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Pulsation analysis of the high amplitude δ Scuti star CW Serpentis *

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Abstract Time-series photometric observations were made for the high amplitude δ Scuti star CW Ser between 2011 and 2012 at the Xinglong Station of National Astronomical Observatories, Chinese Academy of Sciences. After performing the frequency analysis of the light curves, we confirmed the fundamental frequency of $f = 5.28677$ c d^{-1}, together with seven harmonics of the fundamental frequency, which are newly detected. No additional frequencies were detected. The $O - C$ diagram, produced with the 21 newly determined times of maximum light combined with those provided in the literature, helps to obtain a new ephemeris formula of the times of maximum light with the pulsation period of $0.189150355 \pm 0.000000003$ d.

Key words: stars: variables: δ Scuti — stars: individual (CW Ser) — techniques: photometric

1 INTRODUCTION

δ Scuti stars are a class of pulsating variable stars that lies in the classical instability strip crossing the main sequence on the Hertzsprung-Russell diagram, whose pulsations arise from the $\kappa-$mechanism which drives the pulsations of both Cepheids and RR Lyrae stars. With masses between 1.5 and 2.5$M_\odot$, periods between 0.03 and 0.3 d and luminosities between 10 and 50 $L_\odot$, δ Scuti stars pulsate with amplitudes from mmag up to tenths of a magnitude (Breger 2000).

High amplitude δ Scuti stars (hereafter HADSs) are a subgroup of δ Scuti stars that are slow rotators with one or two dominant radial modes whose amplitudes are larger than 0.1 mag, although some of them may have low-amplitude, non-radial modes in addition to the main pulsation modes (Poretti 2003). It is interesting to probe whether the non-radial mode is a general property of the pulsations of all HADSs.

Pulsations of the HADS CW Serpentis (hereafter CW Ser = HIP 077798, $\alpha_{2000} = 15^{\rm h}52^{\rm m}10^{\rm s}$, $\delta_{2000} = 06^\circ05'26''$, $\langle V\rangle = 11.83^{\rm m}$, $P_0 = 0.1892^{\rm d}$, $\Delta V = 0.47^{\rm m}$, A–F) were discovered by Hoffmeister (1935). Gieren et al. (1975) collected time-series photometry for CW Ser, derived two times of maximum light and the period value of $P = 0.18915054^{\rm d} \pm 0.00000001$. CW Ser has been observed in only a few runs since its pulsation period is rather long. The spectral type of CW Ser was classified as F by Halprin & Moon (1983) and Lopez de Coca et al. (1990) by using $uvby\beta$ photometry. Xu et al. (2002) calibrated its spectral type as A-F. There were also several runs of photometric observations carried out at Konkoly Observatory from 1975 to 2005 (Gieren et al.

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1975; Agerer & Hubscher 1996; Agerer & Huebscher 1998; Agerer et al. 1999, 2001; Hubscher et al. 2005).

In the following sections, we present a detailed study of the pulsations and period changes of CW Ser, mainly based on extended time-series photometric observations from 2011 to 2012 at the Xinglong Station of National Astronomical Observatories, Chinese Academy of Sciences (NAOC). The organization of the paper is as follows: Section 2 describes the data collection and reduction; Section 3 introduces the pulsation analysis of the new data; Section 4 discusses the calculated changes of the period with the $O - C$ method; Section 5 gives our conclusions.

2 OBSERVATIONS AND DATA REDUCTION

Time-series photometric observations for CW Ser were made with the 85-cm telescope located at the Xinglong Station of NAOC between March 2011 and June 2012. The 85-cm telescope was equipped with a standard Johnson-Cousin-Bessel multicolor filter system and a PI1024 BFT CCD camera mounted on the primary focus (Zhou et al. 2009). The CCD camera has 1024×1024 pixels, corresponding to a field of view of $16.5' \times 16.5'$. Since March 2012, this CCD camera was replaced by a PI512 BFT, which has 512×512 pixels corresponding to a field of view of $15' \times 15'$. The observations were carried out through a standard Johnson V filter with exposure time ranging from 20 to 150 seconds, depending on the atmospheric conditions. A journal of the new observations is listed in Table 1.

