KAO-EGYPT J064512.06+341749.2 is a Low Amplitude and Multi-Periodic δ Scuti Variable Star

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Received March 11, 2019; revised April 23, 30, 2019; accepted April 7, 2019

Abstract CCD photometric observations with *BVRI* filters using the 1.88-m telescope of Kottamia Astronomical Observatory (KAO), Egypt, revealed that the star KAO-EGYPT J064512.06+341749.2 is a low-amplitude (Δm < 0.3 mag) δ Scuti star. The peak-to-peak amplitude is 0.014 magv. Two modes are present ($f_1 = 23.600 \pm 0.133$ c/d and $f_2 = 18.314 \pm 0.202$ c/d). The frequency ratio, $f_2 / f_1 = 0.776$, suggests that the star is a radial pulsator. By using the empirical relations for KAO-EGYPT J064512.06+341749.2, we determined the global physical parameters.

1. Introduction

δ Scuti stars are pulsating variable stars useful for studies of stellar structure and evolution. The class of δ Scuti stars includes stars situated under the classical Cepheids in the instability strip on the main sequence or moving from the main sequence to the giant branch. δ Scuti stars normally have small amplitude variations, with radial pulsation, non-radial p-mode pulsation, and short periods. Many modes can be excited simultaneously. In general, the period range is limited from 30 minutes to 6 hours and the masses range from 1.0 to 3.0 $M_{\odot}$. Observations for several decades revealed that the low amplitude δ Scuti stars (LADS) show a large variety of non-radial modes, complex light variability, multi-periodicity, and phase and amplitude variations. High amplitude (> 0.3 mag.) δ Scuti stars (HADS) have been thought to be classical radial pulsating stars, mostly mono-periodic, though double mode in some cases, but always pulsating in radial modes (Kjurkchieva *et al.* 2013). However, recently many HADS have been found to be multi-periodic variable stars with non-radial as well as radial pulsations (Zhou 2002; Poretti 2003; Poretti *et al.* 2005). The differentiation between LADS and HADS is that the non-radial modes in HADS have much smaller amplitudes than the radial modes. The period and amplitude variations can be considered as small perturbations of a mode visible in the light curve.

The variability of the star KAO-EGYPT J064512.06+341749.2 was discovered by Essam (2013). It has many alternative identifications, including 2MASS J06451206+3417492, GSC 02444-00241, UCAC4 622-035906, and USNO-B1.0 1242-0138204. Table 1 contains the basic data for the comparison and check stars used as well as for the variable.

2. Observations

Observations were carried out by Essam (2013) on two consecutive nights, 7/8 February and 8/9 February 2013, in addition to the night of 20/21 January 2015 (data available at https://www.aavso.org/apps/webobs/results/?star=KAO-EGYPT+J064512.06%2B341749.2&obscode=EAEA&num_results=200&obs_types=all), at the Newtonian focus (f/4.84) of the 1.88-meter telescope of the Kottamia Astronomical Observatory (KAO), Egypt (for more details about KAO see Azzam *et al.* 2010). The observations were performed using the back-illuminated EEV 42-40 CCD chip with 2048 × 2048 pixels. The pixel size, scale, and total field of view were 13.5μ, 0.305"/pixel, and 10 × 10 arcmin, respectively. The standard *BVRI* Johnson photometric system was used. All raw images are bias-subtracted and flat-fielded corrected. The exposures were 180, 60, 20, and 10 sec. in the *B, V, R,* and *I* bands, respectively. The light curves were then produced by computing the magnitude differences between the variable KAO-EGYPT J064512.06+341749.2 and the comparison star.

Table 1. Coordinates, magnitudes, and color index of the variable and comparison stars.

Star	*Name*	*R.A. (2000)* *h m s*	*Dec. (2000)* *° ' "*	*V*	*B–V*
V[1]	KAO-EGYPT J064512.06+341749.2	06 45 12.064	+34 17 49.17	13.452 ± 0.08	0.319 ± 0.094
	UCAC4 622-035906				
C1[2]	USNO-A2.01200-05104801	06 44 58.05	+34 23 52.8	14.037 ± 0.061	0.648 ± 0.087
C2[2]	USNO-A2.01200-05103968	06 44 54.65	+34 24 09.6	13.564 ± 0.071	0.713 ± 0.074

Notes: 1. UCAC4 catalogue (Zacharias et al. *2013). 2. USNO-A2.0 catalogue (Monet* et al. *1998).*

3. Light curve analysis

The Δb, Δv, Δr, and Δi light curves of the star KAO-EGYPT J064512.06+341749.2 are presented in Figure 1. KAO-EGYPT J064512.06+341749.2 is a pulsating variable with a total amplitude of 0.083, 0.068, 0.042, and 0.051 mag. in the *B, V, R,* and *I* bands, respectively. Using the standard *B* and *V* magnitudes of the comparison star (B = 14.681, V = 14.052) to determine the standard magnitude of the variable, we found that the average magnitude and color index for the variable are $V = 13.391 \pm 0.013$ and $B-V = 0.373 \pm 0.005$.

4. Frequency analysis

All light curves of KAO-EGYPT J064512.06+341749.2 were examined in more detail using the Phase-Dispersion-Method within the software PERANSO (Vanmunster 2013). Also, PERIOD04 (Lenz and Breger 2005) was used to make Fourier transformations of the light curves to search for the significant peaks in the amplitude spectra; the results are listed in Table 2. The DFT method can be used to detect a signal, remove the detected frequency and its harmonics from the data, and search for additional frequencies in the residuals. Also, the first step was to construct the "periodogram" by fitting a sinusoid to the highest-amplitude period obtained from an initial fit to the observed magnitudes. The derived sinusoid was then subtracted from the original magnitudes. The analysis was repeated on the pre-whitened data in an iterative fashion, until no more significant periods were found. The analysis of the *B*-band light curve shows that there are two frequencies in the periodogram, at 0.0413 d (24.175 c/d) and 0.0556d (18.681 c/d) (see Figure 2).

