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Pulsation and Long-Term Variability of the High-Amplitude δ Scuti Star AD Canis Minoris *

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Abstract Time-series photometry was made for the large-amplitude δ Scuti star AD CMi in 2005 and 2006. High-quality photometric data provided in the literature were used to analyze the pulsation of the star, with the derived multiple frequencies fitted to our new data. Besides the dominant frequency and its harmonics, one low frequency (2.27402 c d $^{-1}$) is discovered, which provides a reasonable interpretation for the long-noticed luminosity variation at the maximum and minimum light. Combining the nine new times of light maxima determined from the new data with the 64 times collected from the literature, we analyzed the long-term variability of AD CMi with the $O-C$ technique. The results provide the updated value of period of 0.122974478 days, and seem to be in favor of the model of combination of the evolutionary effect and light-time effect of a binary system, of which some parameters are hereby deduced.

Key words: techniques: photometric — stars: variables: δ Scuti — stars: individual: AD CMi

1 INTRODUCTION

High-amplitude δ Scuti stars (HADS) form a subgroup of δ Scuti stars: they are located in the lower part of the Cepheids instability strip and show single or double pulsation modes with short periods ($<0.^{\rm d}3$) and large amplitudes ($\Delta V \geq 0.^{\rm m}3$). Now, the period changes caused by stellar evolution permit an observational test of the theory of stellar evolution, provided that other physical factors for period changes can be excluded, and the period changes for a number of HADS have been studied extensively. Breger (2000) has summarized the observed period changes of 18 radial δ Scuti pulsators. However, the measured period changes and the interpretations for most of them, including AD CMi, are inconclusive.

AD CMi was discovered to be a variable star by Hoffmeister (1934). Abhyankar (1959) found a period of 0.122972 days and identified it as an ultra-short period variable. Anderson & McNamara (1960) made two-color photometric observations of the star and improved the formula for maximum light times. Jiang (1987) carried out photometry in V, and found indications that the luminosity at maximum and minimum light varied slightly from cycle to cycle, and that the period increased. Rodriguez et al. (1988) published a large set of observations and supported the increasing period. Rodriguez et al. (1990) and Yang et al. (1992) reported some new times of light maxima and new linear and quadratic solutions. Kilambi & Rahman (1993) presented $UBVR$ observations of AD CMi, that suggest it to be a normal population-I δ Scuti star. Fu et al. (1996) found that the period variation in the $O-C$ diagram may be explained by the light-time effect in a binary system. Fu (2000) summarized the binary models for AD CMi, BS Aqr and CY Aqr.

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In order to study the pulsation and to examine its period changes, we observed AD CMi in 2005 and 2006. In Sections 2 and 3, we report the observations and analyses of its pulsation, incorporating the photometric data in the literature. The updated list of times of light maxima and the $O-C$ analysis are presented in Section 4. Finally, Sections 5 and 6 give a discussion and some conclusions, respectively.

2 NEW OBSERVATIONS AND DATA REDUCTION

A 16-inch Schmidt-Cassegrain telescope equipped with an ST-8 CCD camera was used to observe AD CMi in white light from 2005 January 30 to February 10, and between 2006 February 9 and 19; the telescope was located at the top of Physics Building of Naresuan University, Thailand. Three and Six nights of data were acquired in 2005 and 2006, respectively. Table 1 lists the coordinates of AD CMi and the two constant stars used as comparison and check stars. The CCD frames were reduced with standard procedure, then the magnitudes of the variable, comparison, and check stars were extracted with aperture photometry, hence the light curves of AD CMi relative to the comparison. Figure 1 shows the light curves of 2006. The light curves of the comparison relative to the check star prove that they are both constant stars.