Table 1 Journal of the New Observations in V with the 85-cm Telescope between 2011 and 2012

CCD	Year	Month	Nights	Frames
PI BFT1024	2011	March	4	1249
		May	7	2247
PI BFT512	2012	March	5	830
		April	2	245

Table 2 Information on the Comparison and the Check Stars

ID	Star Name	α (2000) (h m s)	δ (2000) (° ′ ″)	V (mag)
Comparison	USNOA2 0900-08292504	15 53 17.32	05 59 13.6	11.15
Check	USNOA2 0900-08293690	15 53 24.81	05 59 15.5	13.50

In total, 4571 CCD frames of data were collected for CW Ser within 18 nights. Figure 1 shows an image of CW Ser taken with the 85-cm telescope, where the comparison star and the check star are marked (see Table 2). After bias, dark and flat-field corrections, aperture photometry was performed by using the DAOPHOT program of IRAF. The light curves were then produced by computing the magnitude differences between CW Ser and the comparison star. The standard deviations of the magnitude differences between the check star and the comparison star yielded an estimation of photometric precision, with a typical value of $0.003^{\rm m}$ in good observation conditions and $0.011^{\rm m}$ in poor cases. Although there were slight shifts in the zero point, we made adjustments with the fitted light curves of the data for every month (assuming the frequencies were stable during one month).

Figure 2 shows the light curves of CW Ser in the Johnson V band observed with the 85-cm telescope in 2011 and 2012, which were used for the frequency analysis.

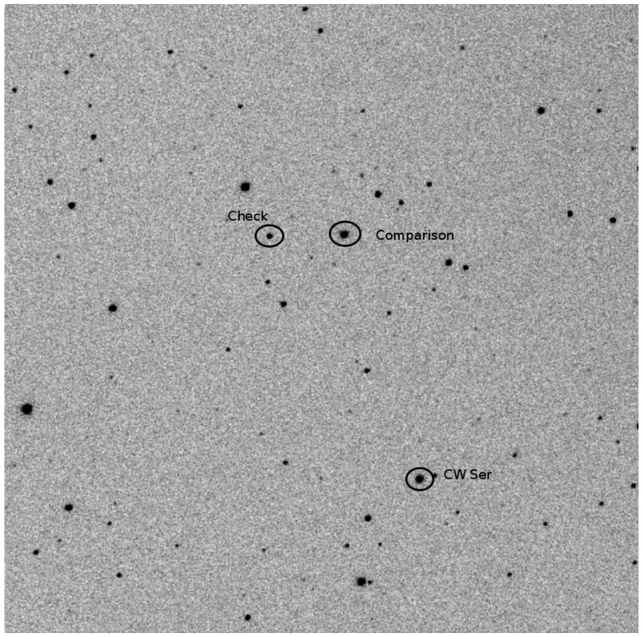

Fig. 1 CW Ser, the comparison star and the check star are marked in an image taken with the 85-cm telescope. The field of view is $16.5' \times 16.5'$. North is down and East is to the right.

3 PULSATION ANALYSIS

Frequency analysis was performed with the light curves of CW Ser in 2011–2012 with the software PERIOD04 (Lenz & Breger 2005), which calculates Fourier transformations of the light curves to search for significant peaks in the amplitude of the power spectrum. The light curves are fitted with the following formula,

$$m = m_0 + \sum_i A_i \sin(2\pi(f_i t + \phi_i)) \, . \tag{1}$$

The solutions with frequencies whose signal-to-noise ratio (S/N) are larger than 4.0 (Breger et al. 1993) are listed in Table 3. The solid curves in Figure 2 show the fits with the solution for frequency in 2011–2012. From Table 3, one notes that the eight frequencies are composed of the fundamental frequency and its seven harmonics. No frequencies other than the fundamental frequency and the harmonics are detected.

