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New photometric studies of two contact binaries CE Leo and V366 Cas with possible tertiary companions

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HIGHLIGHTS

- We present new photometric observations and several eclipsing times for CE Leo and V366 Cas.
- The O'Connell effect for CE Leo disappear in our BVR light curves.
- Photometric solution of V366 Cas was first deduced.
- Except the period secularly increasing, we found that there exist light-time orbit due to the third body.
- The secular period decrease rates of +1.63 × $10^{(-7)}$ d/yr for CE Leo and +5.55 × $10^{(-7)}$ d/yr for V366 Cas.
- The light-time orbits with P_3 = 39.7 yr and A = 0.0166 day for CE Leo, P_3 = 16.7 yr and A = 0.0079 day for V366 Cas.

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ABSTRACT

We present new photometry for CE Leo and V366 Cas, performed using three small telescopes in China from 2008 December to 2012 March. Using the updated Wilson–Devinney program, the photometric solutions of two binaries were deduced from new *BVR* light curves. Their photometric mass ratios and geometric fill-out factors are $q = 0.533(\pm 0.002)$ and $f = 15.8\%(\pm 0.3\%)$ for CE Leo, $q = 0.887(\pm 0.007)$ and $f = 38.7\%(\pm 1.0\%)$ for V366 Cas, respectively. By analyzing the $O{-}C$ curves, it is found that their orbital periods show a long-time increase with a light-time orbit due to a third body. The periods of the tertiary components are $P_3 = 39.7(\pm 0.9)$ yr for CE Leo and $P_3 = 16.7(\pm 0.4)$ yr for V366 Cas, respectively. With the existence of addition companion, those two binaries appear to be triple systems. The period increase rates are $dP/dt = 1.63(\pm 0.05) \times 10^{-7}$ d yr^{-1} for CE Leo and $dP/dt = +5.55(\pm 0.03) \times 10^{-7}$ d yr^{-1} for V366 Cas, respectively. This kind of period increase may be interpreted by the conservative mass transfer from the secondary component to the primary one. With periods increasing, CE Leo and V366 Cas will evolve into broken-contact configurations as predicted by the thermal relaxation oscillation theory.

1. Introduction

The short-period eclipsing binary CE Leo (=GSC 1985–1209) was discovered by Hoffmeister (1963) in a search for variables near the north galactic pole. Wenzel and Zeigler (1996) classified it as an W UMa-type variable with a period of 0.3034286 days. First complete *BVRI* light curves of this star were published by Samec et al. (1993), whose results revealed that CE Leo is a W-type binary with a mass ratio of 0.50 and a fill-out factor of 2.8%. The asymmetric light curves were modeled by the presence of a large superluminous region on the cooler component. They derived a secular period decrease rate of $dP/dt = -1.0 \times 10^{-7}$ d yr^{-1}, interpreted by angular momentum loss caused by stellar wind. However, Qian (2002) obtained a long-term period increase with a rate of $dP/dt = +7.2 \times 10^{-7}$ d yr^{-1}. Yang and Liu (2002) published light curves and included Samec et al. (1993) results. They concluded that the orbital period of CE Leo oscillates with a cycle of about 14 yr and an semi-amplitude of 0.004 days, and its O'Connell effect is due to a dark spot on the primary component. Kang et al. (2004) comprehensively studied the chromospherical activity of this binary based on their light curves and early published ones (Samec et al., 1993; Yang and Liu, 2002). They pointed out that the orbital period is changing due to a secular period increase (i.e., $dP/dt = +3.05 \times 10^{-7}$ d yr^{-1}) combined with a light-time orbit (i.e., $P' = 22.6$ yr and $e' = 0.61$).

Another eclipsing binary V366 Cas (=GSC 3681–0494) was found by Hoffmeister (1949), who announced it as a short-period variable star. Its visual magnitude ranges from $12.^m0$ to $12.^m7$

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(Pribulla et al., 2003). Brancewicz and Dworak (1980) estimated its spectral type of G1 and its mass 1.19 $M_\odot$ of the primary component. Based on sky patrol plates, Perova (1957) classified it as a W UMa-type binary with a period of $0.^d7292714$, which was confirmed by Berthold (1978). For the neglected eclipsing binary V366 Cas, Agerer et al. (1999) made CCD photometry without filters. Based on 53 light minimum times, they proposed that the $O-C$ curve of V366 Cas changes either suddenly or continuously. The orbital period increases at a rate of $+7.6 \times 10^{-10}$ day/cycle, which was interpreted by the mass transfer from the less massive component to the more massive one. Up to now, no photometric solution has been published.

2. Observations and data reduction

New photometry of two binaries CE Leo and V366 Cas was acquired from 2008 December to 2012 March, using several telescopes in China. Image reductions were done using the Image Reduction (IMRED) and Aperture Photometry (APPHOT) packages in the Image Reduction and Analysis Facility (IRAF) in a standard fashion. Differential magnitudes were then determined by aperture photometry.

Photometric observations of CE Leo were obtained on three consecutive nights from 2012 December 21 to 23, using the 85-cm telescope (Zhou et al., 2009) at the Xinglong station of National Astronomical Observatories of China (NAOC). In the observing process, TYC 1985-1274-1 and TYC 1985-265-1 were chosen as the comparison and check stars, whose coordinates are listed in Table 1. Exposure times in B, V and R bands were 80 s, 40 s and 30 s, respectively. In each band, a total of 166 images was obtained. All individual observations, in the form of HJD and Δm, are available on request. The precisions of individual points do not exceed 0.007 mag. The complete light curves are displayed in the *left panel* of Fig. 1, where the phases were computed with a period of $0.^d30342785$ (Meinunger and Wenzel, 1968). From this figure, the light curves of CE Leo are symmetric, which are different from the previous published ones with large O'Connell effect (i.e., $Max.II - Max.I \sim 0.04$ mag; Samec et al., 1993; Yang and Liu, 2002; and Kang et al., 2004). This implies that the chromospheric activity of CE Leo may disappear. As displayed in the *right panel* of Fig. 1, the incomplete light curve in R band for this binary was obtained on 2010 March 21, using the 1.0-m telescope at Yunnan Astronomical Observatory (YNAO). From this figure, CE Leo possesses a duration of totality of about 20 min.