Table 1 Coordinates of AD CMi, Comparison and Check Stars (Epoch=2005.1)

Name	α	δ
AD CMi	$07^h53^m02\overset{s}{.}99$	$01°35'02''$
Comparison	$07^h53^m16\overset{s}{.}20$	$01°38'18''$
Check	$07^h53^m17\overset{s}{.}27$	$01°40'45''$

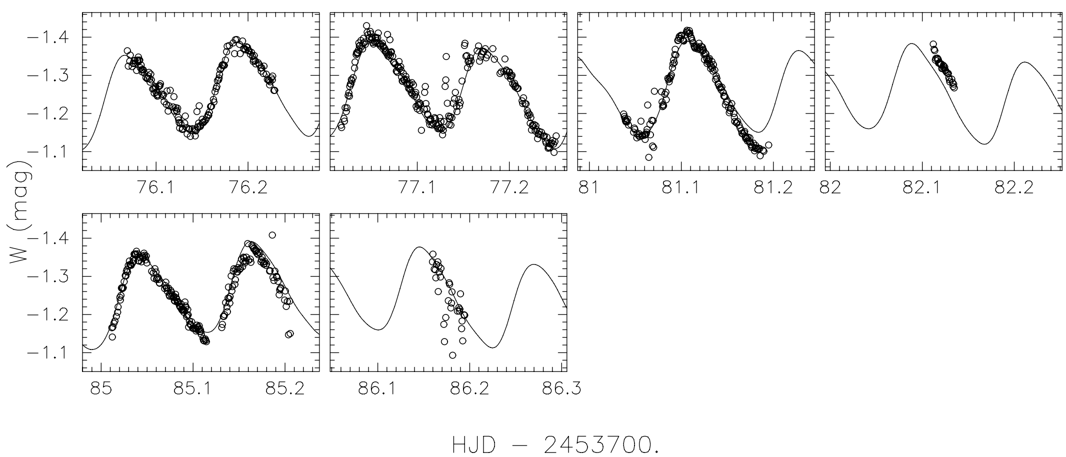

Fig. 1 Light curves of AD CMi in white light in 2006 plotted as open circles. The solid curves show the fitting with the four frequencies listed in Table 2. Note that variation in the luminosity at maximum and minimum light is visible from cycle to cycle.

3 PULSATION ANALYSIS

As one may see from Figure 1, the quality of photometry for AD CMi in 2006 is not high, and that of 2005 is even poorer. In contrast, high quality data were collected in 1984 (Rodriguez et al. 1988) in V and from 1985 to 1992 (Kilambi & Rahman 1993) in $UBVR$. So, we analyzed the pulsation of AD CMi with the combined data in V from 1984 to 1992, then fitted the resolved frequencies to the new observations in white light of 2006.

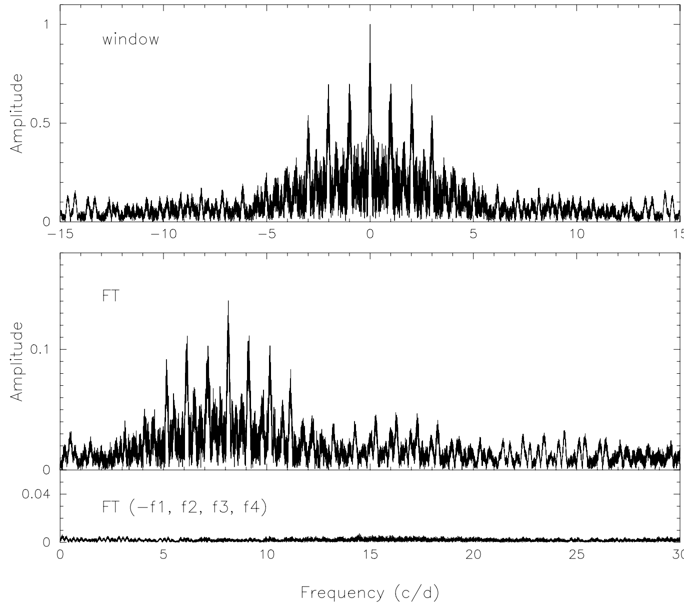

Fig. 2 From top to bottom: Window function, Fourier amplitude spectra of the combined data in V, and of the residuals with four frequencies pre-whitened.

