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Apsidal Motion Study of Close Binary System CW Cephei

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New observations for the times of minimum lights of a well-known apsidal motion star CW Cephei were made using a 0.6 m wide field telescope at Jincheon station of Chungbuk National University Observatory, Korea during the 2015 observational season. We determined new times of minimum lights from these observations and analyzed *O-C* diagrams together with collected times of minima to study both the apsidal motion and the Light Time Effect (LTE) suggested in the system. The new periods of the apsidal motion and the LTE were calculated as 46.6 and 39.3 years, respectively, which were similar but improved accuracy than earlier ones investigated by Han et al. (2002), Erdem et al. (2004) and Wolf et al. (2006).

Keywords: clipsing variables, apsidal motion, photometry

1. INTRODUCTION

CW Cep is a well-known apsidal motion binary system observed by many investigators (Abrami & Cester 1960; Nha 1975; Han et al. 2002; Wolf et al. 2006) since its discovery by Petrie (1947) as a double lined spectroscopic eclipsing binary. The spectral types of two components of CW Cep were determined as B0.5 + B0.5, and masses were calculated as 11.7 $M_\odot$ and 11.0 $M_\odot$ by Popper (1974). The light curves were analyzed by many authors using well observed full-light curves with different models for the parameters of the binary system, related with its apsidal motion (Cester et al. 1978) with the WINK model, Clausen & Giménez (1991) by the EBOP model, and Terrell (1991), and Han et al. (2002) by the WD model. While Popper & Hill (1991) discussed the radial velocity curve based on the spectroscopic observations by Popper (1974), high resolution IUE observations for the radial velocity curve were made by Stickland et al. (1992). Most of these studies suggested that CW Cep is a detached main sequence binary system, composed of two stars of slightly different mass and radius.

With regard to the apsidal motion study of the close eclipsing binary systems, CW Cep showed one of the shortest apsidal period, among similar binary systems, which leads particular interests for this binary system. Based on intensive photoelectric observations with *UBV* filters, Nha (1975) calculated the apsidal motion period of CW Cep as 39 years, while Han (1984) derived the apsidal motion period as 43.1 years with more times of minimum lights based on the *UBV* photoelectric observations. After their studies, more times of minimum lights were available by many investigators recently, according to the new observations. Therefore, the apsidal motion period of CW Cep was improved in time order as 45.5 years by Gimenez et al. (1987), 45.6 years by Clausen & Giménez (1991), and 45.7 years by Han et al. (2002). The last authors, for the first time, noticed a new type of complication confusing the apsidal motion behavior, which shows about 34 years periodic variation with an amplitude of 0.003 days. Erdem et al. (2004) calculated the apsidal motion period of CW Cep as 46.1

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years through the variation of the longitude of periastron (ω) of the system's orbit, with new observations using *BVR* filters. More recently, with new observations by Wolf et al. (2006), they suggested the apsidal motion period of CW Cep as 46 years, which is similar to those of other previous authors (Clausen & Giménez 1991; Han et al. 2002). They confirmed an extra periodic change suggested by Han et al. (2002) and proposed a Light Time Effect (LTE) with the period of 38.5 years and the small semi-amplitude of 0.002 days caused by an unseen third body.

It is nearly 10 years since the observations by Wolf et al. (2006), and this indicates the necessity of new observations for this binary system to examine more accurate apsidal motion period. In line with this, we made new observations for CW Cep in the 2015 season and obtained three new times of minimum lights to confirm the apsidal motion period of this system, together with available minimum times from the published literatures.

