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Photometric study and period analysis of the W UM-type binary system QW Gem

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Abstract New multi-color photometric observations of the previously unstudied contact binary QW Gem are presented. Completely covered $BVRI$ band light curves were obtained, including four new times of light minima. The light curves were simultaneously analyzed with the 2013 version of the Wilson-Devinney method, assuming a third light. The photometric solutions confirm that QW Gem is a W-type W UMa system with a fill-out factor of $f \sim 17\%$. The absolute parameters of the components were determined to be $M_p = 1.33 \pm 0.03\,M_\odot$, $M_s = 0.44 \pm 0.01\,M_\odot$, $R_p = 1.25 \pm 0.01\,R_\odot$, $R_s = 0.77 \pm 0.01\,R_\odot$, $L_p = 1.68 \pm 0.03\,L_\odot$ and $L_s = 0.68 \pm 0.01\,L_\odot$. The orbital period change of QW Gem was investigated by the $O - C$ method using all available data. The results show that this binary system could have undergone a continuous orbital period decrease during the past two decades at a rate of about $dP/dt = -2.55 \times 10^{-7}$ d yr^{-1}. In addition, a small-amplitude oscillation was detected to be superimposed on a long-term decrease.

Key words: stars: binaries: eclipsing — stars: individual (QW Gem)

1 INTRODUCTION

W UMa-type binary stars are composed of two cool, solar-type components sharing a common convective envelope, with spectral types ranging from F to K (Rucinski 1998; Qian et al. 2014). The two light minima of the light curves of W UMa stars have nearly equal depths, indicating that both components have approximately equal surface temperature, but the masses of the two stars are typically unequal. W UMa stars are subdivided into A- and W-type systems (Binnendijk 1970), where in W-type systems the smaller, less massive star is eclipsed at the primary minimum (i.e., the less massive component is the hotter one). In addition, the light curves of many W UMa systems show a poorly understood feature called the O'Connell effect (Milone 1968; Wang et al. 2015), where the two maxima are unequally high. Those peculiar observational properties challenge the current theory of stellar evolution. Although W UMa stars are the most common type of close binaries, their origin, structure and evolution have still not been conclusively explained. To understand these questions, the absolute parameters for more W UMa stars need to be precisely determined.

Light variability of QW Gem was discovered by the *Hipparcos* mission. Rucinski et al. (2003) contributed the first radial velocity orbital solution and estimated the mass ratio to be 0.334 ± 0.009. Based on the *Hipparcos* ephemeris, they classified this contact binary as W subtype. Kreiner et al. (2003) published the only ground-based $BVRI$ light curves for this binary star. The photometric solutions were obtained with their relatively poor light curves and the spectroscopic mass ratio was given by Kreiner et al. (2003), assuming a third light in the model. Pribulla & Rucinski (2006) later listed QW Gem as a triple system by analyzing data from the *Hipparcos* mission and the Washington Double Star Catalog. The system was observed by the Large Sky Area Multi-Object Fiber Spectroscopic Telescope (LAMOST) on 2013 January 2 and its stellar atmospheric parameters were determined as follows: $T = 5890$ K, $\log(g) = 4.12$ and [Fe/H]$= -0.14$ (Luo et al. 2016). Recently, Qian et al. (2017) cataloged the stellar atmospheric parameters of 5363 EW-type binary stars based on LAMOST spectroscopic observations. Comparing the stellar atmospheric parameters of QW Gem with those of other EWs reveals that this system is a typical EW-type contact binary.

These observations indicate that QW Gem has not been thoroughly investigated photometrically and the published light curves look relatively poor, although the spectroscopic elements of the system were published ten years ago. Additionally, many CCD times of minimum light for QW Gem were reported after the photometric study of Kreiner et al. (2003). The times of light minima that have a time span of more than twenty years could be used to study the orbital period changes in detail. All of these suggest that QW Gem is an interesting object for further investigation. We have therefore performed new high-precision, multi-color photometry for this binary system and the results of these observations will be presented in this paper.

