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# The low-mass classic Algol-type binary UU Leo revisited *

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**Abstract** New multi-color photometry of the eclipsing binary UU Leo, acquired from 2010 to 2013, was carried out by using the 60-cm and 85-cm telescopes at the Xinglong station, which is administered by National Astronomical Observatories, Chinese Academy of Sciences. With the updated Wilson-Devinney code, the photometric solution was derived from $BVR$ light curves. The results imply that UU Leo is a semi-detached Algol-type binary, with a mass ratio of $q = 0.100(\pm 0.002)$. The change in orbital period was reanalyzed based on all available eclipsing times. The $O - C$ curve could be described by an upward parabola superimposed on a quasi-sinusoidal curve. The period and semi-amplitudes are $P_{\rm mod} = 54.5(\pm 1.1)$ yr and $A = 0.0273^{\rm d}(\pm 0.0015^{\rm d})$, which may be attributed to the light-time effect via the presence of an invisible third body. The long-term period increases at a rate of $dP/dt = +4.64(\pm 0.14) \times 10^{-7}{\rm d\,yr^{-1}}$, which may be interpreted by the conserved mass being transferred from the secondary to the primary. With mass being transferred, the low-mass Algol-type binary UU Leo may evolve into a binary system with a main sequence star and a helium white dwarf.

**Key words:** stars (including multiple): binaries: close — stars: individual (UU Leo)

## 1 INTRODUCTION

UU Leo (=AN 351.1934, $\alpha_{\rm J2000.0} = 09^{\rm h}47^{\rm m}49.69^{\rm s}$ and $\delta_{\rm J2000.0} = +12^\circ 59' 02.51''$) was photographically identified by Hoffmeister (1934). Its magnitude varies from $11.4^{\rm m}$ to $12.7^{\rm m}$ (Malkov et al. 2006). The spectral type of A2 was estimated by Brancewicz & Dworak (1980), who classified this star as an Algol-type eclipsing binary (Budding 1984). Soydugan et al. (2006) then cataloged it as a candidate of an oEA (i.e., oscillating EA) star (Mkrtichian et al. 2003), although this was not identified by photometry (Liakos et al. 2011). Jensch (1935) determined an orbital period of $1.67975^{\rm d}$, which was subsequently updated to be $1.6797459^{\rm d}$ (Whitney 1959), $1.6797366^{\rm d}$ (Mallama 1980) and $1.67974627^{\rm d}$ (Kreiner et al. 2001). Erdem et al. (2007) studied its changes in orbital period and obtained a secular period increase superimposed on a quasi-cyclic oscillation with a period of $P_{\rm mod} = 62(2)$ yr and a high eccentricity of $e = 0.77(4)$, which was interpreted by mass transfer and magnetic activity, respectively. However, their database only included five high-precision CCD data. During a 20-year gap between HJD 21427926.448 (Jensch 1935) and HJD 2434241.745 (Whitney 1959), only a single light minimum time was recorded (i.e.,

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HJD 2430849.220; Soloviev 1943), which evidently deviated from the computed curve. Recently, Liakos et al. (2011) reanalyzed the $O - C$ curve of UU Leo and derived a light-time orbit with $A = 0.48(2)^{\rm d}$ and $P_{\rm mod} = 72(1)$ yr. Unfortunately, they neglected Soloviev's (1943) eclipsing time. Liakos et al. (2011) also derived a photometric solution that included a third light (i.e., $l_3 = 11.5\%$) from their observations. The results show that UU Leo may be a detached eclipsing binary with a mass ratio of $q = 0.286(2)$.

## 2 OBSERVATIONS AND REDUCTIONS

New photometry of UU Leo was carried out on five continuous nights from 2011 January 16 to 20, using the 85-cm telescope at the Xinglong station (XLs), which is administered by National Astronomical Observatories, Chinese Academy of Sciences (NAOC). This reflecting telescope was equipped with a PI $1024 \times 1024$ CCD photometric system. It had a measured field of view of $16.5' \times 16.5'$ at a focal ratio of 3.27 with a scale of $0.96''$ per pixel (Zhou et al. 2009). The telescope has mainly been used to study variable stars. In the past two years, we have photometrically performed several studies of eclipsing binaries, such as V551 Aur (Liu et al. 2012), EI CVn (Yang 2011), EF Dra (Yang 2012), V1034 Her (Zhang 2012), PS Per (Yuan 2011a), V1123 Tau and V1128 Tau (Zhang et al. 2011) and FT UMa (Yuan 2011b). Standard $BVRI$ filters were used. Data reduction was performed using IRAF software in a standard fashion.