2. NEW OBSERVATIONS

New CCD photometric observations presented in this work were made in the 2015 observational season at the Jincheon station of Chungbuk National University Observatory (CBNUOJ), Korea. The altitude of the Jincheon station is 87 m sea level and the 60-cm reflecting telescope is installed by Korea Astronomy and Space Science Institute (KASI), and operated by CBNUOJ. An electronically cooled SBIG STX-16803 4K CCD camera is equipped with a Johnson standard *BVRI* filter set, and is attached at the reflector f/2.9 prime focus of the 60 cm wide field telescope. Since our observations are focused on the acquisition of accurate eclipse timings, only B filter is used for fast time-resolved photometry for the first two nights. The observations of the last night were made with *BVR* filters to derive the weighted average of each filters for higher accuracy. The field of view of the CCD camera is 72’ × 72’ with a pixel scale of 1.05 arcsec/pixel, which is wide enough to cover the many field stars around CW Cep including the comparison star GSC 04282-00330, and differential photometry was applied for this observation. All of the observed CCD frames were exposed 15 ~ 80 seconds depending on the observational circumstances, and corrected with bias, dark and flat-field images for the differential photometry. The IRAF/DIPHO software package was applied to process the observed CCD frames. The details of the data reduction were extensively described by Kim et al. (2014) based on the same observational circumstances. We obtained three times of minimum lights, two for primary and one secondary minima, and determined the times of minimum lights by conventional Kwee & van Woerden (1956) method as listed in Table 1 together with other times of minima determined by previous investigators.

3. MINIMUM LIGHTS AND *O*-C DIAGRAM

With our new times of minimum lights of CW Cep, we collected all published times of minimum lights from the literature to analyze the apsidal motion of this binary system. Among the available times of minimum lights, the visual and photographic data observed at the early stage of apsidal motion were excluded in this study because those data could increase uncertainty of period variations. Only photoelectric and CCD times of minimum lights were used in our analysis and listed in Table 1, including our timings.

These times of minima were simultaneously analyzed with the apsidal motion plus the light-time effect ephemeris represented by:

$$C = To + Ps\,E + \tau_{ap} + \tau_3 \qquad (1)$$

where *Ps* is the sidereal period, τ_{ap} and τ_3 denote the apsidal motion and the LTE terms, respectively. τ_{ap} is a function of four parameters (anomalous period P_a, eccentricity e, longitude of the periastron ω_0, angular velocity of the line of apsides $\dot{\omega}$) The formalism for τ_3 was given up to sixth power of the eccentricity by Giménez & Bastero (1995). Irwin (1952) gave an exact form for τ_3 with five unknown parameters which are the semi-amplitude K, the eccentricity e_3, the period P_3, the periastron passage time T_3, the longitude of periastron ω_3 for the light orbit of mass center of the eclipsing pair around the mass center of the triple system.

All the timings were fitted to Eq. (1) by using the code (available at http://sirrah.troja.mff.cuni.cz/~zasche/Programs.html) given by Zasche et al. (2009) and Zasche & Wolf (2013). We made small corrections of the code by considering the inclination of the eclipsing pair in it and involving up to sixth power of the eccentricity. With the initial values of the apsidal motion and LTE parameter given by Wolf et al. (2006), we improved iteratively the apsidal motion and LTE parameters. In the calculation we fixed the inclination of the eclipsing pair as derived by Clausen & Giménez (1991) and Han et al. (2002). The final solution was listed in the sixth column of Table 2, together with those of Han et al. (2002), Wolf et al. (2006) and Bulut et al. (2011) for comparison. The resultant O-C diagram was drawn with the linear term of our result in the top of Fig. 1 where the solid continuous curves denote the combination of τ_{ap} and τ_3 and the dashed curve represents only τ_3 term. In the middle the