2 OBSERVATIONS AND DATA REDUCTIONS

New CCD photometric observations were carried out on 2014 December 21 and 22, with the 85 cm reflecting telescope at Xinglong Station of National Astronomical Observatories, Chinese Academy of Sciences. The detector was an Andor iKon-L 936 2k×2k CCD camera with a field view of $33' \times 33'$, corresponding to an image scale of about $0.97''\,\mathrm{pixel}^{-1}$. The standard Johnson-Cousins-Bessel set of $BVRI$ filters was alternately used during the observations. We have collected about 820 useful images in each B-, V-, R- and I-band.

The CCD frames were preliminarily processed using the standard routines of the IRAF/CCDPROC package, including bias and dark subtraction, and flat-field correction. Photometry was then extracted with the aperture photometry package IRAF/PHOT since the field of QW Gem is not crowded. A nearby star UCAC4 598–036879 ($\alpha_{2000} = 06:50:55.66$, $\delta_{2000} = +29:29:17.2$) was used as the comparison star of QW Gem, and another one, UCAC4 598–036940 ($\alpha_{2000} = 06:51:22.01$, $\delta_{2000} = +29:28:23.1$), was applied as the check star. The standard deviations of the differential magnitude between the check and comparison stars were calculated to be about 0.008 mag (BV), 0.008 mag (R) and 0.01 mag (I). With respect to the comparison star, the differential magnitudes of QW Gem were then extracted in each image. We converted the mid-exposure time of each measurement to Heliocentric Julian Date (HJD) and obtained the light curves.

3 PERIOD ANALYSIS AND DETERMINATION OF EPHEMERIS

Four primary and secondary eclipses were recorded during our observations. The epochs of these light minima were computed from parabolic fits (Kwee & van Woerden 1956), as listed in Table 1. Beyond such newly-determined times of minima, we have collected another 60 CCD times of light minima from publications. All of the times of light minima have a time span of more than twenty years and thus can be used to make a precision period analysis. Linear and quadratic ephemerides were derived from all eclipse timings by applying least squares fitting.

$$\mathrm{Min.I} = 2457013.2676(4) + 0.35812261(6) \times E\,, \quad (1)$$

$$\begin{aligned}\mathrm{Min.I} = {} & 2457013.2651(1) + 0.35812062(4) \times E \\ & - 1.25(2) \times 10^{-10} \times E^2\,,\end{aligned} \quad (2)$$

where Min.I is the calculational time of minimum light and E stands for the eclipse cycle number. The $O-C$ residuals that were calculated with the linear and quadratic ephemerides above are listed in Table 1.

An $O-C$ diagram of the period analysis is shown in Figure 1. The solid line in the upper panel of Figure 1 displays the quadratic fit to the linear residuals from Equation (2), suggesting that the binary system was undergoing a rapid orbital period decrease. The rate of period decrease is calculated to be about $dP/dt = 2.55 \times 10^{-7}\,\mathrm{d\,yr}^{-1}$. The resulting residuals based on Equation (2) are shown in the lower panel of Figure 1, in which there seems to be a trend. As Kreiner et al. (2003) and Pribulla & Rucinski (2006) pointed out, QW Gem could be a triple system, indicating that this trend may be attributed to the light-time effect due to a tertiary body. However, the orbital elements of the third body cannot be determined from the current data, with a relatively short time span of about twenty years and a lower semi-amplitude of about 0.0025 d.

4 PHOTOMETRIC SOLUTIONS WITH THE WILSON-DEVINNEY METHOD

The light curves of QW Gem were phased using the reference epoch and the orbital period in Equation (2). The phased light curves, Δmag versus phase, are displayed

Table 1 Eclipse Timings and the Residuals of QW Gem, Computed from the Linear And Quadratic Ephemerides