The coordinates of the comparison star TYC 834-99-1 are $\alpha_{\rm J2000.0} = 09^{\rm h}47^{\rm m}07.56^{\rm s}$ and $\delta_{\rm J2000.0} = +13^\circ03'14.01''$. Meanwhile, the chosen check star is 2MASS J09471988+1253385. Exposure times in $B$, $V$ and $R$ bands were adopted to be 40s, 30s and 25s, respectively. All individual observations (i.e., 781 for the $B$ band, 784 for the $V$ band and 785 for the $R$ band) are available on request. The typical precision of the variable star's differential magnitudes is smaller than 0.01 mag for all $BVR$ measurements. The complete light curves are displayed in the left panel of Figure 1, where phases were computed by using a period of $1.67964627^{\rm d}$ (Kreiner et al. 2001). The primary eclipses are deeper than the secondary ones by up to $0.981^{\rm m}$ in the $B$ band, $1.144^{\rm m}$ in the $V$ band and $1.289^{\rm m}$ in the $R$ band. Two additional primary eclipses of UU Leo, displayed in the right panel of Figure 1, were acquired on 2007 March 31 using the 1.0-m telescope at Yunnan Observatory, and on 2013 January 16 using the 60-cm telescope at the XLs of NAOC. From our new observations, we determined four light minimum times, which are listed in Table 1.

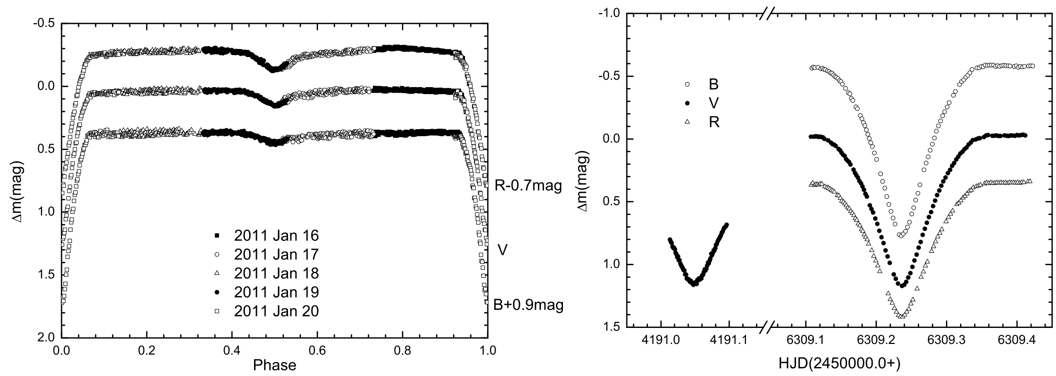


**Fig. 1** *Left panel*: $BVR$ photometric observations of UU Leo, obtained during 2011 January using the 85-cm telescope. *Right panel*: two primary eclipses of UU Leo observed in 2007 and 2013, respectively.

**Table 1** New Observed Eclipsing Times of UU Leo

| JD (Hel.) | Min | Error | Filter | Telescope |
|---|---|---|---|---|
| 2454191.04874 | I | ±0.00019 | $V$ | 1.0-m |
| 2455579.37912 | II | ±0.00133 | $B$ | 85-cm |
| 2455579.38055 | II | ±0.00101 | $V$ | 85-cm |
| 2455579.37941 | II | ±0.00094 | $R$ | 85-cm |
| 2455580.21771 | I | ±0.00035 | $B$ | 85-cm |
| 2455580.21790 | I | ±0.00033 | $V$ | 85-cm |
| 2455580.21767 | I | ±0.00042 | $R$ | 85-cm |
| 2456309.23635 | I | ±0.00041 | $B$ | 60-cm |
| 2456309.23636 | I | ±0.00034 | $V$ | 60-cm |
| 2456309.23637 | I | ±0.00039 | $R$ | 60-cm |

## 3 REANALYSIS OF PERIOD CHANGES

The complicated period variations were recently studied by Erdem et al. (2007) and Liakos et al. (2011), who gave some inconsistent results. Therefore, the $O - C$ curve needed to be reanalyzed. All available light minimum times (i.e., 9 photographic, 72 visual and 37 CCD ones) are tabulated in Table 2. According to the different measurement precisions, a weight of 1 was assigned to both photographic and visual data, and a weight of 10 to CCD measurements. Using those data, we updated the linear ephemeris as follows,

$$\text{Min. I} = \text{HJD } 2456309.2695(\pm 0.0040) + 1.67975904^{\text{d}}(\pm 0.00000093) \times E. \tag{1}$$

The residuals of $(O - C)_1$ are listed in Table 2, and are plotted against the epoch number in the upper panel of Figure 2.

