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Photometric study and period variation investigation of the W UMa-type binary EQ UMa

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Abstract

Four-color light curves of EQ UMa were obtained with the 1.0 m telescope at Weihai Observatory, Shandong University. The light variability of EQ UMa is typical of a W UMa-type binary. By analyzing the four-color light curves simultaneously, we found that EQ UMa is a semi-detached binary with the less massive component filling its inner Roche lobe. The very short period and the Algol-type configuration make EQ UMa a very good target to challenge the formation and evolution theory of low-mass Algols. We investigated the orbital period change of EQ UMa by all available times of minimum light. It is shown that the orbital period of EQ UMa displays a cyclic oscillation with a period of 12.1 yr superimposed on long-term increase with a rate of $dp/dt = 1.77 \times 10^{-7}\,\mathrm{d\,yr^{-1}}$. The long-term period increase should be caused by the mass transfer from the less massive component to the more massive one. The cyclic modulation is very probably produced by the light travel time effect of a third component.

Key words: binaries: close — binaries: eclipsing — stars: individual (EQ UMa)

1 Introduction

W UMa-type binaries usually contain two main-sequence stars which have F to K spectral types. Both component stars are usually in contact with each other and share a common convective envelope. This type of binary usually shows EW-type light curves, where the light variation is continuous and the difference between the depths of the two minima is very small. Though this type of binaries has been analyzed by many authors (e.g., Liu et al. 2011; Qian et al. 2013; Li et al. 2015), their origin, structure, and evolution are still confused. More observation and investigation are needed for W UMa-type binaries.

The light variability of EQ UMa was first discovered by De Young and Schmidt (1992) during an observation program to collect data on superhump phenomena, and they obtained the *I* band light curve. They thought this binary to be a borderline semi-detached/contact type binary system. The nearly equal depths of the two minima and continuous light variation indicate that EQ UMa is a W UMa-type binary. The light curve of EQ UMa shows a clear O'Connell effect. Preliminary analysis of the light curve was also carried out by De Young and Schmidt (1992): it was found that the inclination is $56\overset{\circ}{.}5$; no other parameters of EQ UMa were determined. Therefore, this binary is worth further study.

2 Observations

EQ UMa was monitored using the 1.0 m telescope at Weihai Observatory, Shandong University (Hu et al. 2014) on

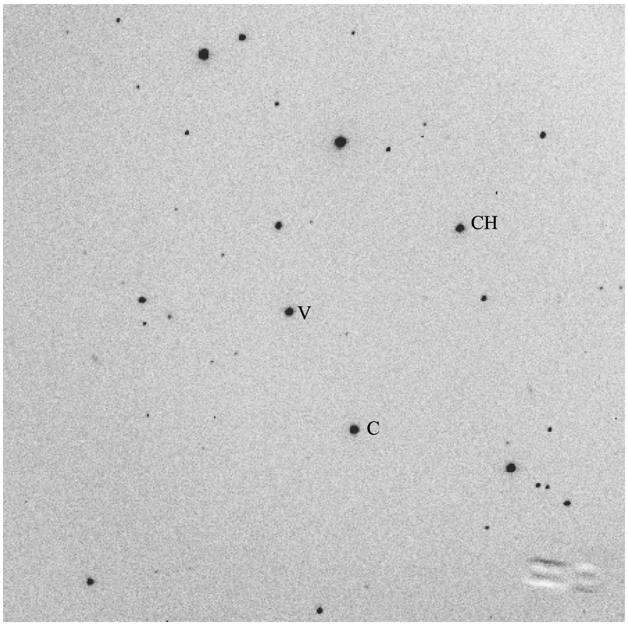

Fig. 1. One CCD image of EQ UMa derived by the 1.0 m telescope. "V" shows the variable EQ UMa, "C" represents the comparison star, and "CH" shows the check star. North is up and east is to the left.