HJD (2400000+)	Min.	Filter	E	$(O-C)_1$ (d)	$(O-C)_2$ (d)	Reference
48500.3060	I	V	–23771.0	–0.0289	–0.0031	the O-C gateway
51278.8270	II		–16012.5	–0.0023	0.0005	the O-C gateway
51927.3928	II	$BVRI$	–14201.5	0.0035	0.0030	Drozdz & Ogloza (2005)
51927.5723	I	$BVRI$	–14201.0	0.0039	0.0034	Drozdz & Ogloza (2005)
52308.2570	I		–13138.0	0.0043	0.0022	the O-C gateway
52655.2764	I		–12169.0	0.0029	–0.0003	Diethelm (2003)
52689.2991	I		–12074.0	0.0039	0.0006	Diethelm (2003)
52694.3140	I		–12060.0	0.0051	0.0018	Diethelm (2003)
53040.6172	I		–11093.0	0.0037	–0.0004	Nelson (2005)
53057.2714	II		–11046.5	0.0052	0.0010	Krajci (2005)
53697.7729	I	R	–9258.0	0.0044	–0.0007	Nelson (2006)
54417.2420	I	I	–7249.0	0.0052	–0.0001	the O-C gateway
54454.8445	I	V	–7144.0	0.0048	–0.0005	Dvorak (2008)
54506.4138	I	V	–7000.0	0.0045	–0.0008	Hubscher et al. (2009)
54544.3743	I		–6894.0	0.0040	–0.0013	the O-C gateway
54544.3746	I		–6894.0	0.0043	–0.0010	Marino et al. (2010)
54821.7408	II	R	–6119.5	0.0045	–0.0004	Nelson (2009)
55628.4095	I	I	–3867.0	0.0020	–0.0013	Hoňková et al. (2013)
55628.4097	I	R	–3867.0	0.0022	–0.0011	Hoňková et al. (2013)
55628.4099	I	B	–3867.0	0.0024	–0.0009	Hoňková et al. (2013)
55628.4099	I	V	–3867.0	0.0024	–0.0009	Hoňková et al. (2013)
55835.5826	II	B	–3288.5	0.0012	–0.0015	Hoňková et al. (2013)
55835.5830	II	R	–3288.5	0.0016	–0.0011	Hoňková et al. (2013)
55835.5832	II	I	–3288.5	0.0018	–0.0009	Hoňková et al. (2013)
55835.5833	II	V	–3288.5	0.0019	–0.0008	Hoňková et al. (2013)
55969.3412	I	V	–2915.0	0.0010	–0.0012	Hoňková et al. (2013)
55969.3414	I	I	–2915.0	0.0012	–0.0010	Hoňková et al. (2013)
55969.3414	I	R	–2915.0	0.0012	–0.0010	Hoňková et al. (2013)
55969.3415	I	B	–2915.0	0.0013	–0.0009	Hoňková et al. (2013)
55990.2920	II	I	–2856.5	0.0016	–0.0005	Hoňková et al. (2013)
55990.2922	II	R	–2856.5	0.0018	–0.0003	Hoňková et al. (2013)
55990.2923	II	B	–2856.5	0.0019	–0.0002	Hoňková et al. (2013)
55990.2925	II	V	–2856.5	0.0021	–0.0000	Hoňková et al. (2013)
56376.3463	II	I	–1778.5	–0.0003	–0.0009	Honková et al. (2014)
56376.3469	II	V	–1778.5	0.0003	–0.0003	Honková et al. (2014)
56376.3473	II	B	–1778.5	0.0007	0.0001	Honková et al. (2014)
56376.3477	II	R	–1778.5	0.0011	0.0005	Honková et al. (2014)
56407.3238	I	B	–1692.0	–0.0004	–0.0008	Honková et al. (2014)
56407.3240	I	V	–1692.0	–0.0002	–0.0006	Honková et al. (2014)
56407.3242	I	I	–1692.0	0.0000	–0.0004	Honková et al. (2014)
56407.3248	I	R	–1692.0	0.0006	0.0002	Honková et al. (2014)
56629.5378	II	B	–1071.5	–0.0014	–0.0009	Honkova et al. (2015)
56629.5380	II	I	–1071.5	–0.0012	–0.0007	Honkova et al. (2015)
56629.5381	II	V	–1071.5	–0.0011	–0.0006	Honkova et al. (2015)
56629.5387	II	B	–1071.5	–0.0005	0.0000	Honkova et al. (2015)
56630.4330	I	I	–1069.0	–0.0015	–0.0010	Honkova et al. (2015)
56630.4338	I	V	–1069.0	–0.0007	–0.0002	Honkova et al. (2015)
56630.4340	I	B	–1069.0	–0.0005	0.0000	Honkova et al. (2015)
56949.5198	I	B	–178.0	–0.0020	0.0002	Juryšek et al. (2017)