Table 1. The times of minimum lights of CW Cep

JD Hel (2400000+)	Internal error	Epoch	Me.1)	Type	Reference2)
35369.3678	-	-2308.5	PE	II	Nha (1975)
35373.4370	±0.001	-2307.0	PE	I	Abrami & Cester (1960)
35732.3382	-	-2175.5	PE	II	Nha (1975)
36563.3546	±0.0003	-1871.0	PE	I	Söderhjelm (1976)
39064.5894	-	-954.5	PE	II	Nha (1975)
39405.7283	-	-829.5	PE	II	Nha (1975)
39442.6204	-	-816.0	PE	I	Nha (1975)
39783.7618	-	-691.0	PE	I	Nha (1975)
40505.5710	-	-426.5	PE	II	Nha (1975)
40509.7157	-	-425.0	PE	I	Nha (1975)
40520.6316	-	-421.0	PE	I	Nha (1975)
40524.6750	-	-419.5	PE	II	Nha (1975)
40861.7714	-	-296.0	PE	I	Nha (1975)
40984.5832	-	-251.0	PE	I	Giménez et al. (1987)
41054.1280	-	-225.5	PE	II	Nha (1975)
41058.2700	-	-224.0	PE	I	Nha (1975)
41250.6240	-	-153.5	PE	II	Giménez et al. (1987)
41639.5750	-	-11.0	PE	I	Nha (1975)
41669.5953	-	0.0	PE	I	Nha (1975)
41695.4825	-	9.5	PE	II	Nha (1975)
42653.4061	±0.0032	360.5	PE	II	Brancewicz & Kreiner (1976)
44909.0580	-	1187.0	PE	I	Giménez et al. (1987)
45161.5094	-	1279.5	PE	II	Giménez et al. (1987)
45613.1685	-	1445.0	PE	I	Giménez et al. (1987)
45617.2770	-	1446.5	PE	II	Giménez et al. (1987)
45618.6270	±0.003	1447.0	PE	I	Clausen & Giménez (1991)
45665.0231	-	1464.0	PE	I	Giménez et al. (1987)
46007.5480	±0.0004	1589.5	PE	II	Clausen & Giménez (1991)
46013.0066	±0.0006	1591.5	PE	II	Han et al. (2002)
46017.0792	±0.0003	1593.0	PE	I	Han et al. (2002)
46032.1133	±0.0007	1598.5	PE	II	Han et al. (2002)
46351.4230	±0.0002	1715.5	PE	II	Clausen & Giménez (1991)
46688.4402	±0.0006	1839.0	PE	I	Clausen & Giménez (1991)
47362.5350	-	2086.0	PE	I	Diethelm (1988)
47897.4465	±0.002	2282.0	PE	I	Ogloza (1995)
48197.6535	±0.0002	2392.0	PE	I	Caton & Burns (1993)
48537.4790	-	2516.5	PE	II	Hübscher et al. (1992)
48859.5181	±0.0006	2634.5	PE	II	Diethelm (1992)
48926.3323	-	2659.0	PE	I	Brelstaff (1994)
49177.4116	±0.0006	2751.0	PE	I	Hübscher et al. (1994)
49544.5324	-	2885.5	PE	II	Brelstaff (1995)
49952.4878	±0.0005	3035.0	PE	I	Agerer & Hübscher (1996)
49978.4665	±0.0008	3044.5	PE	II	Agerer & Hübscher (1996)
50037.0918	±0.0006	3066.0	CCD	I	Han et al. (2002)
50045.2793	±0.0007	3069.0	PE	I	Jordi et al. (1996)
50300.5007	±0.0007	3162.5	PE	II	Agerer & Hübscher (1997)
50348.2156	±0.0003	3180.0	CCD	I	Han et al. (2002)
51449.4690	±0.001	3583.5	CCD	II	Bíró & Borkovits (2000)
51504.0434	±0.0008	3603.5	CCD	II	Han et al. (2002)
51514.9567	±0.0007	3607.5	CCD	II	Han et al. (2002)
51771.4959	±0.0009	3701.5	PE	II	Agerer & Hübscher (2002)
51786.4812	±0.0011	3707.0	PE	I	Soydugan et al. (2001), Erdem et al. (2004)
51797.3977	±0.0010	3711.0	PE	I	Soydugan et al. (2001), Erdem et al. (2004)
51831.5383	±0.0016	3723.5	PE	II	Soydugan et al. (2001), Erdem et al. (2004)
51871.0789	±0.0005	3738.0	CCD	I	Han et al. (2002)
52549.2981	±0.0009	3986.5	CCD	II	Agerer & Hübscher (2003)
52568.3980	±0.001	3993.5	CCD	II	Wolf et al. (2006)
52901.3528	±0.0067	4115.5	CCD	II	Hübscher (2005a)
52976.3940	±0.001	4143.0	CCD	I	Wolf et al. (2006)
52983.2240	±0.0004	4145.5	CCD	II	Hübscher et al. (2005b)