2015 January 2, March 3, and March 9. The observations were obtained using an Andor DZ936 CCD camera. The effective field of view of the photometric system is about $12' \times 12'$. Light curves of EQ UMa in the Johnson–Cousin–Bessel BVR_cI_c bands were derived. Typical integration times were 60 s in B band, 40 s in V band, 25 s in R_c band, and 20 s in I_c band, respectively. Figure 1 displays one CCD image in V band observed by the 1.0 m telescope. The target, the comparison star, and the check star are shown in this figure. All the CCD images were reduced using the IRAF software. We did not make extinction corrections because the comparison star is very close to the target. The $(V - C)$ magnitude differences versus HJD times of the four-color light curves are plotted in figure 2. During our observations, five times of minimum light were obtained. Including epochs of minimum light determined from the AAVSO (American Association of Variable Stars Observers) International database,[1] ten newly determined times of minimum light are listed in table 1.

3 Period investigation

Since the discovery of EQ UMa, no one has analyzed the orbital period change. To this end, we collected all available times of minimum light from the literature and combined our newly determined minima to analyze the orbital period variation of EQ UMa. For the period investigation of EQ UMa, we have collected a total of 24 timings. The

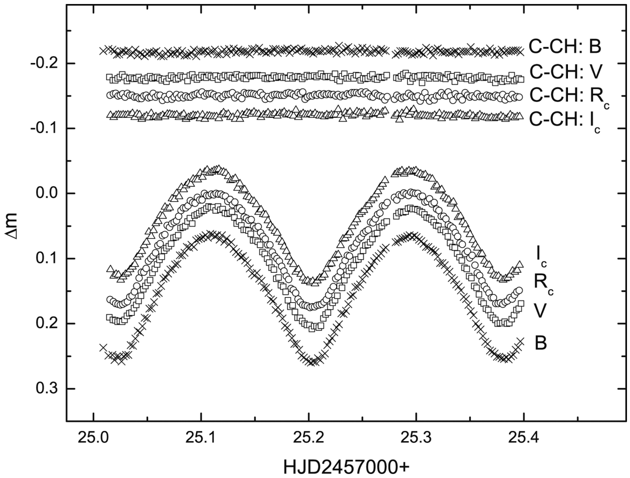

Fig. 2. The observed four-color light curves of EQ UMa. Different symbols represent different light curves in different filters.

Table 1. New determined times of minimum light for EQ UMa.

JD (Hel.)	Errors	Min.	Method	Source
2453822.7751	±0.0005	p	ccd	AAVSO
2453779.9695	±0.0011	p	ccd	AAVSO
2453779.7924	±0.0011	p	ccd	AAVSO
2453746.8448	±0.0005	p	ccd	AAVSO
2453496.6754	±0.0008	p	ccd	AAVSO
2457025.0237	±0.0005	p	ccd	1 m
2457025.2034	±0.0003	p	ccd	1 m
2457025.3802	±0.0003	p	ccd	1 m
2457085.0149	±0.0004	p	ccd	1 m
2457091.1022	±0.0002	s	ccd	1 m

$O - C$ residuals are calculated using the same linear ephemeris as the $O - C$ Gateway,[2]

$$\mathrm{Min.I} = 2448706.7253 + 0.3581533\, E. \quad (1)$$

The determined $(O - C)_1$ values are listed in table 2 and the resultant $(O - C)_1$ curve is shown in the upper panel of figure 3. As seen in figure 3, a simple quadratic polynomial cannot make a good fit—a cyclic term is needed. Therefore, we used the equation (Irwin 1952)

$$\begin{aligned}(O - C)_1 &= T_0 + \Delta T_0 + (P_0 + \Delta P_0)E + \frac{\beta}{2}E^2 \\ &\quad + A\left[(1 - e^2)\frac{\sin(\nu + \omega)}{(1 + e\cos\nu)} + e\sin\omega\right] \\ &= T_0 + \Delta T_0 + (P_0 + \Delta P_0)E + \frac{\beta}{2}E^2 \\ &\quad + A[\sqrt{(1 - e^2)}\sin E^*\cos\omega + \cos E^*\sin\omega] \quad (2)\end{aligned}$$

[1] ⟨http://www.aavso.org/⟩.