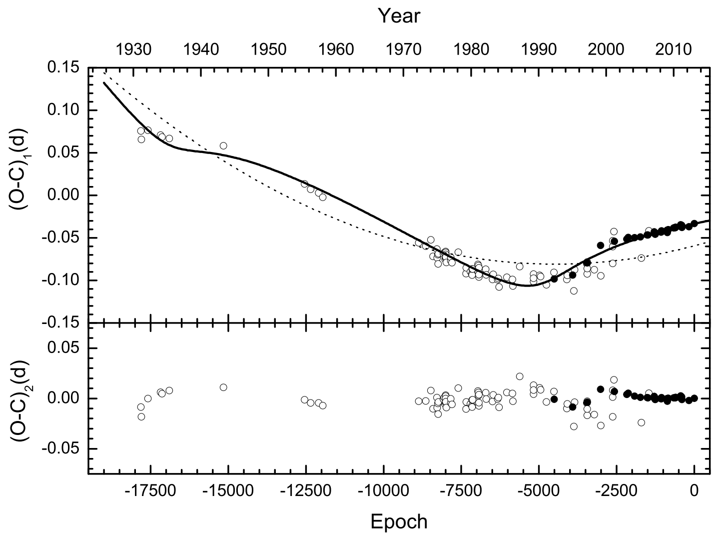


**Fig. 2** The $(O - C)$ curve (*upper panel*) and the resulting residuals (*lower panel*) for the eclipsing binary UU Leo. The open circles refer to visual or photographic observations, while the filled ones represent CCD measurements. The solid and dotted lines are constructed by including all the components in Equation (2) and only its parabolic part, respectively.