3.1 Data Collected from 1984 to 1992

The combined data in V from 1984 to 1992 spanned some 2942 days, providing a frequency resolution of 0.00034 d^{-1}, with a low duty cycle value. The software `PERIOD04` (Lenz & Breger 2005) was applied to calculate the amplitude spectrum in a search for significant frequency peaks. Table 2 lists the multi-frequency solution. Figure 2 shows the window function, the amplitude spectra of the original data, and of the residuals with four frequencies pre-whitened, whose signal-to-noise (S/N) ratios are higher than 4.0 (as listed in the 4th column of Table 2, following the criterion of Breger et al. 1993 and Kuschnig et al. 1997). Figure 3 shows the observed light curves of AD CMi from 1984 to 1992 and the fitting curves with the four-frequency solution listed in Table 2.

Table 2 Multi-frequency Solution of the Combined Data in V for AD CMi

	Frequency (d^{-1})	Amplitude (mag)	S/N
f_1	8.131768	0.143	92.6
	±2	±1	
f_2	16.263902	0.027	13.0
	±8	±1	
f_3	2.274017	0.010	4.4
	±23	±1	
f_4	25.385106	0.009	5.6
	±26	±1	

3.2 New Data

Since the data collected in 2005 are of poor quality, we do not use it in the pulsation analysis of AD CMi. The data in 2006 are fitted with the four frequencies listed in Table 2, with the frequency and amplitude values free for fitting. Figure 1 shows the fitting as the solid curves.

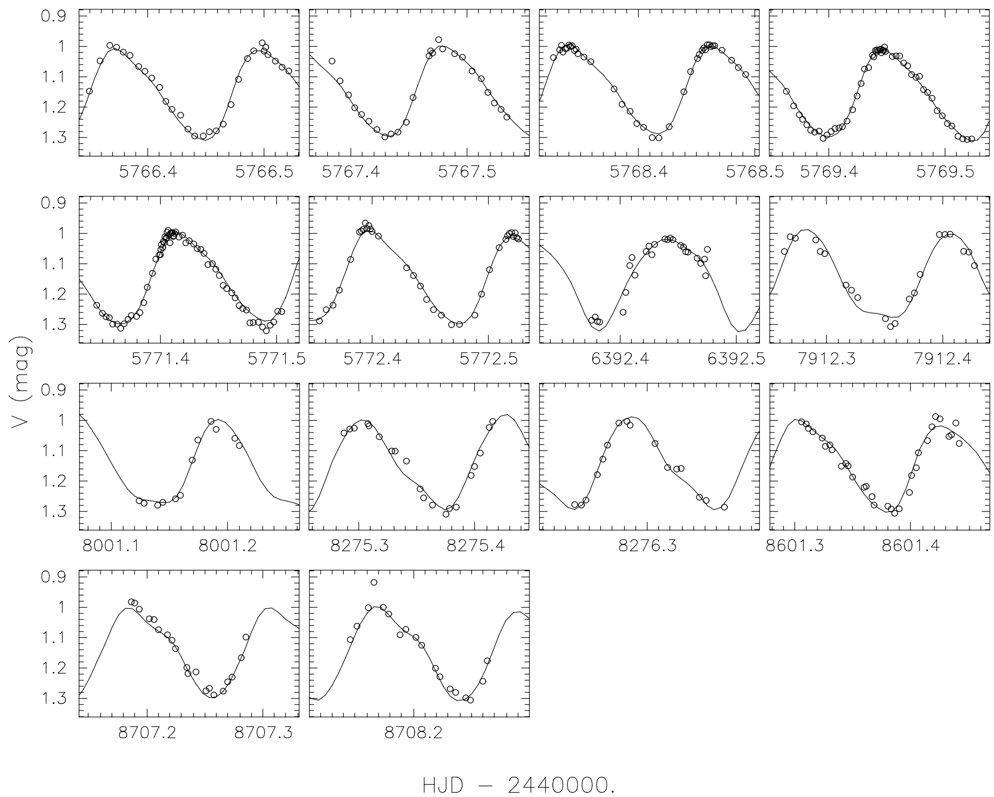

Fig. 3 Light curves of AD CMi in V from 1984 to 1992 plotted as open circles, the solid curves show the fitting with the solution listed in Table 2.