[2] ⟨http://var.astro.cz/ocgate/⟩.

Table 2. Times of minimum light for EQ UMa.

JD (Hel.)	Method	Type	E	$(O-C)_1$	$(O-C)_2$	Residuals	Reference
2448706.5403	ccd	s	−0.5	−0.0059	0.0006	−0.0039	De Young and Schmidt (1992)
2448706.7259	ccd	p	0	0.0006	0.0071	0.0026	De Young and Schmidt (1992)
2448710.6645	ccd	p	11	−0.0005	0.0060	0.0014	De Young and Schmidt (1992)
2448713.7062	ccd	s	19.5	−0.0031	0.0034	−0.0014	De Young and Schmidt (1992)
2448762.5986	ccd	p	156	0.0014	0.0079	0.0012	De Young and Schmidt (1992)
2451308.6950	ccd	p	7265	−0.0140	−0.0090	−0.0002	$O-C$ Gateway
2454015.2800	ccd	p	14822	0.0065	0.0052	0.0022	VSOLJ 45
2454507.5530	ccd	s	16196.5	−0.0022	−0.0052	−0.0035	$O-C$ Gateway
2455671.3721	ccd	p	19446	−0.0023	−0.0099	−0.0012	Hubscher and Lehmann (1992)
2454507.5573	ccd	s	16196.5	0.0021	−0.0009	0.0008	Brat et al. (2008)
2455264.5132	ccd	p	18310	0.0010	−0.0049	0.0020	Brat et al. (2011)
2455905.4269	ccd	s	20099.5	−0.0007	−0.0094	0.0000	Hoňková et al. (2013)
2455992.4584	ccd	s	20342.5	−0.0004	−0.0095	−0.0001	Hoňková et al. (2013)
2455993.5334	ccd	s	20345.5	0.0001	−0.0090	0.0005	Hoňková et al. (2013)
2457025.0237	ccd	s	23225.5	0.0089	−0.0053	0.0007	This paper
2457025.2034	ccd	p	23226	0.0095	−0.0047	0.0013	This paper
2457025.3802	ccd	s	23226.5	0.0073	−0.0069	−0.0009	This paper
2457085.0149	ccd	p	23393	0.0095	−0.0050	0.0002	This paper
2457091.1022	ccd	p	23410	0.0081	−0.0064	−0.0013	This paper
2453822.7751	ccd	s	14284.5	0.0090	0.0083	0.0035	This paper
2453779.9695	ccd	p	14165	0.0027	0.0021	−0.0032	This paper
2453779.7924	ccd	s	14164.5	0.0047	0.0042	−0.0012	This paper
2453746.8448	ccd	s	14072.5	0.0071	0.0067	0.0009	This paper
2453496.6754	ccd	p	13374	0.0079	0.0081	−0.0002	This paper

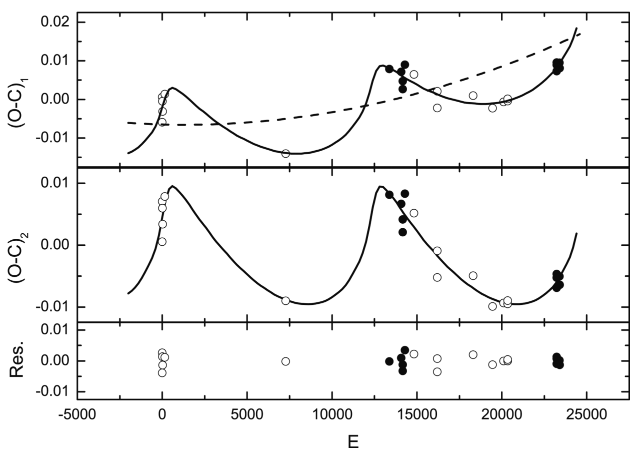

Fig. 3. $O-C$ diagram of EQ UMa. Upper panel shows $(O-C)_1$ curve determined by the linear ephemeris of equation (1) based on all available times of minimum light. The $(O-C)_2$ values, with the quadratic term from the $(O-C)_1$ curve removed, are plotted in the middle panel. The residuals from the full ephemeris of equation (2) are displayed in the lower panel. Open circles refer to the minima compiled from the literature, while filled circles represent the minima determined by the present paper.