**Table 2** All Available Light Minimum Times of UU Leo

| JD (Hel.) | Epoch | Method | Min. | $(O-C)_1$ (d) | $(O-C)_2$ (d) | Ref |
|---|---|---|---|---|---|---|
| 2426384.438 | −17815.0 | pg | I | +0.0758 | −0.0087 | [1] |
| 2426411.304 | −17799.0 | pg | I | +0.0657 | −0.0182 | [2] |
| 2426767.424 | −17587.0 | pg | I | +0.0767 | +0.0000 | [3] |
| 2427459.479 | −17175.0 | pg | I | +0.0710 | +0.0061 | [3] |
| 2427533.386 | −17131.0 | pg | I | +0.0686 | +0.0047 | [3] |
| 2427926.448 | −16897.0 | vi | I | +0.0670 | +0.0078 | [3] |
| 2430849.220 | −15157.0 | vi | I | +0.0583 | +0.0110 | [4] |
| 2435241.745 | −12542.0 | pg | I | +0.0134 | −0.0013 | [5] |
| 2435567.612 | −12348.0 | pg | I | +0.0071 | −0.0044 | [5] |
| 2435997.626 | −12092.0 | pg | I | +0.0028 | −0.0044 | [5] |
| 2436227.748 | −11955.0 | pg | I | −0.0022 | −0.0071 | [5] |
| 2441411.431 | −8869.0 | vi | I | −0.0556 | −0.0029 | [6] |
| 2441794.412 | −8641.0 | vi | I | −0.0596 | −0.0024 | [7] |
| 2442061.501 | −8482.0 | vi | I | −0.0523 | +0.0079 | [8] |
| 2442177.385 | −8413.0 | vi | I | −0.0717 | −0.0102 | [9] |
| 2442390.723 | −8286.0 | vi | I | −0.0631 | +0.0009 | [10] |
| 2442402.471 | −8279.0 | vi | I | −0.0734 | −0.0093 | [11] |
| 2442449.508 | −8251.0 | vi | I | −0.0697 | −0.0051 | [11] |
| 2442464.615 | −8242.0 | vi | I | −0.0805 | −0.0157 | [11] |
| 2442471.346 | −8238.0 | vi | I | −0.0685 | −0.0036 | [12] |
| 2442748.506 | −8073.0 | vi | I | −0.0688 | −0.0008 | [13] |
| 2442785.462 | −8051.0 | vi | I | −0.0675 | +0.0010 | [13] |
| 2442837.527 | −8020.0 | vi | I | −0.0750 | −0.0060 | [14] |
| 2442859.373 | −8007.0 | vi | I | −0.0659 | +0.0034 | [14] |
| 2442864.411 | −8004.0 | vi | I | −0.0671 | +0.0022 | [14] |
| 2442869.444 | −8001.0 | vi | I | −0.0734 | −0.0040 | [14] |
| 2442869.448 | −8001.0 | vi | I | −0.0694 | +0.0000 | [14] |
| 2442874.484 | −7998.0 | vi | I | −0.0727 | −0.0032 | [14] |
| 2442901.354 | −7982.0 | vi | I | −0.0788 | −0.0090 | [15] |
| 2443144.921 | −7837.0 | vi | I | −0.0769 | −0.0044 | [16] |
| 2443144.925 | −7837.0 | vi | I | −0.0729 | −0.0004 | [16] |
| 2443200.351 | −7804.0 | vi | I | −0.0790 | −0.0059 | [17] |
| 2443549.753 | −7596.0 | vi | I | −0.0668 | +0.0102 | [16] |
| 2443966.308 | −7348.0 | vi | I | −0.0921 | −0.0105 | [18] |
| 2443979.753 | −7340.0 | vi | I | −0.0851 | −0.0034 | [16] |
| 2444206.516 | −7205.0 | vi | I | −0.0896 | −0.0055 | [19] |
| 2444285.462 | −7158.0 | vi | I | −0.0923 | −0.0073 | [20] |
| 2444290.500 | −7155.0 | vi | I | −0.0936 | −0.0086 | [21] |
| 2444290.507 | −7155.0 | vi | I | −0.0866 | −0.0016 | [20] |
| 2444317.383 | −7139.0 | vi | I | −0.0867 | −0.0014 | [22] |
| 2444614.706 | −6962.0 | vi | I | −0.0811 | +0.0073 | [16] |
| 2444631.502 | −6952.0 | vi | I | −0.0827 | +0.0058 | [23] |
| 2444636.538 | −6949.0 | vi | I | −0.0859 | +0.0027 | [20] |
| 2444663.404 | −6933.0 | vi | I | −0.0961 | −0.0073 | [24] |
| 2444663.407 | −6933.0 | vi | I | −0.0931 | −0.0043 | [20] |
| 2444663.415 | −6933.0 | vi | I | −0.0851 | +0.0037 | [25] |
| 2445034.640 | −6712.0 | vi | I | −0.0868 | +0.0057 | [16] |
| 2445051.431 | −6702.0 | vi | I | −0.0934 | −0.0007 | [25] |
| 2445397.456 | −6496.0 | vi | I | −0.0988 | −0.0029 | [26] |
| 2445439.456 | −6471.0 | vi | I | −0.0928 | +0.0035 | [27] |
| 2445674.616 | −6331.0 | vi | I | −0.0990 | −0.0007 | [25] |
| 2445711.572 | −6309.0 | vi | I | −0.0977 | +0.0009 | [28] |
| 2445753.556 | −6284.0 | vi | I | −0.1077 | −0.0088 | [29] |
| 2446168.468 | −6037.0 | vi | I | −0.0962 | +0.0058 | [30] |
| 2446470.822 | −5857.0 | vi | I | −0.0988 | +0.0051 | [16] |
| 2446499.370 | −5840.0 | vi | I | −0.1067 | −0.0027 | [31] |
| 2446875.659 | −5616.0 | vi | I | −0.0837 | +0.0219 | [16] |