Table 3 Multiple Frequencies of CW Ser in 2011–2012

	Frequency (c d^{-1})	Amp (mmg)	S/N
f_0	5.28677	187.34	47.1
$2f_0$	10.57354	66.37	39.4
$3f_0$	15.86032	19.86	27.2
$4f_0$	21.14712	10.11	17.9
$5f_0$	26.43660	5.02	15.6
$6f_0$	31.72064	2.83	7.8
$7f_0$	37.00211	1.81	6.0
$8f_0$	43.29979	1.04	4.9

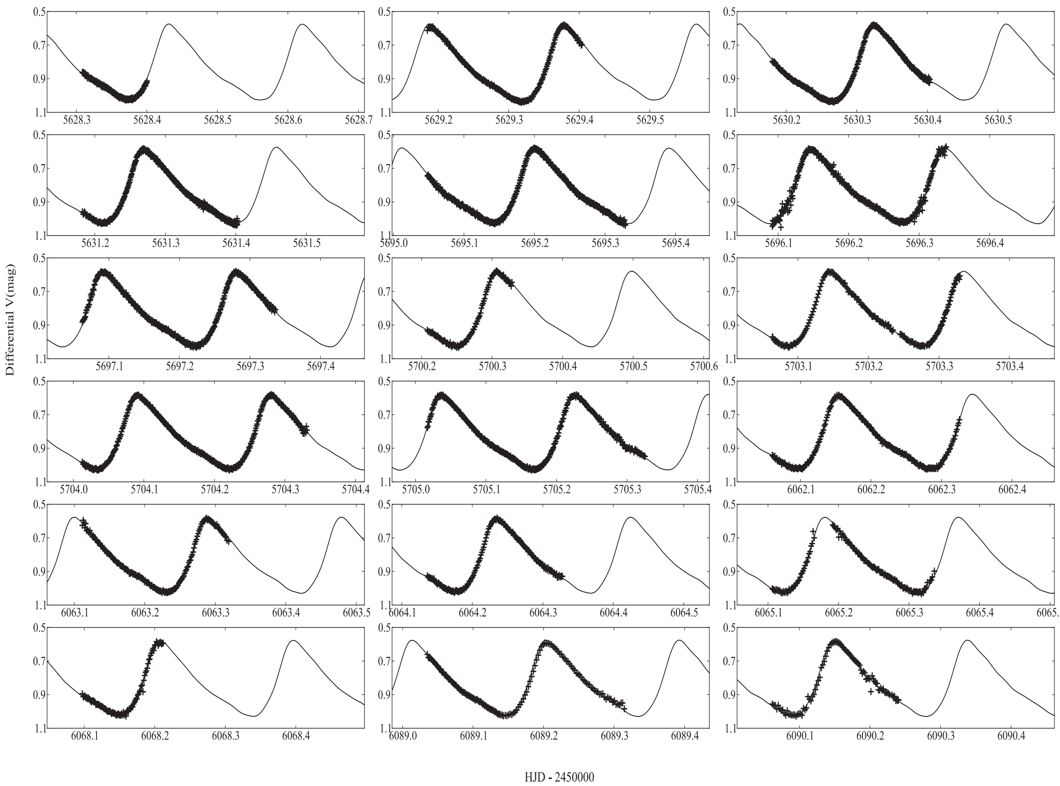

Fig. 2 Light curves of CW Ser in the V band from 2011 to 2012. The solid curves represent the fitting with the eight-frequency solution listed in Table 3.

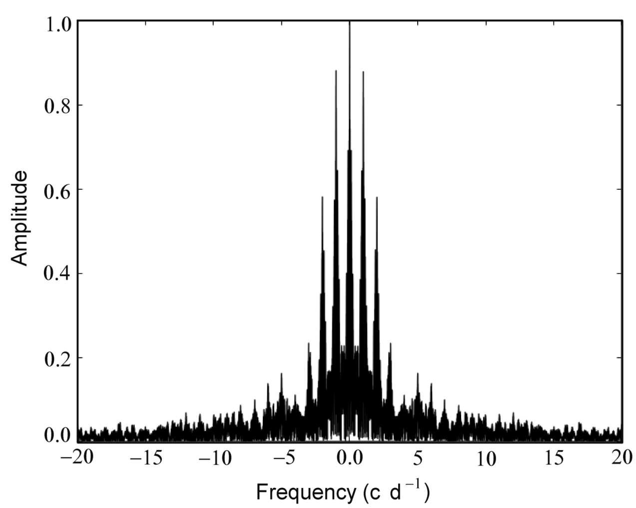

Fig. 3 Window function of the light curves in V for CW Ser from 2011 to 2012.