Table 1 — *Continued.*

HJD (2400000+)	Min.	Filter	E	$(O-C)_1$ (d)	$(O-C)_2$ (d)	Reference
56949.5208	I	V	–178.0	–0.0010	0.0012	Juryšek et al. (2017)
56949.5211	I	R	–178.0	–0.0007	0.0015	Juryšek et al. (2017)
56949.5211	I	R	–178.0	–0.0007	0.0015	Juryšek et al. (2017)
56958.4722	I	I	–153.0	–0.0027	–0.0004	Juryšek et al. (2017)
56958.4728	I	V	–153.0	–0.0021	0.0002	Juryšek et al. (2017)
56958.4731	I	B	–153.0	–0.0018	0.0005	Juryšek et al. (2017)
56958.4731	I	R	–153.0	–0.0018	0.0005	Juryšek et al. (2017)
57013.0865	II	B	–0.5	–0.0021	0.0005	present work
57013.0862	II	V	–0.5	–0.0024	0.0002	present work
57013.0866	II	R	–0.5	–0.0020	0.0006	present work
57013.0863	II	I	–0.5	–0.0023	0.0003	present work
57013.2655	I	B	0.0	–0.0021	0.0004	present work
57013.2651	I	V	0.0	–0.0025	0.0000	present work
57013.2649	I	R	–0.0	–0.0027	–0.0002	present work
57013.2659	I	I	0.0	–0.0017	0.0008	present work
57014.1608	II	B	2.5	–0.0021	0.0004	present work
57014.1613	II	V	2.5	–0.0016	0.0009	present work
57014.1611	II	R	2.5	–0.0018	0.0007	present work
57014.1613	II	I	2.5	–0.0016	0.0009	present work
57014.3400	I	B	3.0	–0.0020	0.0006	present work
57014.3398	I	V	3.0	–0.0022	0.0004	present work
57014.3404	I	R	3.0	–0.0016	0.0010	present work
57014.3402	I	I	3.0	–0.0018	0.0008	present work
57122.3131	II	B	304.5	–0.0029	0.0003	Juryšek et al. (2017)
57122.3133	II	V	304.5	–0.0027	0.0005	Juryšek et al. (2017)
57122.3130	II	R	304.5	–0.0030	0.0002	Juryšek et al. (2017)
57122.3136	II	I	304.5	–0.0024	0.0008	Juryšek et al. (2017)

in Figure 2. The general feature of the light curves is shown to be typical of W UMa systems with nearly equal minima. The brightness differences between the primary minima at phase 0.0 and the first light maxima at phase 0.25 were measured to be about 0.451, 0.395, 0.347 and 0.307 mag in the B, V, R and I filters, respectively. The moderately large amplitudes suggest that QW Gem is a totally eclipsing binary system with a very high orbital inclination angle. The two light maxima have nearly equal brightness in all bands.

To explore the nature and geometrical layout, multicolor light curves of QW Gem were simultaneously analyzed with the 2013 version of the Wilson-Devinney method (Wilson & Devinney 1971; Wilson 1979, 1990, 2012), assuming the Kurucz, rather than blackbody, stellar atmosphere model. A circular orbit ($e = 0$) and synchronous rotation ($F_1 = F_2 = 1.0$) were adopted, considering the evolutionary status and short orbital period of this binary. Since this binary has been argued to be a W-subtype system, we designated the less-massive component as star 1 (the star eclipsed at primary minimum), and the more massive one as star 2. The mean temperature of star 2, the luminous component, is set at $T_2 = 5890$ K from the LAMOST DR2 catalogs (Luo et al. 2016). The mass ratio is fixed at $q = M_2/M_1 = 2.994$, the inverse value of the spectroscopic mass ratio $q_{\rm sp} = 0.334$ reported by Rucinski et al. (2003). The bolometric (X_1, X_2, Y_1, Y_2) and monochromatic limb-darkening coefficients (x_2, x_2, y_1, y_2) were interpolated from van Hamme (1993) tables with the logarithmic law. The bolometric albedos $A_{1,2}$ and gravity darkening exponents $g_{1,2}$ were taken as 0.5 (Ruciński 1969) and 0.32 (Lucy 1967), respectively.