**Table 2** — *Continued.*

| JD (Hel.) | Epoch | Method | Min. | $(O-C)_1$ (d) | $(O-C)_2$ (d) | Ref |
|---|---|---|---|---|---|---|
| 2447614.744 | −5176.0 | vi | I | −0.0927 | +0.0132 | [16] |
| 2447616.415 | −5175.0 | vi | I | −0.1015 | +0.0043 | [32] |
| 2447616.419 | −5175.0 | vi | I | −0.0975 | +0.0083 | [33] |
| 2447947.335 | −4978.0 | vi | I | −0.0940 | +0.0104 | [34] |
| 2447992.687 | −4951.0 | vi | I | −0.0955 | +0.0086 | [16] |
| 2448308.472 | −4763.0 | vi | I | −0.1052 | −0.0035 | [35] |
| 2448723.387 | −4516.0 | vi | I | −0.0907 | +0.0068 | [36] |
| 2448733.458 | −4510.0 | CCD | I | −0.0982 | −0.0008 | [37] |
| 2449418.799 | −4102.0 | vi | I | −0.0989 | −0.0099 | [16] |
| 2449445.680 | −4086.0 | vi | I | −0.0941 | −0.0055 | [16] |
| 2449734.599 | −3914.0 | CCD | I | −0.0936 | −0.0086 | [38] |
| 2449793.372 | −3879.0 | vi | I | −0.1122 | −0.0279 | [39] |
| 2449840.430 | −3851.0 | vi | I | −0.0874 | −0.0037 | [40] |
| 2450488.824 | −3465.0 | vi | I | −0.0804 | −0.0045 | [16] |
| 2450517.368 | −3448.0 | vi | I | −0.0923 | −0.0167 | [41] |
| 2450517.3810 | −3448.0 | CCD | I | −0.0793 | −0.0037 | [41] |
| 2450517.382 | −3448.0 | vi | I | −0.0783 | −0.0027 | [41] |
| 2450520.740 | −3446.0 | vi | I | −0.0798 | −0.0042 | [16] |
| 2450525.773 | −3443.0 | vi | I | −0.0861 | −0.0106 | [16] |
| 2450900.358 | −3220.0 | vi | I | −0.0874 | −0.0160 | [42] |
| 2451241.3776 | −3017.0 | CCD | I | −0.0589 | +0.0090 | [43] |
| 2451256.4597 | −3008.0 | vi | I | −0.0946 | −0.0269 | [44] |
| 2451901.5019 | −2624.0 | vi | I | −0.0799 | −0.0183 | [45] |
| 2451901.5214 | −2624.0 | vi | I | −0.0604 | +0.0012 | [45] |
| 2451901.5283 | −2624.0 | vi | I | −0.0535 | +0.0081 | [45] |
| 2451958.651 | −2590.0 | vi | I | −0.0426 | +0.0185 | [46] |
| 2451995.5943 | −2568.0 | CCD | I | −0.0540 | +0.0068 | [46] |
| 2452655.7422 | −2175.0 | CCD | I | −0.0514 | +0.0040 | [46] |
| 2452736.3725 | −2127.0 | CCD | I | −0.0495 | +0.0052 | [47] |
| 2453082.4026 | −1921.0 | CCD | I | −0.0498 | +0.0023 | [48] |
| 2453394.8387 | −1735.0 | CCD | I | −0.0489 | +0.0010 | [46] |
| 2453443.527 | −1706.0 | vi | I | −0.0736 | −0.0240 | [49] |
| 2453764.388 | −1515.0 | CCD | I | −0.0466 | +0.0008 | [50] |
| 2453764.3880 | −1515.0 | CCD | I | −0.0466 | +0.0008 | [45] |
| 2453799.6629 | −1494.0 | CCD | I | −0.0466 | +0.0006 | [46] |
| 2453848.3807 | −1465.0 | vi | I | −0.0418 | +0.0051 | [45] |
| 2454137.2982 | −1293.0 | CCD | I | −0.0429 | +0.0022 | [51] |
| 2454140.6560 | −1291.0 | CCD | I | −0.0446 | +0.0004 | [46] |
| 2454177.6101 | −1269.0 | CCD | I | −0.0452 | −0.0004 | [46] |
| 2454191.0487 | −1261.0 | CCD | I | −0.0447 | +0.0000 | [52] |
| 2454199.4466 | −1256.0 | CCD | I | −0.0455 | −0.0008 | [50] |
| 2454199.4478 | −1256.0 | CCD | I | −0.0443 | +0.0004 | [50] |
| 2454200.2862 | −1255.5 | CCD | II | −0.0458 | −0.0011 | [53] |
| 2454496.7665 | −1079.0 | CCD | I | −0.0430 | −0.0001 | [54] |
| 2454520.2829 | −1065.0 | CCD | I | −0.0432 | −0.0005 | [53] |
| 2454533.7225 | −1057.0 | CCD | I | −0.0417 | +0.0010 | [55] |
| 2454844.4787 | −872.0 | CCD | I | −0.0409 | +0.0000 | [56] |
| 2454852.8748 | −867.0 | CCD | I | −0.0436 | −0.0028 | [57] |
| 2454891.5123 | −844.0 | CCD | I | −0.0406 | +0.0000 | [53] |
| 2454907.4703 | −834.5 | CCD | II | −0.0403 | +0.0002 | [53] |
| 2455193.8711 | −664.0 | CCD | I | −0.0384 | +0.0006 | [58] |
| 2455249.3034 | −631.0 | CCD | I | −0.0381 | +0.0006 | [59] |
| 2455285.4185 | −609.5 | CCD | II | −0.0379 | +0.0006 | [59] |
| 2455301.3768 | −600.0 | CCD | I | −0.0373 | +0.0011 | [60] |
| 2455568.4594 | −441.0 | CCD | I | −0.0364 | +0.0006 | [61] |
| 2455579.3797 | −434.5 | CCD | II | −0.0345 | +0.0024 | [52] |
| 2455580.2176 | −434.0 | CCD | I | −0.0365 | +0.0004 | [52] |