As can be seen from Figure 2, the constructed curves fit the observed light curves well, which shows that the fundamental frequency and its harmonics can explain the pulsation behavior of CW Ser.

Figure 3 shows the window function of the light curves of CW Ser in V from 2011 to 2012. Figure 4 shows the amplitude of the power spectrum of the pre-whitening process for frequency. Note that the peaks located in the low-frequency domain ($0 - 3$ c d^{-1}) are not considered to be significant signals of the variable star due to instabilities in the sensitivity of the instrument and variations of sky transparency in the low frequency domain.

4 THE $O - C$ DIAGRAM

With the new observations from 2011 to 2012, the light curves around the maximum light were fitted with third order polynomials, which are sufficient to derive times of maximum light. 21 new times of maximum light in the V band are determined with the data from 2011–2012.

Table 4 Times ($T_{\rm max}$ in HJD 2400000+ d) of Maximum Light of CW Ser

No.	$T_{\rm max}$	E	$O-C$	Det	Weight	S
0	31212.2800	0	—	?	—	[1]*
1	42575.5000	60075	−0.0171	pe	1.0	[2]
2	42576.4430	60080	−0.0199	pe	1.0	[2]
3	49888.4551	98737	0.0068	CCD	2.0	[3]
4	50599.4746	102496	0.0102	CCD	2.0	[4]
5	50944.4831	104320	0.0084	CCD	2.0	[5]
6	51325.4376	106334	0.0141	CCD	2.0	[6]
7	53143.3699	115945	0.0223	pe	1.0	[7]
8	53462.6549	117633	0.0215	pe	1.0	[7]
9	55628.3966	129083	−0.0082	CCD	2.0	[8]
10	55629.3504	129088	−0.0002	CCD	2.0	[8]
11	55630.2919	129093	−0.0045	CCD	2.0	[8]
12	55631.2388	129098	−0.0033	CCD	2.0	[8]
13	55695.1719	129436	−0.0030	CCD	2.0	[8]
14	55696.3073	129442	−0.0025	CCD	2.0	[8]
15	55697.2545	129447	−0.0011	CCD	2.0	[8]
16	55700.2832	129463	0.0011	CCD	2.0	[8]
17	55703.1135	129478	−0.0057	CCD	2.0	[8]
18	55703.3018	129479	−0.0066	CCD	2.0	[8]
19	55704.0575	129483	−0.0075	CCD	2.0	[8]
20	55704.2503	129484	−0.0038	CCD	2.0	[8]
21	55705.1970	129489	−0.0029	CCD	2.0	[8]
22	56062.1276	131376	0.0009	CCD	2.0	[8]
23	56063.2610	131382	−0.0005	CCD	2.0	[8]
24	56064.2072	131387	−0.0001	CCD	2.0	[8]
25	56065.1490	131392	−0.0040	CCD	2.0	[8]
26	56065.3436	131393	0.0013	CCD	2.0	[8]
27	56068.1823	131408	0.0028	CCD	2.0	[8]
28	56089.1783	131519	0.0031	CCD	2.0	[8]
29	56090.1231	131524	0.0021	CCD	2.0	[8]

E: cycle number. $O-C$: in days. Det: Detector. pe: photoelectric photometer. Points not used in the $O-C$ analysis are marked with an asterisk. S: Source; [1] Hoffmeister (1935); [2] Gieren et al. (1975); [3] Agerer & Hubscher (1996); [4] Agerer & Huebscher (1998); [5] Agerer et al. (1999); [6] Agerer et al. (2001); [7] Hubscher et al. (2005); [8] this work.