Table 3 New Times of Light Maxima of AD CMi in HJD-2453000 and the Uncertainties

409.2332 ±3	411.2005 ±20	412.1855 ±2	776.1928 ±2	777.0537 ±2
777.1778 ±1	781.1087 ±1	785.0454 ±2	785.1704 ±1	

4 TIMES OF LIGHT MAXIMA AND $O-C$ ANALYSIS

4.1 Times of Light Maxima Collection

With the new observations in 2005 and 2006, three and six times of light maxima were respectively determined, and the uncertainties were estimated from Monte Carlo simulations. Table 3 lists the nine new times of light maxima and their uncertainties. Combined with the times listed in Fu (2000) and determined from the other papers, a total of 73 times of light maxima are collected and listed in Table 4.

4.2 $O-C$ Analysis

A straight-line fit to the 73 times of light maxima yields the ephemeris formula

$$C = \mathrm{HJD}\ 2436601.8219 + 0.122974478E, \tag{1}$$

where the uncertainties of the fit to T_0 and P are 0.0005 d and 0.000000006 d, respectively. The $O-C$ values of 73 times of maximum light are listed in the 4th column of Table 4 and plotted in Figure 4. As one

Table 4 Times of Light Maxima of AD CMi

No.	$T_{\rm max}$	E	$O-C$ (d)	Ref	No.	$T_{\rm max}$	E	$O-C$ (d)	Ref
1	36601.8228	0.0	0.001275	FU	38	47220.4228	86348.0	0.000582	FU
2	36602.8066	8.0	0.001279	FU	39	47506.5825	88675.0	–0.001341	BU
3	36602.9296	9.0	0.001304	FU	40	47912.2780	91974.0	0.001339	KR
4	36604.8971	25.0	0.001213	FU	41	47912.4008	91975.0	0.001164	KR
5	36627.7700	211.0	0.000859	FU	42	48001.1867	92697.0	–0.000513	KR
6	36628.7538	219.0	0.000863	FU	43	48275.3000	94926.0	0.002664	KR
7	36629.7373	227.0	0.000567	FU	44	48276.2814	94934.0	0.000268	KR
8	36629.8602	228.0	0.000492	FU	45	48601.4231	97578.0	–0.002566	KR
9	36931.7620	2683.0	–0.000064	FU	46	48653.2017	97999.0	0.003776	FU
10	36932.7470	2691.0	0.001140	FU	47	48656.1511	98023.0	0.001789	FU
11	36934.8364	2708.0	–0.000026	FU	48	48656.2762	98024.0	0.003914	FU
12	36969.7620	2992.0	0.000820	FU	49	48708.1664	98446.0	–0.001118	KR
13	41010.6985	35852.0	–0.004204	FU	50	48713.0884	98486.0	0.001903	FU
14	42429.4582	47389.0	–0.001119	FU	51	48714.0724	98494.0	0.002107	FU
15	43182.4290	53512.0	–0.003081	FU	52	48717.0242	98518.0	0.002519	FU
16	43536.3488	56390.0	–0.003844	FU	53	49399.1625	104065.0	0.001360	FU
17	43536.4714	56391.0	–0.004219	FU	54	49400.1462	104073.0	0.001264	FU
18	44645.0877	65406.0	–0.002886	FU	55	49401.1320	104081.0	0.003268	FU
19	45766.3713	74524.0	–0.000626	FU	56	50153.3664	110198.0	0.002753	FU
20	45768.3377	74540.0	–0.001818	FU	57	50517.3688	113158.0	0.000682	FU
21	45768.4606	74541.0	–0.001892	FU	58	51268.3696	119265.0	–0.003688	FU
22	45771.4134	74565.0	–0.000480	FU	59	51577.5300	121779.0	–0.001139	AG
23	45772.3961	74573.0	–0.001576	FU	60	51598.3120	121948.0	–0.001827	AH
24	45772.5187	74574.0	–0.001950	FU	61	52695.3662	130869.0	–0.002993	AH
25	46392.4356	79615.0	0.000579	KR	62	52984.5980	133221.0	–0.007178	HU
26	46417.3991	79818.0	0.000259	FU	63	53028.5055	133578.0	–0.001569	HU
27	46418.2596	79825.0	–0.000063	FU	64	53409.2332	136674.0	–0.002869	pp
28	46418.3825	79826.0	–0.000137	FU	65	53411.2005	136690.0	–0.003161	pp
29	46419.2434	79833.0	–0.000058	FU	66	53412.1855	136698.0	–0.001957	pp
30	46419.3663	79834.0	–0.000133	FU	67	53776.1928	139658.0	0.000872	pp
31	46443.1010	80027.0	0.000492	FU	68	53777.0537	139665.0	0.000951	pp
32	46443.2243	80028.0	0.000817	FU	69	53777.1778	139666.0	0.002076	pp
33	46443.3470	80029.0	0.000543	FU	70	53781.1087	139698.0	–0.002207	pp
34	46444.0850	80035.0	0.000696	FU	71	53785.0454	139730.0	–0.000691	pp
35	46444.2082	80036.0	0.000921	FU	72	53785.1704	139731.0	0.001335	pp
36	46444.3312	80037.0	0.000947	FU	73	53810.6259	139938.0	0.001117	KL
37	47219.4395	86340.0	0.001078	FU					