**Table 2** — *Continued.*

| JD (Hel.) | Epoch | Method | Min. | $(O-C)_1$ (d) | $(O-C)_2$ (d) | Ref |
|---|---|---|---|---|---|---|
| 2455625.5725 | −407.0 | CCD | I | −0.0351 | +0.0016 | [62] |
| 2455633.9687 | −402.0 | CCD | I | −0.0377 | −0.0010 | [63] |
| 2456018.6344 | −173.0 | CCD | I | −0.0368 | −0.0021 | [64] |
| 2456309.2364 | +0.0 | CCD | I | −0.0331 | +0.0002 | [52] |

References: [1]Guthnick & Prager 1936; [2] Soloviev 1936; [3] Jensch 1935; [4] Soloviev 1943; [5] Whitney 1959; [6] Diethelm 1972; [7] Locher 1973; [8] Locher 1974a; [9] Locher 1974b; [10] Locher 1975a; [11] Locher 1975b; [12] Locher 1976a; [13] Locher 1976b; [14] Locher & Peter 1976; [15] Germann 1976; [16] Baldwin & Samolyk 1999; [17] Locher 1977; [18] Locher 1979a; [19] Locher 1979b; [20] Polorny 1982; [21] Locher 1980a; [22] Locher 1980b; [23] Locher 1981a; [24] Locher 1981b; [25] Mikulasek 1985; [26] Locher 1983; [27] Peter 1983; [28] Locher 1984a; [29] Locher 1984b; [30] Peter 1985; [31] Locher 1986; [32] Paschke 1989; [33] Brno observers 1992; [34] Peter 1990; [35] Peter 1991; [36] Zejda 1995; [37] Paschke 1992; [38] Paschke 1995; [39] Peter 1995a; [40] Peter 1995b; [41] Peter et al. 1997; [42] Peter 1998; [43] Safar & Zejda (2002); [44] Brno observers 2002; [45] Brát et al. 2007; [46] Baldwin & Samolyk 2007; [47] Bakis et al. 2005; [48] Hubscher et al. 2005; [49] Locher 2005; [50] Hubscher 2007; [51] Nagai 2008; [52] Present work; [53] Liakos & Niarchos 2009; [54] Samolyk 2008a; [55] Samolyk 2008b; [56] Dogru et al. 2009; [57] Diethelm 2009; [58] Samolyk 2010; [59] Liakos & Niarchos 2010; [60] Brat et al. (2011); [61] Dogru et al. 2011; [62] Hubscher et al. (2012); [63] Nagai 2012; [64] Diethelm 2012.

In order to find the frequency from the residuals, Fourier analysis was applied using PERIOD04 (Lenz 2004). The power spectrum is displayed in Figure 3, where a significant peak is apparent around the frequency $f = 4.678 \times 10^{-5}\ \mathrm{d}^{-1}$, which corresponds to a period of $\sim 58.5$ yr. As shown in the upper panel of Figure 2, the $(O-C)_1$ curve was described by an upward parabola with a light-time orbit, in a similar way to what was done by Erdem et al. (2007). A nonlinear least-squares fitting method yielded the following equation,

$$(O-C)_1 = -0.0593(\pm 0.0014) + 9.58(\pm 0.54) \times 10^{-6} E + 10.68(\pm 0.32) \times 10^{-10} \times E^2 + \tau, \quad (2)$$

with

$$\tau = A \times \left[ \frac{1-e^2}{1+e\cos\nu} \sin(\nu+\omega) + e\sin\omega \right], \quad (3)$$

where $A = a_{12}/c$ is the semi-amplitude of the light-time orbit, and several other parameters are taken from Irwin (1952). The well-fitted parameters are as follows, $A = 0.0273(\pm 0.0015)$ d, $e = 0.455(\pm 0.019)$, $P_{\rm mod} = 54.5(\pm 0.8)$ yr, $\omega = 5.328(\pm 0.056)$ and $T_p =$ HJD 2448152.8(±90.2). The rate of period increase is $dP/dt = +4.64(\pm 0.14) \times 10^{-7}$ d yr$^{-1}$, which is a bit larger than the value of $+3.04(\pm 0.43) \times 10^{-7}$ d yr$^{-1}$ (Erdem et al. 2007). The modulated period is near the searching period of 58.5 yr (i.e., $1/f$), which is smaller than the derived values of 62(2) yr (Erdem et al. 2007) and 72(±1) yr (Liakos et al. 2011). The final residuals are tabulated in Table 2, and displayed in the lower panel of Figure 2. The solid and dotted lines were constructed by including all the components in Equation (2) and only its parabolic part, respectively. From this figure, HJD 2430849.220 (Soloviev 1943) was fitted well by the solid line.