Table 3. Parameters for the fit of times of minimum light.

Parameters	Values	Errors
ΔT_0 (d)	−0.0065	±0.0018
ΔP_0 (d)	1.16×10^{-7}	$\pm 0.36 \times 10^{-7}$
β (d yr^{-1})	1.77×10^{-7}	$\pm 0.55 \times 10^{-7}$
A (d)	0.0120	±0.0052
e	0.78	±0.22
P_3 (yr)	12.1	±0.5
ω (°)	39.2	±18.5
T_P (HJD)	2439985.5	±471.4

to fit the $(O-C)_1$ curve. In this equation, T_0 is the initial epoch, P_0 is the orbital period, and β is the long-term period change. The explanation of other parameters can been seen in Irwin (1952). The Levenberg–Marquart (LM) algorithm (Press et al. 1992) was applied to fit all the timings to equation (2). The derived parameters from the fit are listed in table 3. The orbital period of EQ UMa has a secular increase with a rate of $1.77 \pm 0.55 \times 10^{-7}$ d yr^{-1}. The amplitude of the cyclic oscillation is 0.0120 d, and the period of the cyclic change is 12.1 yr. Obtained by removing the quadratic term from the $(O-C)_1$ curve, the $(O-C)_2$ values are displayed in the middle panel of figure 3. The residuals from equation (2) are shown in the lower panel, where no regular changes can be traced.

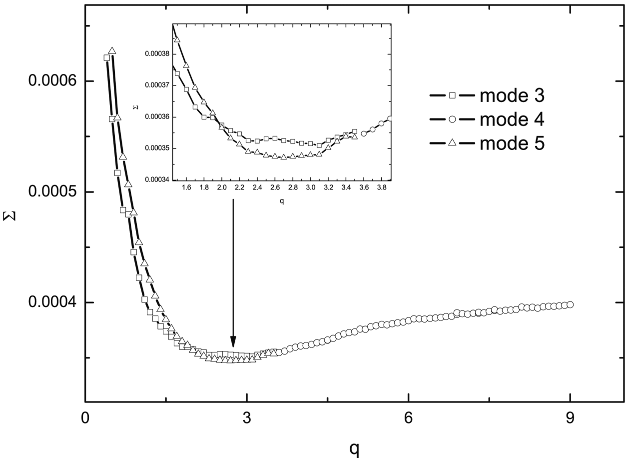

Fig. 4. Σ–q curves for EQ UMa; the small insert figure is an enlargement around $q = 2.70$. Different symbols represent different modes.

4 Photometric solutions

The light curve of EQ UMa was first analyzed by De Young and Schmidt (1992), and an inclination of 56°.5 was determined. No other parameters were published. Therefore, we obtained new light curves for EQ UMa and tried to determine the physical parameters.

The newly derived four-color light curves of EQ UMa were simultaneously analyzed by using the W-D code (Wilson & Devinney 1971; Wilson 1990, 1994). Based on simbad,[3] the color index of EQ UMa was found to be $B - V = 0.70$. From the NASA/IPAC Extragalactic Database (NED),[4] $E(B - V) = 0.034 \pm 0.030$ [the uncertainty was estimated according to Schlafly and Finkbeiner (2011)] was derived and the $(B - V)_0$ should be 0.666. Accordingly, the temperature of Star 1 can be determined to be 5600 ± 150 K (Cox 2000). Then, the gravity-darkening coefficients are set to be $g_{1,2} = 0.32$, and bolometric albedo coefficients are set to be $A_{1,2} = 0.5$ following Lucy (1967) and Ruciński (1969). Bolometric and bandpass limb-darkening coefficients were taken from van Hamme (1993). No mass ratio has been obtained for this system; the q-search method was used to determine the mass ratio. A series of solutions for different values of q were determined. We found that the solutions can be converged at mode 4 and mode 5 when the mass ratio is less than 3.5, and that the solutions can only be converged at mode 3 when the mass ratio is more than 3.5. The weighted sum of the squared residuals, $\sum W_i(O - C)_i^2$, for different solutions are displayed in figure 4. Different symbols represent different modes. As shown in figure 4, the minimum value of $\sum W_i(O - C)_i^2$ is gained at $q = 2.70$ of mode 4. Thus, 2.70 was chosen as an initial value of q, and the mass ratio q was made an adjustable parameter. In the previous section, we found that the orbital period of EQ UMa has a secular increase, indicating a mass transfer from the less massive component to the more massive one. The less massive component filling the inner Roche lobe corresponds to the result of the orbital period variation investigation. Therefore, a new solution with mode 4 was performed. When it had converged, the final solution was obtained; the results determined are listed in table 4. The comparison between the observed and theoretical light curves is shown in figure 5. We can see that the theoretical light curves fit with the observed ones very well.