$T_{\rm max}$ is in HJD-2400000. Ref: FU = Fu (2000), AG = Agerer et al. (2001), AH = Agerer & Hubscher (2003), BU = Burchi et al. (1993), HU = Hubscher (2005), KR = Kilambi & Rahman (1993), KL = Klingenberg et al. (2006), pp = present paper.

may see from Figure 4, the $O-C$ diagram displays a strong cyclic variation, which leads us to fit the times of maximum light with a quadratic plus a sinusoidal,

$$C' = \mathrm{HJD}_0 + P_{\rm pul}\cdot E + \frac{1}{2}\beta E^2 + A\sin\phi + B\cos\phi, \tag{2}$$

where ϕ is the solution of Kepler's equation,

$$\phi - e\sin\phi = \frac{2\pi}{P_{\rm orb}}(P_{\rm pul}\cdot E - t_0). \tag{3}$$

Equation (2) is equivalent to equation (2) of Irwin (1952) and equation (1) of Ribas et al. (2002) and describes the light time effect (where $P_{\rm orb}$ is the orbital period, $P_{\rm pul}$ the pulsation period of the variable star, t_0 the time of periastron passage). The solid curves in Figure 4 show the fitting.

5 DISCUSSION

5.1 For the Pulsation

As seen from Figure 3, the multi-frequency solution listed in Table 2 fits the observed light curves very well for the data spanning over 8 years, showing that the pulsation of AD CMi is very stable on this time scale.

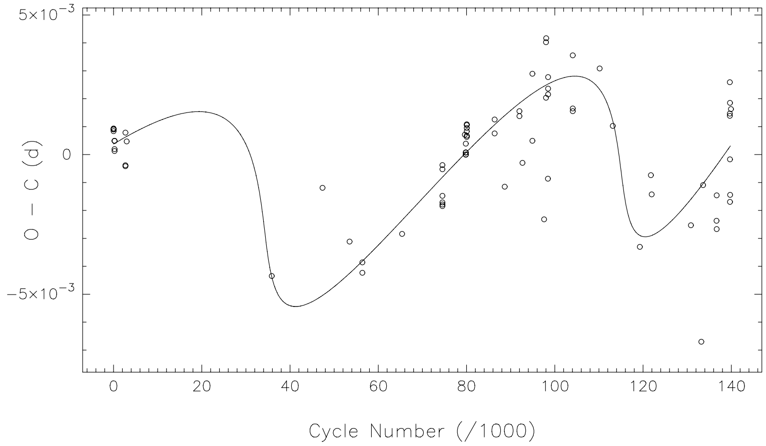

Fig. 4 $O - C$ diagram based on Equation (1). The line is the fitted quadratic function plus the light-time effect solution.