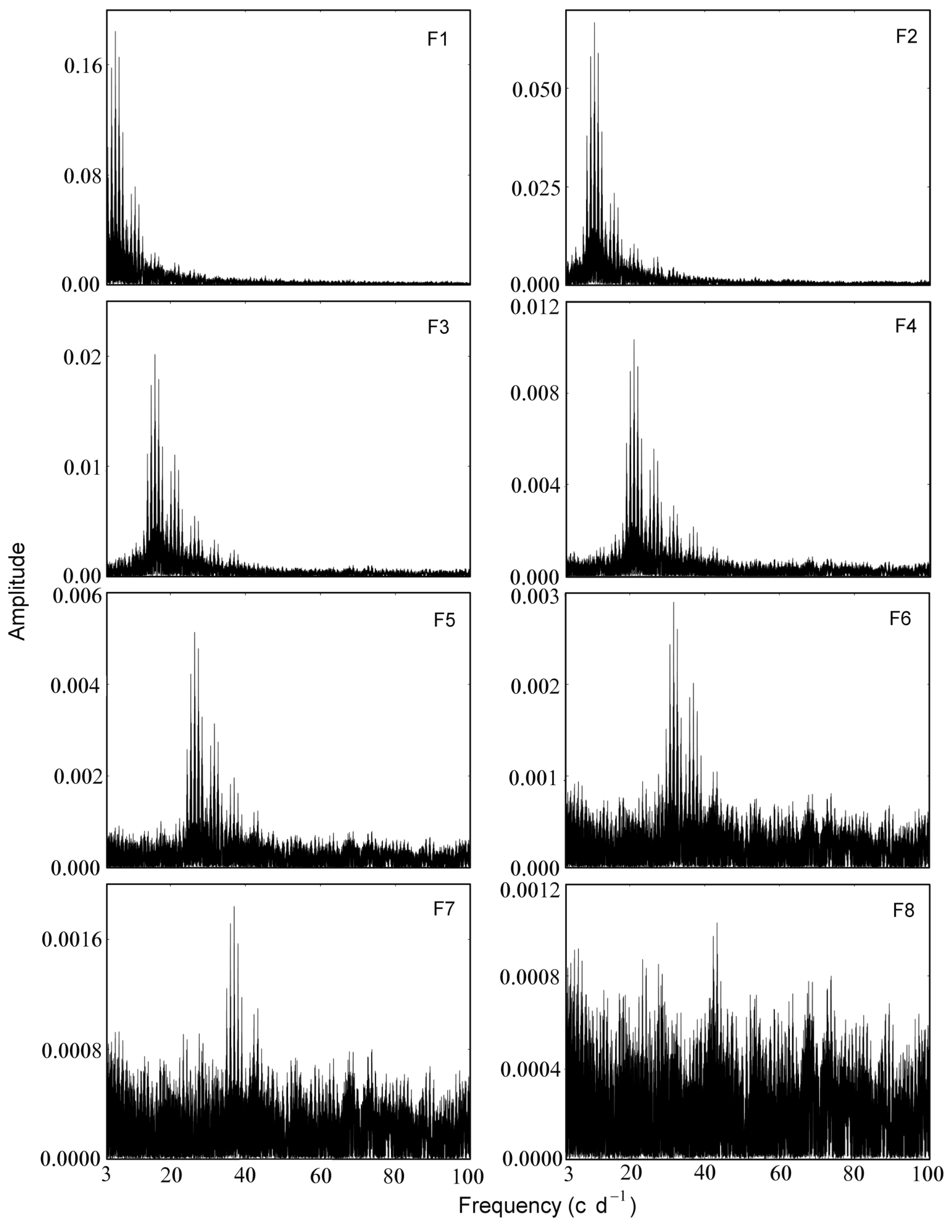

Fig. 4 Amplitudes of the power spectrum of the pre-whitening process of frequency for the light curves in V observed with the 85 cm telescope of NAOC in 2011–2012.