[3] ⟨http://simbad.u-strasbg.fr/simbad/sim-id?Ident=eq+uma&NbIdent=1&Radius=2&Radius.unit=arcmin&submit=submit+id⟩.

[4] ⟨http://ned.ipac.caltech.edu/⟩.

Table 4. Photometric solutions for EQ UMa determined by analyzing the four-color light curves simultaneously.

Parameters	Photometric elements	Errors
$g_1 = g_2$	0.32	Assumed
$A_1 = A_2$	0.5	Assumed
$x_{1bol} = x_{2bol}$	0.231	Assumed
$y_{1bol} = y_{2bol}$	0.481	Assumed
$x_{1B} = x_{2B}$	0.633	Assumed
$y_{1B} = y_{2B}$	0.246	Assumed
$x_{1V} = x_{2V}$	0.344	Assumed
$y_{1V} = y_{2V}$	0.500	Assumed
$x_{1R_c} = x_{2R_c}$	0.212	Assumed
$y_{1R_c} = y_{2R_c}$	0.573	Assumed
$x_{1I_c} = x_{2I_c}$	0.125	Assumed
$y_{1I_c} = y_{2I_c}$	0.574	Assumed
T_1 (K)	5600	±150
q (M_2/M_1)	2.699	±0.026
T_2 (K)	5536	±165
i°	55.3	±0.2
Ω_1	6.2152	Assumed
Ω_2	6.2489	±0.0099
L_{1B}/L_B	0.3044	±0.0020
L_{1V}/L_V	0.3003	±0.0016
L_{1R_c}/L_{R_c}	0.2984	±0.0014
L_{1I_c}/L_{I_c}	0.2971	±0.0012
r_1 (pole)	0.2767	±0.0005
r_1 (point)	0.3995	±0.0004
r_1 (side)	0.2884	±0.0005
r_1 (back)	0.3211	±0.0005
r_2 (pole)	0.4366	±0.0009
r_2 (point)	0.5667	±0.0057
r_2 (side)	0.4662	±0.0010
r_2 (back)	0.4917	±0.0013

5 Discussion and conclusions

New BVR_cI_c light curves of EQ UMa were determined using the 1.0 m telescope at Weihai Observatory, Shandong University. By analyzing all available times of minimum light,

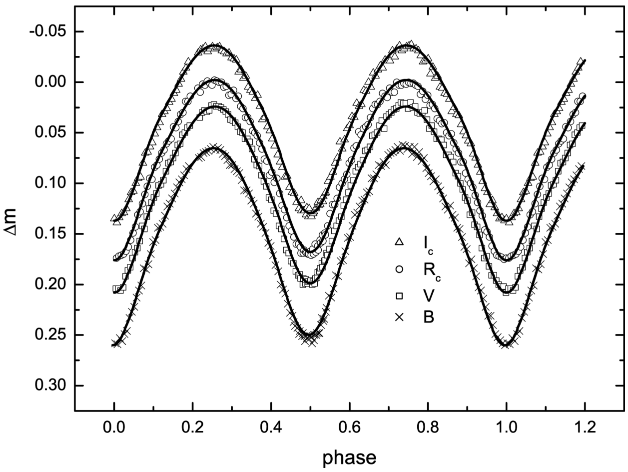

Fig. 5. Observed and theoretical light curves determined by analyzing the four-color light curves simultaneously. The phases are calculated using the linear ephemeris: Min. I = HJD2457025.2034+0.3581533*E*.