53227.4800	±0.007	4235.0	CCD	I	Hübscher et al. (2005b)
53504.4873	±0.006	4336.5	CCD	II	Wolf et al. (2006)
53519.4994	±0.0007	4342.0	CCD	I	Wolf et al. (2006)
53609.5600	±0.001	4375.0	CCD	I	Wolf et al. (2006)
53972.5420	±0.003	4508.0	CCD	I	Marino et al. (2010)
54020.2848	±0.0005	4525.5	CCD	II	Brat et al. (2008)
54024.3951	±0.0038	4527.0	CCD	I	Hübscher & Walter (2007)
54039.3938	±0.0072	4532.5	CCD	II	Hübscher & Walter (2007)
54331.4020	±0.0001	4639.5	PE	II	Dogru et al. (2009)
54357.3533	±0.0003	4649.0	PE	I	Dogru et al. (2009)
54432.3890	±0.0012	4676.5	CCD	II	Hübscher et al. (2008)
54750.3458	±0.0015	4793.0	CCD	I	Hübscher et al. (2009)
54765.3332	±0.0008	4798.5	CCD	II	Hübscher et al. (2009)
55117.3970	±0.0004	4927.5	CCD	II	Bulut et al. (2011)
55353.5002	±0.0069	5014.0	CCD	I	Hübscher & Monninger (2011b)
55398.4932	±0.005	5030.5	CCD	II	Hübscher & Monninger (2011b)
55480.3673	±0.009	5060.5	CCD	II	Hübscher (2011a)
55645.5235	±0.0169	5121.0	CCD	I	Huebscher et al. (2012b)
55844.7439	±0.0009	5194.0	CCD	I	Diethelm (2012)
55858.3854	±0.0026	5199.0	CCD	I	Hübscher & Lehmann (2012a)
55873.3583	±0.001	5204.5	CCD	II	Hübscher & Lehmann (2012a)
56038.5091	±0.0004	5265.0	CCD	I	Zasche et al. (2014)
56180.4323	±0.0032	5317.0	CCD	I	Hübscher & Lehmann (2013)
56584.3425	±0.0069	5465.0	CCD	I	Hübscher (2014)
56629.3261	±0.0019	5481.5	CCD	II	Hübscher (2014)
56644.3857	±0.0049	5487.0	CCD	I	Hübscher (2014)
57297.9687	±0.0003	5726.5	CCD	II	This paper (CBNUOJ)
57302.1079	±0.0004	5728.0	CCD	I	This paper (CBNUOJ)
57332.1291	±0.0005	5726.5	CCD	I	This paper (CBNUOJ)

1) PE: Photoelectric photometry, CCD photometry
2) CBNUOJ : Chungbuk National University Observatory at Jincheon

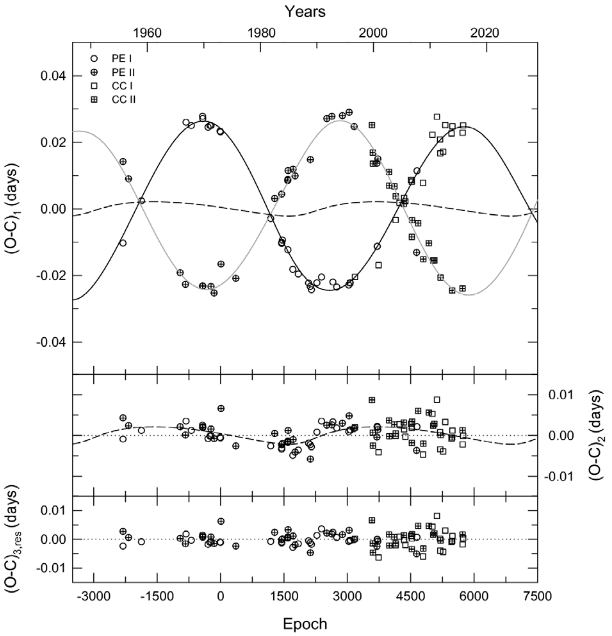

Fig. 1. Eclipse timing variation diagram with theoretical lines calculated with the parameters in Table 2. Open and cross symbols refer to primary and secondary minimum timings, respectively, where circle and square represent Photoelectric (PE) and CCD timings, respectively. The black and grey solid lines on the top panel represent the theoretical apsidal motion plus LTE terms for primary and secondary eclipses, respectively. The dash lines on the top and middle panels also represent the theoretical LTE (τ_3). The bottom panel indicates the residual from Eq (1).

residuals from the linear plus the apsidal motion ephemeris were plotted with the theoretical LTE τ_3 term. The residuals from the full contribution of Eq. (1) were plotted in the bottom panel. The standard deviation of the residuals with a relatively large scatter was calculated to be ±0.0025 days which is slightly larger than the small semi-amplitude of 0.0021 days for the LTE orbit as listed in Table 2.