In order to perform the $O-C$ analysis for the period changes of CW Ser, the newly determined maximum times were combined with those provided by Gieren et al. (1975), Agerer & Hubscher (1996), Agerer & Huebscher (1998), Agerer et al. (1999), Agerer et al. (2001) and Hubscher et al. (2005). In total, 30 times of maximum light are collected and listed in Table 4, where the first time of maximum light is not included since we do not know the detector used or the precision of the data.

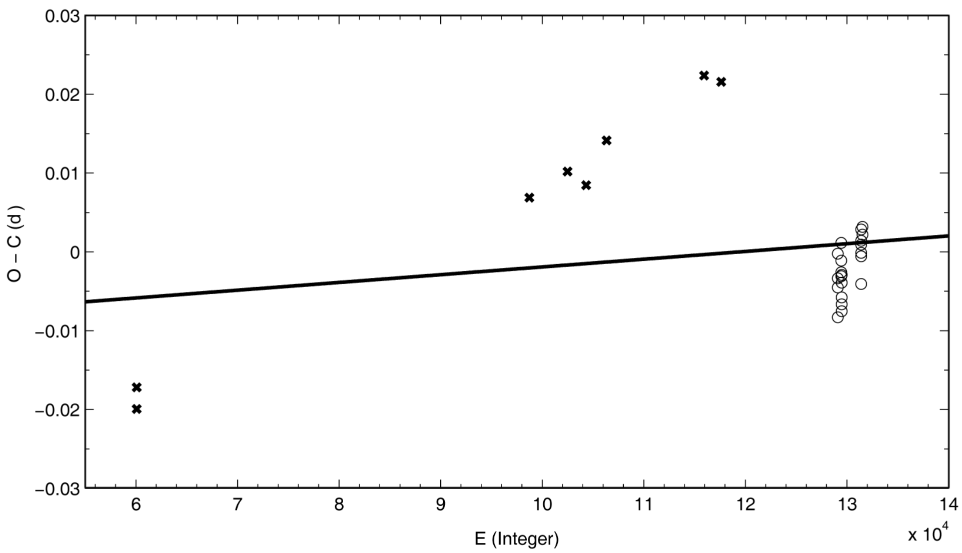

Fig. 5 $O - C$ diagram constructed with the data from the literature (*cross*) and the new data (*open circle*). The $O - C$ values are in day. E: cycle number.

In addition, there exists a large time gap between the first time of maximum light and the other data points.

The $O - C$ values are calculated and also listed in Table 4. The $O - C$ diagram is shown in Figure 5. A straight-line fit to the 30 times of light maxima yields the ephemeris formula,

$$\mathrm{HJD_{max}} = 2431212.3095(8) + 0.189150355(3)\, E, \tag{2}$$

with a standard deviation of $\sigma = 0.0091(7)$ d.

Since there are too many free data points in the $O - C$ diagram, we do not try to calculate a second-order polynomial fit to estimate the rate of change for the period.

5 CONCLUSIONS AND DISCUSSION

On the basis of the time-series photometric data from 2011 to 2012, we determined the fundamental frequency of pulsation to be $5.28677 \pm 0.00001\ \mathrm{c\ d^{-1}}$. No additional frequencies were resolved in the residual spectrum after prewhitening the fundamental frequency and its seven harmonics. The light variations of CW Ser can be well reproduced with the fundamental radial mode and its seven harmonics.

Analysis of the light curves of CW Ser suggests that no nonradial mode pulsations with amplitudes larger than 1.04 mmag are detected, which shows that the nonradial mode is not an overall property of the pulsations for all HADS at this amplitude level.

The seven harmonics resolved in the pulsations of CW Ser indicate a distortion of the light curves compared to a standard sinusoidal function, which does not help the asteroseismological analysis for CW Ser since no new independent modes are presented. However, the existence of multiple harmonics sheds light on the nonlinear behavior of the pulsation-excitation zone in the star.

According to the $O - C$ method, we provide a new ephemeris formula of the times of maximum light with the pulsation period of $0.189150355 \pm 0.000000003$ d.

More observations, including time-series photometry with a high duty cycle and high quality spectroscopic observations, are urgently needed to calculate the rate of change for period of CW Ser and deduce the properties of this HADS.

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