mean fractional radii of the components is $r_{\text{mean}} = r_{\text{mean}} + r_{\text{mean}} = (0.81) > 0.75$.

Regarding the quantities obtained for the absolute parameters, we computed the distances of GW Leo. The values of $V_h = 12.75 \pm 0.15$ and $M_{\text{bol}} = 4.218$ were calculated for the hotter component. We used $BC_h = -0.05$ according to Flower’s table [29]. Hence, we measured the distance to the binary system by inserting certain parameters in the equation below,

$$d(\text{pc}) = 10^{\left(\frac{V_h - M_{\text{bol}} + 5}{5}\right)}, \quad (6)$$

which yielded $d = 483.5 \pm 41$ pc.

The 3D view of this binary system is shown in Fig. 7.

### 5. RESULTS AND CONCLUSION

The DSLR photometric observations of two W UMa binary systems GW Leo and QT Boo, were carried out in two observatories and using a $V$ filter. The MCMC method was used to find times of minima for this study observations. A new ephemeris was suggested to determine the times of primary minima for both contact binary GW Leo and QT Boo.

The first photometric solution of the short period binary system GW Leo was done by analyzing its light curve. As a result, it is found that GW Leo is a contact binary with a mass ratio of $q = 0.44 \pm 0.03$, a fillout factor of $f = 59.6\%$, and an inclination of $i = 50.77\% \pm 0.09\%$. As indicated by the light curve solution, a cool starspot is placed on the hotter component. The difference in temperatures of the compo-

### Table 6. Photometric solution of GW Leo

| Parameter | Results |
|-----------|---------|
| $T_c$ (K) | 5719(43) |
| $T_h$ (K) | 5870 |
| $\Omega_c = \Omega_h$ | 2.60(8) |
| $i$ (deg) | 50.77(9) |
| $q$ | 0.44(3) |
| $l_c/l_{\text{tot}}$ | 0.466 |
| $h_c/h_{\text{tot}}$ | 0.534(7) |
| $A_c = A_h$ | 0.50 |
| $g_c = g_h$ | 0.32 |
| $f$ (%) | 59.6 |
| $r_c(\text{back})$ | 0.408 |
| $r_c(\text{side})$ | 0.341 |
| $r_c(\text{pole})$ | 0.322 |
| $r_h(\text{back})$ | 0.534 |
| $r_h(\text{side})$ | 0.492 |
| $r_h(\text{pole})$ | 0.455 |
| $r_c(\text{mean})$ | 0.356(17) |
| $r_h(\text{mean})$ | 0.494(18) |
| Colatitude$_{\text{spot}}$ (deg) | 111 |
| Longitude$_{\text{spot}}$ (deg) | 116(6) |
| Radius$_{\text{spot}}$ (deg) | 27(11) |
| $T_{\text{spot}}/T_{\text{star}}$ | 0.80(4) |
| Phase shift | $-0.038(2)$ |

### Table 7. Estimated absolute parameters of GW Leo

| Parameters | Hotter star | Cooler star |
|------------|-------------|-------------|
| Mass ($M_\odot$) | 1.373(24) | 0.604(27) |
| Radius ($R_\odot$) | 1.261(41) | 0.909(39) |
| Luminosity ($L_\odot$) | 1.694(49) | 0.793(51) |
| $M_{\text{bol}}$ | 4.168(16) | 4.992(15) |
| log $g$ | 4.374(39) | 4.302(38) |
| $a/R_\odot$ | 2.553(4) | |
ponents for this binary system is 151 K, so the components may have a magnetic activity that causes the observed unbalanced light curves of GW Leo. This suggestion for a magnetic activity can be checked with future spectrometric observations and investigation of period varieties with more minima occasions.

We estimated absolute parameters related to both components of the GW Leo. Mass, radius, and luminosity of the system were obtained using the binary systems modeling of the Wilson–Devinney. According to the estimated absolute parameters, we measured the distance as 483.5 ± 41 pc. This value is in good agreement with the quantity obtained by the Gaia EDR3 as 458.1 ± 30 pc.

From the color index of GW Leo and Allen’s table [25], the spectral type is suggested G0V-G2V. The components’ positions of GW Leo are plotted in the Hertzsprung–Russell (H–R) diagram (Fig. 8). It seems that both are on the main sequence. The hotter component is near the TAMS line, and the cooler component is in the middle of the main sequence.

The decreasing of the orbital period has been easily seen in the O–C diagram, a low mass ratio, and high overcontact degree; we can conclude that this is an A-type W UMa binary system. Similar behavior has been studied in other overcontact binaries, e.g., GR Vir [30] and FG Hya [31].

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