## 4 LIGHT-CURVE SOLUTION

Multi-color light curves of UU Leo were simultaneously analyzed by using the updated Wilson-Devinney program (Wilson & Devinney 1971; Wilson 1990), which is widely used as a standard tool for modeling the light curves of eclipsing binaries. The bolometric albedos and gravity darkening coefficients were adopted as $A_1 = 1$ and $g_1 = 1$, and $A_2 = 0.5$ and $g_2 = 0.32$, which are appropriate

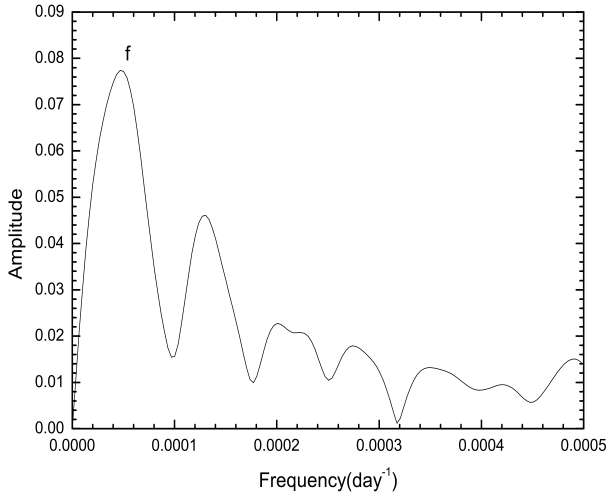


**Fig. 3** Power spectrum of the residuals for the eclipsing binary UU Leo.

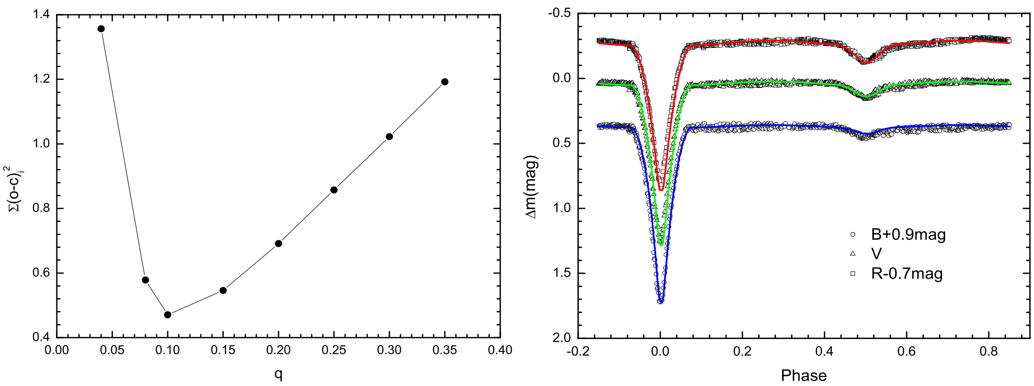


**Fig. 4** *Left panel*: the $q-\Sigma$ curve derived from new $BVR$ observations. *Right panel*: the comparison between observed and theoretical light curves. The solid lines are plotted by using our photometric solution.

for stars with radiative or convective envelopes respectively (Ruciński 1969; von Zeipel 1924 & Lucy 1967). The logarithmic bolometric and monochromatic limb-darkening coefficients ($X$ and $Y$; $x$ and $y$) were taken from the tables of van Hamme (1993). A set of adjustable parameters (i.e., $i$, $q$, $T_2$, $\Omega_1$ and $L_1$) was used in the calculation process.

For UU Leo, Liakos et al. (2011) deduced that there is a detached configuration from $BVRI$ observations. The mean effective temperature of the primary was fixed to be $T_1 = 9000$ K, which corresponds to the spectral type A2 (Brancewicz & Dworak 1980). For several fixed mass ratios from $0.04$ to $0.35$, we performed the "$q$-search" process. From the test solutions, the result implies that UU Leo is a semi-detached binary with the less component filling its Roche lobe (i.e., Mode 5). The $q - \Sigma$ curve is plotted in the right panel of Figure 4, where the minimum sum of squared residuals occurs around a mass ratio of $0.10$. The mass ratio was then included as an adjustable parameter. After some iterations, we obtained the final solution, which is tabulated in Table 3. The final mass ratio is $q = 0.100(\pm 0.002)$, which is similar to the previously studied object AL Gem