The system configuration was set as mode 3 (contact configuration), according to the results given by Rucinski et al. (2003) and Kreiner et al. (2003). The temperature of

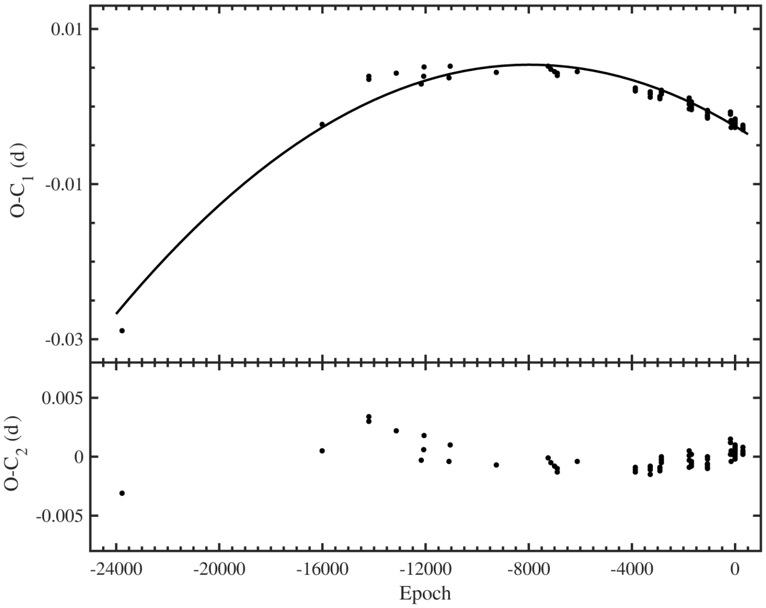

Fig. 1 $O-C$ diagram of QW Gem. The $(O-C)_1$ values, calculated with Eq. (1), are shown by *dark dots*. The *solid line* in the *upper panel* represents the quadratic fit to the linear residuals from Eq. (2). The $(O-C)_2$ values with respect to the quadratic ephemeris are displayed in the *lower panel*.

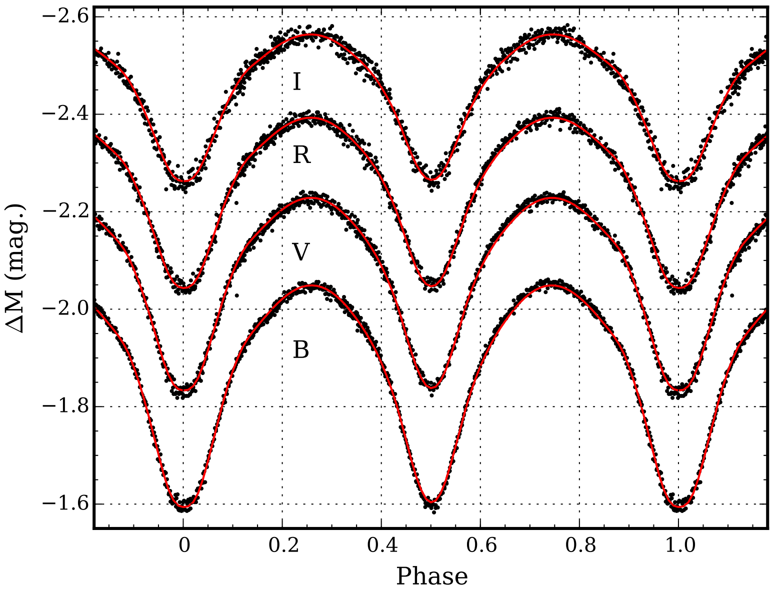

Fig. 2 Observed B-, V-, R- and I-band light curves of QW Gem plotted along with their theoretical synthesis. The *dark dots* and *red lines* represent the individual observations and theoretical curves, respectively.

star 1 T_1, the inclination i, the dimensionless potential of star 1 Ω_1, the monochromatic luminosity of star 1 and the phase shift were varied. Additionally, a third light was set as an adjustable parameter due to the possible existence of third bodies in this binary system, as mentioned earlier. Finally, we obtained the photometric solutions with best fitting, assuming a third light. The results are illustrated in Table 2 and the synthetical light curves from the best-fit solution are shown in Figure 2. A geometric configuration of the system is displayed in Figure 3.