The complete light curves of V366 Cas were obtained on 2010 December 19, 20 and 21, using the 85-cm telescope. The comparison and check stars are GSC 3681-640-1 and GSC 3681-0988, listed in Table 1. Typical exposure times in BVR bands were adopted to be 30 s, 20 s and 10 s, respectively. In total, we obtained 588, 566 and 578 images in B, V and R bands. Photometric error for individual observation in each band is a bit large up to $0.^m012$ due to bad weather. All individual observations (i.e., HJD and Δm) are also available on request. Differential B, V and R magnitudes are plotted against orbital phases in the *left panel* of Fig. 2, where phases were calculated with a period of $0.^d7292766$ (Kreiner et al., 2001). The light curves reveal that V366 Cas is an typical W UMa-type binary. The amplitudes of variable light are $0.^m66, 0.^m63$ and $0.^m59$ in B, V and R bands, respectively. The primary eclipses are almost as deep as the secondary ones, which implies that the temperature difference between both components is very small.

Table 1
The coordinates of the variable, comparison star and check stars.

Star	$\alpha_{J2000.0}$	$\delta_{J2000.0}$	Mag (V)
CE Leo	11:44:24.23	+23:21:22.86	11.8–12.6
TYC 1985-1274-1(C)	11:44:01.62	+23:22:38.10	12.56
TYC 1985-265-1(Ch)	11:44:07.08	+23:17:49.53	12.29
V366 Cas	01:08:25.60	+58:44:16.60	12.0–12.7
GSC 3681-640-1(C)	01:07:50.69	+58:38:19.37	10.91
GSC 3681-0988(Ch)	01:08:55.38	+58:47:10.90	12.0

3. Eclipsing times and revised period changes

On 2010 April 16, and 2012 March 21 and 23, three light minimum times of CE Leo were obtained using the 1.56-m telescope (Tao et al., 2003) at the Sheshan station of Shanghai Astronomical Observatory (SAO). Using the 85-cm telescope at the Xinglong station of NAOC, another two times of primary minima of V366 Cas were observed on 2008 December 17 and 2012 January 1. Using the K-W method (Kwee and van Woerden, 1956), we determined several light minimum times, which are listed in the online Table 2. In analyzing the period changes, we compiled the databases of all available eclipsing times. Measurement methods of "p", "pg" and "vi" represent patrol plate, photographic and visual observations, which are assigned weight 1. Meanwhile, "pe" and "CCD" refer to photoelectric and charge-coupled device measurements, which are assigned weights 10.

3.1. Period analysis of CE Leo

Based on the different time-interval data, the continuous period variation of CE Leo has been studied by several investigators (i.e., Samec et al., 1993; Yang and Liu, 2002; Qian, 2002; Kang et al., 2004). In order to revise its period changes, we collected all available light minimum times, spreading over 53 yr from 1961 to 2012. The online Table 3 tabulates those compiled light minimum times, including 23 photographic, 31 visual, 19 photoelectric and 69 CCD ones. Using the linear ephemeris (Meinunger and Wenzel, 1968),

$$\text{Min.I} = \text{HJD } 2447679.6689 + 0.30343785 \times E, \tag{1}$$

one can calculate the residuals $(O-C)_1$, which are listed in the fifth column of Table 3, and are shown graphically in the *upper panel* of Fig. 3. The general trend of the $(O-C)_1$ curve may be described by a upward parabolic curve. Using a weighted least-squares method, the following quadratic ephemeris is obtained,

$$\text{Min.I} = \text{HJD } 2447679.683(7) + 0.30342695(3) \times E + 6.8(2) \times 10^{-11} E^2, \tag{2}$$

where the parenthesized numbers represent the uncertainty in units of the last decimal place. Residuals $(O-C)_2$ are listed in the sixth column of Table 3, and are displayed in the *lower panel* of Fig. 3. With the coefficient of the quadratic term, we can obtain a continuous period decrease rate of $dP/dt = +1.63(\pm 0.05) \times 10^{-7}$ d yr^{-1}, which is much smaller than the value of $+3.05 \times 10^{-7}$ d yr^{-1} (Kang et al., 2004). As seen from the $(O-C)_2$ curve, there appears to exist a cyclic variation, i.e., a light-time orbit (Irwin, 1952), which is not purely sinusoidal. Therefore, the residuals $(O-C)_2$ may be fitted by the following equation,

$$(O-C)_2 = \Delta T_0 + A \times \left(\frac{1-e^2}{1+e\cos v} + e \sin \omega \right), \tag{3}$$

where $A = a_{12} \sin i / c$ is the semi-amplitude, and other parameters are taken from Irwin (1952). The fitted parameters are listed in Table 4. The resulting residuals $(O-C)_3$ are also tabulated in the seventh column of Table 3. The solid line is constructed from Eq. (3) as a solid line in the *lower panel* of Fig. 3. Although there exists large scatter for photographic and visual observations, the $(O-C)_2$ curve was fitted fairly well. The period of $P_3 = 39.7$ yr for CE Leo is much different from the previous derived values of 22.6 yr (Kang et al.,