**Table 3** Photometric Elements of the Algol-type Binary UU Leo

| Parameter | Primary | Secondary |
|---|---|---|
| $i$ (°) | 88.17(±0.21) | |
| $q$ | 0.100(±0.002) | |
| $T$ (K) | 9000 | 5402(±14) |
| $X, Y$ | +0.658, +0.105 | +0.650, +0.185 |
| $x_B, y_B$ | +0.739, +0.311 | +0.848, +0.080 |
| $x_V, y_V$ | +0.647, +0.274 | +0.784, +0.182 |
| $x_R, y_R$ | +0.524, +0.238 | +0.695, +0.218 |
| $\Omega$ | 4.3614(±0.0116) | 1.9591 |
| $L/(L_1+L_2)_B$ | 0.9461(±0.0019) | 0.0539 |
| $L/(L_1+L_2)_V$ | 0.9084(±0.0023) | 0.0916 |
| $L/(L_1+L_2)_R$ | 0.8719(±0.0026) | 0.1281 |
| $r$ (pole) | 0.2345(±0.0006) | 0.1899(±0.0006) |
| $r$ (point) | 0.2368(±0.0007) | 0.2825(±0.0140) |
| $r$ (side) | 0.2362(±0.0007) | 0.1974(±0.0006) |
| $r$ (back) | 0.2366(±0.0007) | 0.2283(±0.0007) |
| $\Sigma(O-C)_i^2$ | 0.4675 | |

($q = 0.090 \pm 0.005$; Yang et al. 2012). Therefore, UU Leo may be an R CMa-type star (Kopal 1956). The computed light curves are shown as solid lines in the left panel of Figure 4, which evidently provides a good fit to photometric observations.

## 5 DISCUSSION

UU Leo is a classic Algol-type binary, whose less component fills its Roche lobe with a mass ratio of $q = 0.100(\pm 0.002)$. The $O - C$ curve shows a secular increase in period with light-time orbit. This case may appear in other Algol-type binaries. According to its spectral type, the mass of the primary component is $M_1 = 2.54\ M_\odot$ (Cox 2000). Using the photometric elements, other absolute parameters are listed as follows: $M_2 = 0.25\ M_\odot$, $R_1 = 1.98\ R_\odot$ and $R_2 = 1.88\ R_\odot$.

From Equation (2), there exists a light-time effect via the presence of a third body (Irwin 1952). Using the fitted parameters, we can calculate the value of $a_{12} \sin i = A \times c = 4.73(\pm 0.26)$ AU. The mass function of the third body is then computed by using the following equation,

$$f(M_3) = \frac{4\pi^2}{GP_3^2} \times (a_{12} \sin i')^3 = \frac{(M_3 \sin i)^3}{(M_1 + M_2 + M_3)^2} \,. \tag{4}$$

Assuming the binary follows a coplanar orbit (i.e., $i = 88.17°$), the mass and orbital radii of the additional component are $M_3 = 0.88(\pm 0.04)\ M_\odot$ and $a_{12} = 15.0(\pm 1.5)$ AU, respectively. Therefore, an invisible component may exist in this binary system. Another possible mechanism for the cyclic changes is cyclic magnetic activity (Applegate 1992), which may result in the observed cyclic variation by a gravitational coupling mechanism. For the early spectral type of A2, the cyclic magnetic activity may be attributed to the late-type secondary star. Using the relation $\frac{\Delta P}{P} = -9\frac{\Delta Q}{Ma^2} \simeq \frac{2\pi A}{P_{\rm mod}}$ (Lanza & Rodonò 2002), we can calculate the value of $\Delta Q_2 = 1.64(\pm 0.09) \times 10^{50}$ g cm$^2$, which is much smaller than the order of $10^{51} - 10^{52}$ g cm$^2$ for typical Algol-type binaries (Lanza & Rodonò 1999). Therefore, the light-time effect may be acceptable for interpreting the observed cyclic variation.

For Algol-type binaries, the less massive component fills its Roche lobe. The outflowing matter may be transferred to the more massive one or escape from the binary system. From Equation (2), the orbital period continuously increases at a rate of $dP/dt = +4.64(\pm 0.14) \times 10^{-8}$ d yr$^{-1}$, which may result from the conserved mass being transferred from the secondary to the primary. Using the equation (Singh & Chaubey 1986),

$$\frac{\dot{P}}{P} = -3(1-q)\frac{\dot{M}_2}{M_2}, \tag{5}$$

we can compute the mass loss rate to be $2.60(\pm 0.08) \times 10^{-8}\ M_\odot\ \mathrm{yr}^{-1}$. Assuming the conserved mass transfer has a rate of $\sim \times 10^{-8}\ M_\odot\ \mathrm{yr}^{-1}$, Kippenhahn et al. (1967) proposed that a low-mass Algol-type binary may evolve by Low Mass Case B (Shore et al. 1994). As mass is being transferred, the classic Algol-type binary UU Leo may be transformed into an A-type main sequence star plus a helium white dwarf. In future observations, high-precision photometry and spectroscopy for UU Leo are necessary for identifying changes in period and to determine the absolute parameters.

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