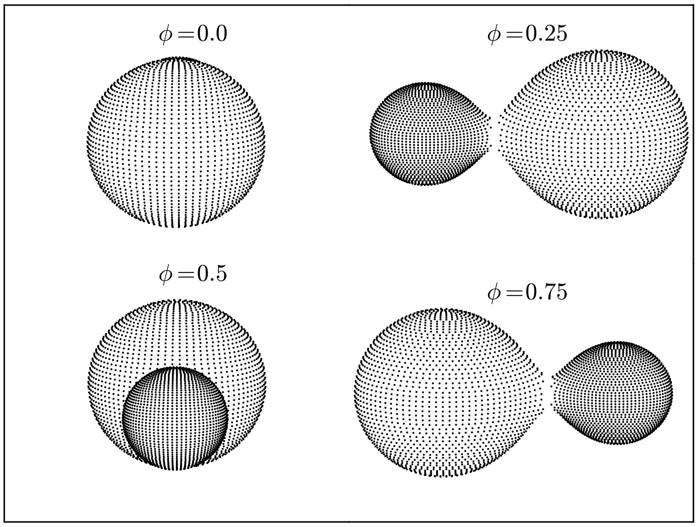

Fig. 3 Geometrical structure of QW Gem at phases 0.0, 0.25, 0.5 and 0.75.

Table 2 Photometric Solutions of Contact Binary QW Gem

Parameter	Best-Fit value	Formal error
$i\,(^\circ)$	79.4	±0.2
$q = M_2/M_1$	2.994	
T_1 (K)	6005	±4
T_2 (K)	5890	
$\Omega_1 = \Omega_2$	6.5014	±0.0045
l_{1B}	0.292	±0.003
l_{1V}	0.283	±0.003
l_{1R}	0.277	±0.003
l_{1I}	0.271	±0.004
l_{3B}	0.017	±0.001
l_{3V}	0.024	±0.001
l_{3R}	0.032	±0.001
l_{3I}	0.044	±0.002
r_1 (pole)	0.2771	±0.0003
r_1 (side)	0.2898	±0.0004
r_1 (back)	0.3290	±0.0007
r_2 (pole)	0.4545	±0.0003
r_2 (side)	0.4890	±0.0004
r_2 (back)	0.5173	±0.0005

Notes: l_1=$L_1/(L_1 + L_2 + L_3)$ - fractional luminosity of the primary star,
l_3=$L_3/(L_1 + L_2 + L_3)$ - fractional luminosity of the third light.

5 DISCUSSION AND CONCLUSIONS

The photometric solutions suggest that QW Gem is a shallow-contact binary system with a degree of contact of $f \sim 17\%$. The system is demonstrated to be a W-type W UMa system, with the less-massive component hotter by 115 K than the more massive component. Combining the spectroscopic elements (Rucinski et al. 2003) and our photometric solutions, the absolute parameters of QW Gem are calculated as follows:

$$M_p = 1.33 \pm 0.03\ M_\odot,$$

$$M_s = 0.44 \pm 0.01\, M_\odot,$$

$$R_p = 1.25 \pm 0.01\, R_\odot,$$

$$R_s = 0.77 \pm 0.01\, R_\odot,$$

$$L_p = 1.68 \pm 0.03\, L_\odot$$

and

$$L_s = 0.68 \pm 0.01\, L_\odot.$$

The general trend of the $(O-C)_1$ curve in Figure 1 reveals a long-term orbital period decrease at a rate of about $dP/dt = -2.55 \times 10^{-7}$ d yr^{-1}. The continuous decrease in the orbital period and the shallow-contact configuration ($f \sim 17\%$) both suggest that QW Gem is a newly-formed contact binary via Case A mass transfer and is evolving into a normal overcontact phase. This situation is similar to other contact binary stars such as MR Com (Qian et al. 2013), AO Cam (Yang et al. 2010) and WZ Cep (Zhu & Qian 2009), all of which show a shallow contact configuration with a long-term decreasing orbital period. The secular period decrease is generally caused by mass transfer from the more massive star to the less massive one and long-term angular momentum loss (AML) via magnetic braking (Qian 2001, 2003). The mass transfer rate can be estimated with the derived absolute parameters and the following well-known equation (Singh & Chaubey 1986), assuming conservative mass transfer

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

where M_2 and $\dot{M_2}$ represent the mass and mass transfer rate of the less massive component, respectively. The value of $\dot{M_2}$ is calculated to be about $-1.57 \times 10^{-7}\, M_\odot$ yr^{-1}. The time scale of possible mass transfer for the more massive component can be estimated as 8.48×10^6 yr. This is obviously shorter than the thermal time scale of the donor, $\tau_{\rm th} \sim \frac{GM^2}{RL} \sim 1.68 \times 10^7$ yr. This may suggest that it is on the AML-controlled stage, as proposed by Qian (2001, 2003). The decreasing period will result in shrinkage of the orbit of the system, accompanied by an increasing degree of contact.