Because the Zasche code we used was based on a differential least-square method (Zasche et al. 2009), our solution of Eq. (1) may be a solution with a local minimum rather than a global solution. It would be very necessary to check whether our solution is globally valid for all parameter space. In line with this validity, we subsequently attempted a Monte Carlo simulation to obtain optimized values of the parameters both of the apsidal motion and the LTE orbit as performed by Lee et al. (2015). After 800 simulations all the apsidal motion parameters showed a quick convergence to nearly the same values listed in Table 2, while the LTE parameters show relatively wide variation as shown in the histograms of Fig. 2. Particularly, the distribution of e_3 showed remarkably wide variation, indicating that the proposed LTE orbit is not well defined with reliable accuracy by present observational data.

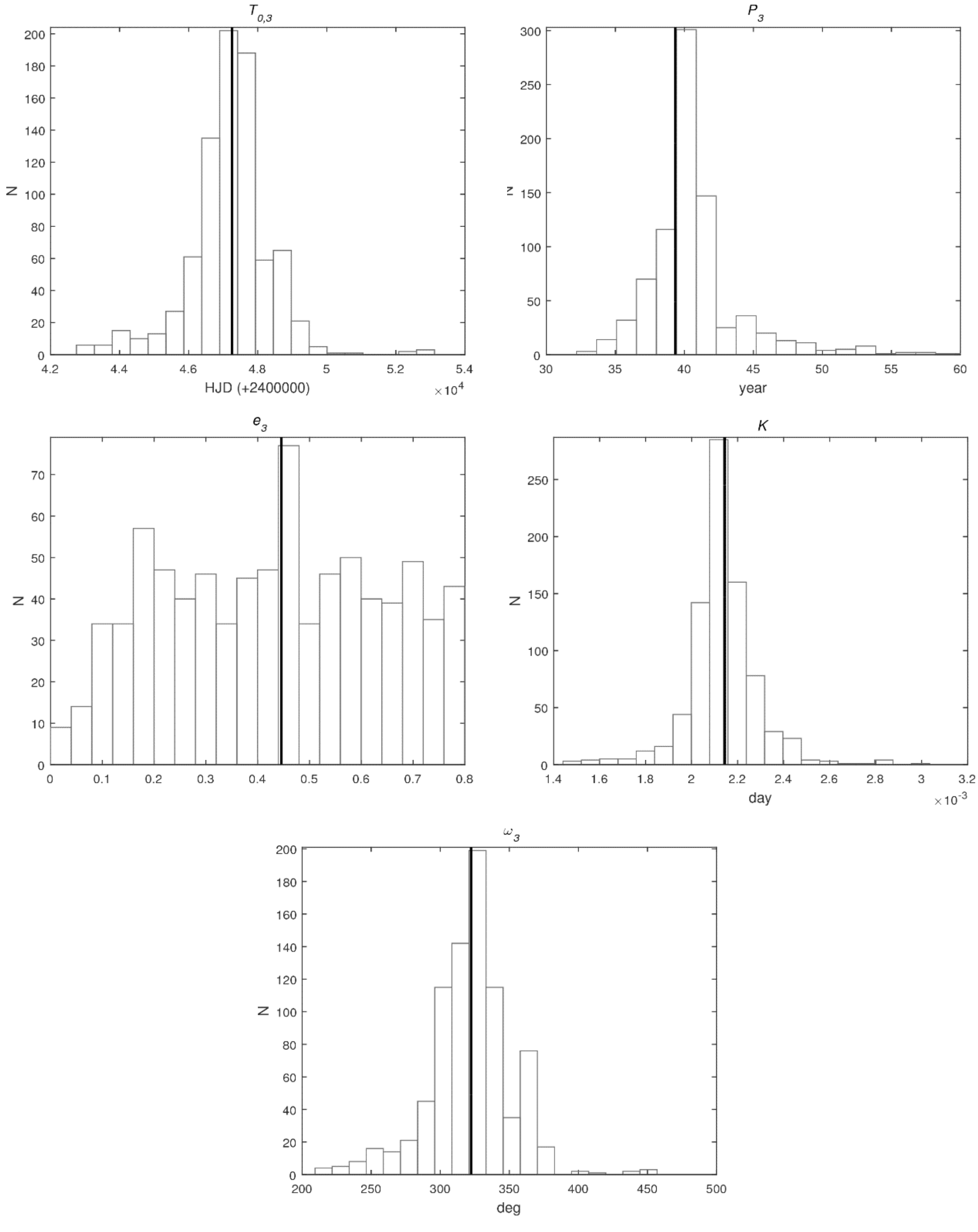

Fig. 2. Histograms for distributions of the third body orbit parameters. The black lines represent the calculated elements of the third body orbit.