we found that the orbital period of EQ UMa has a secular increase plus a cyclic oscillation with a period of 12.1 yr. Four-color light curves of EQ UMa were simultaneously analyzed using the W-D code. We found that EQ UMa is a semi-detached system with the less massive component filling its Roche lobe; the temperature difference between the two components is $\Delta T = 74$ K. The semi-detached construction of Algol-type for EQ UMa can be proofed by the long-term increase of the orbital period. Assuming that the two components of EQ UMa are normal main-sequence stars, the mass of the more massive component can be estimated to be $0.92\,M_{\odot}$ according to Cox (2000). Based on the mass ratio of $q = 2.696$, the mass of the less massive primary can be determined to be $M_1 = M_2/q = 0.34\,M_{\odot}$.

The orbital period of EQ UMa has a secular increase with a rate of $dp/dt = 1.77(\pm 0.55) \times 10^{-7}\,\mathrm{d\,yr^{-1}}$. The long-term period increase should be caused by mass transfer from the less massive component to the more massive one. Assuming that the mass transfer is conservative and using the equation

$$\frac{\dot{P}}{P} = -3\dot{M}_1\left(\frac{1}{M_1} - \frac{1}{M_2}\right), \tag{3}$$

a mass transfer rate of $dM_1/dt = -8.88(\pm 2.76) \times 10^{-8}\,M_{\odot}\,\mathrm{yr^{-1}}$ was determined. The negative sign indicates that the less massive primary component is transferring mass. The period of cyclic oscillation in the orbital period change is 12.1 yr; the semi-amplitude is calculated to be 0.0120 d. As in many other eclipsing binaries, e.g., EP And (Lee et al. 2013), CSTAR 038663 (Qian et al. 2014), and TY UMa (Li et al. 2015), the cyclic period oscillation of EQ UMa is very likely to be caused by the light travel time effect. Using the mass function

$$f(m) = \frac{(m_3 \sin i')^3}{(m_1 + m_2 + m_3)^2} = \frac{4\pi}{GP_3^2} \times (a_{12} \sin i')^3, \tag{4}$$

$f(m) = 0.061 \pm 0.079\,M_{\odot}$ was determined. If the third component is coplanar with the central eclipsing pair ($i_3 = 55^{\circ}\!.3$), the mass of the tertiary companion could be computed to be $m_3 = 0.77(\pm 0.63)\,M_{\odot}$ with a septation of 4.65(±4.31) au. We attempted to fit the light curves of EQ UMa by adding a third light, but the value of L_3 is always negative. Therefore, we speculated that the third companion could be an unseen object such as a white dwarf.

EQ UMa exhibits typical W UMa-type light variation and exhibits a semi-detached configuration. This system is very similar to the Algol-type binary W Crv (Ruciński & Lu 2000). Both of them have short periods (less than 0.45 d) and non-degenerate components. In contrast to W Crv, the temperature difference between the two components of EQ UMa is smaller. Because of the very short period and the Algol-type configuration, EQ UMa can be a great object to challenge the formation and evolution theory of low-mass Algols (Yungelson et al. 1989). Today, more and more such systems are discovered by wide field photometric survey projects (e.g., Norton et al. 2007, 2011; Soszyński et al. 2015). EQ UMa cannot be considered as a target caught in the broken contact stage predicted by the thermal relaxation oscillations model (e.g., Lucy 1976; Flannery 1976; Robertson & Eggleton 1977; Lucy & Wilson 1979). In such systems, effective temperatures between the two components should be very different. In addition, the less massive component fills its inner Roche and transfers mass to the more massive one. EQ UMa is a very interesting eclipsing binary; precise spectroscopic and photometric observations are needed to determine more precise physical parameters and to analyze the orbital period variation.

Acknowledgments

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