Finally, the system will evolve into a deep contact configuration, like other shallow contact binaries with a decreasing orbital period. In addition, the $(O-C)_2$ trend in the lower panel of Figure 1 also suggests that QW Gem is likely a triple system, as pointed out by Kreiner et al. (2003) and Pribulla & Rucinski (2006), superimposed on a possible light-time effect due to the tertiary body. However, we cannot discuss this in detail because of the short time span of the observations. Further high-precision observations for QW Gem are needed to investigate its orbital period changes.

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References

Binnendijk, L. 1970, Vistas in Astronomy, 12, 217
Diethelm, R. 2003, Information Bulletin on Variable Stars, 5438
Drozdz, M., & Ogloza, W. 2005, Information Bulletin on Variable Stars, 5623
Dvorak, S. W. 2008, Information Bulletin on Variable Stars, 5814
Honková, K., Juryšek, J., Lehký, M., et al. 2014, Open European Journal on Variable Stars, 165, 1
Honkova, K., Jurysek, J., Lehky, M., et al. 2015, Open European Journal on Variable Stars, 168, 1
Hoňková, K., Juryšek, J., Lehký, M., et al. 2013, Open European Journal on Variable Stars, 160, 1
Hubscher, J., Steinbach, H.-M., & Walter, F. 2009, Information Bulletin on Variable Stars, 5874
Juryšek, J., Hoňková, K., Šmelcer, L., et al. 2017, Open European Journal on Variable Stars, 179, 1
Krajci, T. 2005, Information Bulletin on Variable Stars, 5592
Kreiner, J. M., Rucinski, S. M., Zola, S., et al. 2003, A&A, 412, 465
Kwee, K. K., & van Woerden, H. 1956, Bull. Astron. Inst. Netherlands, 12, 327
Lucy, L. B. 1967, ZAp, 65, 89
Luo, A.-L., Zhao, Y.-H., Zhao, G., et al. 2016, VizieR Online Data Catalog, 5149
Marino, G., Arena, C., Bellia, I., et al. 2010, Information Bulletin on Variable Stars, 5917
Milone, E. E. 1968, AJ, 73, 708
Nelson, R. H. 2005, Information Bulletin on Variable Stars, 5602
Nelson, R. H. 2006, Information Bulletin on Variable Stars, 5672
Nelson, R. H. 2009, Information Bulletin on Variable Stars, 5875
Pribulla, T., & Rucinski, S. M. 2006, AJ, 131, 2986
Qian, S. 2001, MNRAS, 328, 635
Qian, S. 2003, MNRAS, 342, 1260
Qian, S.-B., He, J.-J., Zhang, J., et al. 2017, arXiv:1705.03996
Qian, S.-B., Liu, N.-P., Liao, W.-P., et al. 2013, AJ, 146, 38
Qian, S.-B., Wang, J.-J., Zhu, L.-Y., et al. 2014, ApJS, 212, 4
Ruciński, S. M. 1969, Acta Astronomica, 19, 245

Rucinski, S. M. 1998, AJ, 116, 2998
Rucinski, S. M., Capobianco, C. C., Lu, W., et al. 2003, AJ, 125, 3258
Singh, M., & Chaubey, U. S. 1986, Ap&SS, 124, 389
van Hamme, W. 1993, AJ, 106, 2096
Wang, K., Zhang, X., Deng, L., et al. 2015, ApJ, 805, 22
Wilson, R. E. 1979, ApJ, 234, 1054
Wilson, R. E. 1990, ApJ, 356, 613
Wilson, R. E. 2012, Journal of Astronomy and Space Sciences, 29, 115
Wilson, R. E., & Devinney, E. J. 1971, ApJ, 166, 605
Yang, Y.-G., Wei, J.-Y., Kreiner, J. M., & Li, H.-L. 2010, AJ, 139, 195
Zhu, L. Y., & Qian, S. B. 2009, AJ, 138, 2002