Although the fitting shown in Figure 1 is not as good as in Figure 3, which is not surprising due to both the poorer data quality in 2006 and the different passbands of the data, it suggests that the four frequencies also fit the data in 2006, hence the main characteristics of the pulsation of AD CMi were stable throughout 1984 to 2006.

A careful inspection of Table 2 shows that $f_2 \approx 2f_1$ and $f_4 \approx 3f_1 + 1$. As all the data were collected at a single site, the 1 c d^{-1} aliasing effect is strong, which can be seen from the window function shown in Figure 1. So, f_2 and f_3 can be identified as the harmonics of the fundamental frequency f_1, or its combination with the 1 c d^{-1} aliasing effect. The frequency of f_3 of 2.27402 c d^{-1} is specially interesting, since it does not show any link with the fundamental frequency f_1, and its value is out of the general frequency range for HADS. However, this frequency should be real since its amplitude is high enough to be detected unambiguously (see Fig. 2), and this low-value frequency provides a strong interpretation for the long-noticed small variation of luminosity at maximum and minimum light from cycle to cycle (see, e.g. Jiang 1987), which can be seen in Figures 1 and 3. The mode identification of f_3 is still unknown. However, since the f_3 value is located in the g-mode frequency domain of δ Scuti stars, is it possible for f_3 to be a g-mode? A multi-site observation campaign for this star may help in confirming this frequency, and multi-band photometry might provide clues for the mode identification of this frequency (see, e.g., Garrido 2000).

5.2 The $O - C$ Diagram

Equation (1) gives the up-to-date value of the pulsation period of AD CMi. The $O - C$ diagram (Fig. 4) shows strong cyclic variation, leading to a solution consisting of a quadratic function plus the light-time effect. The determined period changes are (0.86±0.06)×10^{-12} days cycle^{-1}, or 2.1× 10^{-8} yr^{-1}. This coincides with the theoretically predicted direction of increasing period for most δ Scuti stars, and falls within the range 10^{-10} yr^{-1} to 10^{-7} yr^{-1} (Breger 2000). The binary orbit has a period of 27.2 ±0.5 years, with an eccentricity of 0.8±0.1. However, since there is a big gap between the first 12 data points and the rest, and the bulk of the data spans only one cycle (see Fig. 4), this result should not be considered as an accurate solution of the orbit parameters, although the tendency of light-time effect exists clearly in the $O - C$ diagram.

One may notice the large scatters in the $O - C$ diagram in the data of same observational runs, which seem to be intrinsic. One possible explanation is that the low value of frequency of 2.27402 d^{-1} may not only vary the luminosity of the star at the maximum and minimum lights, but also affects the times of light maxima. Recall that Fu & Sterken (2003) argued that a reasonable fit to the $O - C$ diagram of CY Aqr does not explain the full size of its period change, either.

6 CONCLUSIONS

The analysis of the pulsation resolved four frequencies in AD CMi, including the fundamental frequency and its harmonics, and a low-value one of 2.27402 c d $^{-1}$, which provides reasonable interpretation for the long-noticed, but so far not explained small variation of luminosity at maximum and minimum light. Thus, AD CMi is the first HADS in which an independent, extra low-value frequency is detected, which provides a possible explanation for the large scatters in the $O - C$ diagram in some observation runs (this feature is present in many HADS). Incidentally, although a low frequency of 1.3947 c d $^{-1}$ was reported for the δ Scuti star VZ Cnc, it was identified as a linear combination of two pulsation modes (Fu & Jiang 1999).

The new observed data, when combined with the data collected from the literature, put the updated value of pulsation period at 0.122974478$\pm$0.000000006 days. The $O - C$ diagram is adequately represented by a combination of a continuously increasing period change and the light time effect in a binary configuration. However, the binary model presented in present paper should not be considered as an accurate and unique solution of the $O - C$ diagram of AD CMi. Future observations are needed to confirm the binary model, and to provide more accurate solution for the binary system.

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