4. DISCUSSION OF APSIDAL MOTION PERIOD

In this study, the new times of minimum lights were presented by the observations of CBNUOJ, together with the collected times of minimum lights as shown in Table 1. The *O-C* diagram of a differential least-square fit to the minimum lights were shown in Fig. 1. We calculated the new apsidal motion period as 46.27 ± 0.04 years. The apsidal parameters are listed in Table 2, which shows similar apsidal motion period with those of earlier investigators (Han at al 2002; Wolf et al. 2006), however with much improved accuracy. The existence of a third body in the CW Cep system was also

Table 2. Parameters of the apsidal motion and LTE for CW Cep

Parameter	unit	Han et al. (2002) (Assigned Weight)	Wolf et al. (2006)	Bulut et al. (2011)	This analysis
T_0	HJD	2,441,669.5726(8)	2,441,669.5722(5)	2,441,669.5724(30)	2,441,669.5722(3)
P_s	days	2.72913956(18)	2.72913959(11)	2.729139(1)	2.72913951(9)
P_a	days	2.72958580(38)	2.7295811(2)	2.789602(1)	2.72958036(41)
e	-	0.0292(12)	0.0297(5)	0.028(5)	0.0288(1)
$\dot{\omega}$	deg/Ps	0.05885(5)	0.0582(5)	0.0583(37)	0.0581(1)
$\dot{\omega}$	deg/years	7.88	7.79(7)	7.80	7.78(1)
ω_0	deg	201.3(2.5)	201.6(0.5)	201.4(1.5)	201.7(2)
U	years	45.71(4)	46.2(0.4)	46(3)	46.27(4)
$T_{0,3}$	HJD	2,435,277(7)	2,448,110(300)	2,447,504.2(4)	2,447,254(1191)
P_3	years	34.03(2)	38.5(1.5)	37(13)	39.3(4.4)
K	days	0.0025	0.00243(5)	0.0031	0.00214(15)
ω_3	deg	1(6)	-	346.2(3)	322(99)
e_3	-	0.990(9)	0.0(fixed)	0.0059(5)	0.446(210)

suggested by many previous investigators (Han et al. 2000; Wolf et al. 2006; Bulut et al. 2011). Based on the analysis of currently available minimum lights in Table 1, we calculated the period of the LTE caused by the third body as 39.3 ± 4.4 years as shown dash line in Fig. 1. However, the LTE caused by the third body may not be convinced due to a wide variation of orbital eccentricity (e_3) in Fig. 2 and a small semi-amplitude compatible to a large scatter band of the residuals in Fig. 1.

The masses and radii of CW Cep by the photometric and spectroscopic parameters suggested by Clausen & Giménez (1991) are $M_1 = 11.82 \pm 0.14 M_\odot$, $M_2 = 11.09 \pm 0.14 M_\odot$, $R_1 = 5.48 \pm 0.12 R_\odot$, and $R_2 = 4.99 \pm 0.12 R_\odot$. With these parameters, we calculated the internal structure constant of the system, as $\log k_{2,obs} = -2.106$ that is slightly small value rather than the theoretical internal structure constant -2.08 suggested by Wolf et al. (2006). If the third body component exists around CW Cep, the minimum mass of the third can be calculated by the mass function ($f(M_3)$) of 4×10^{-5}. The results show that the third body component should be 0.279 $M_\odot$ when i_3 is 90°, and in the case of i_3 is 30°, the mass is 0.562 $M_\odot$. These are approximately 2% range of mass of CW Cep binary system, which is too small compared to CW Cep and the masses are close to red dwarfs range. Therefore detecting the third body by photometry and spectroscopy would be very difficult. Apsidal motion period is very important because it can provide the important constant for the stellar internal structure. In this regards, many investigators have paid attention to the apsidal motion of CW Cep, and more accurate observations will be necessary to analyze the apsidal motion of the binary system and periodic variations by the third body.

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