The light curve analysis of the present observations, i.e. from 2013 and 2015, indicates that the amplitudes of the two frequencies are changing with time. We checked the amplitudes for KAO-EGYPT J064512.06+341749.2 but unfortunately we do not have sufficient observations in all bands. The amplitude in V-band for KAO-EGYPT J064512.06+341749.2 dropped from 13.12 mmag in 2013 to 10.51 mmag during 2015; other filters in 2015 have more scatter. This phenomenon was also found in other δ Scuti stars, such as BR Cancri (Zhou *et al.* 2001). More observations are needed to confirm this phenomenon in KAO-EGYPT J064512.06+341749.2.

Breger *et al.* (1993) found that the solutions with frequencies whose signal-to-noise ratios (S/N) are larger than 4.0 are accurate for distinguishing between peaks due to pulsation and noise for the average amplitude in the range 15 to 25 c/d. Present results are in the same range for the two frequencies: S/N=07.862 and 10.732 in the first and second frequencies,

Table 2. Fourier parameters of the best-fitting sinusoids for the *B* light curve of the variable star KAO-EGYPT J064512.06+341749.2.

Filter	*Frequency (c/d)*	*Amplitude (magnitude)*	*Phase*	*S/N*
B_1	24.175 ± 0.086	0.022 ± 0.001	0.989 ± 0.007	07.862
B_2	18.681 ± 0.227	0.008 ± 0.001	0.345 ± 0.019	10.732

Note: The subscripts 1 and 2 refer to the first and the second frequencies, respectively.

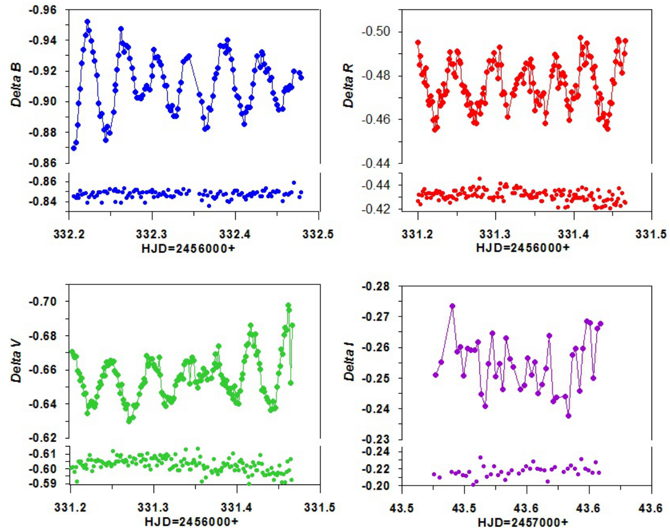

Figure 1. *BVRI* differential magnitude light curves of the pulsating variable KAO-EGYPT J064512.06+341749.2. The dots below each curve represent the magnitude difference between the comparison and check stars.

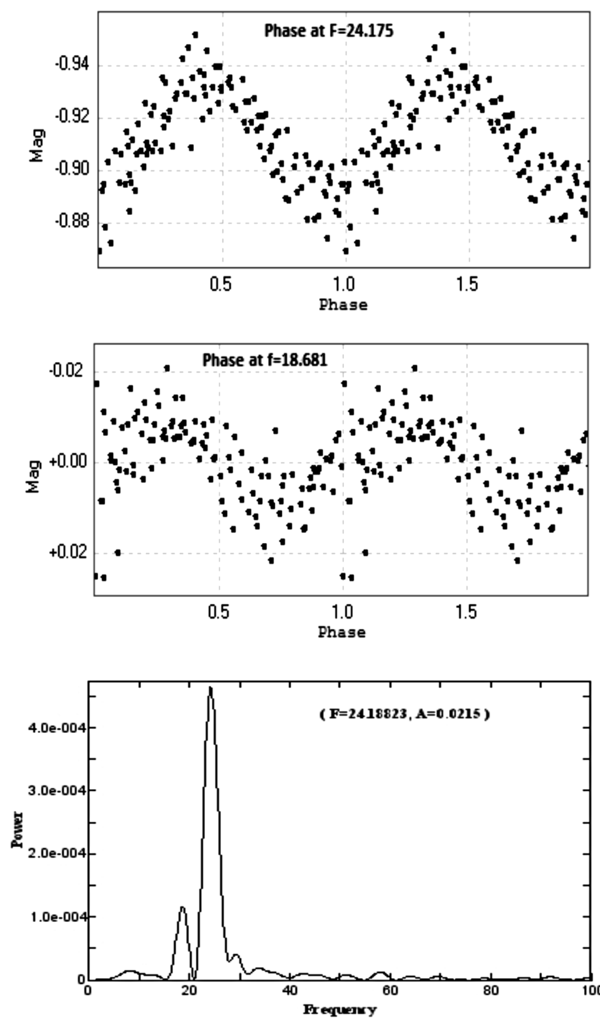

Figure 2. The *B*-band phased light curves at two frequencies' (24.175 c/d) and (18.681 c/d) periods are presented in the upper panels. Amplitude spectra for the same frequencies are presented in the lower panel.

respectively. The uncertainties in frequency, amplitude, and phase are obtained from a Monte Carlo simulation. The spectral window of KAO-EGYPT J064512.06+341749.2 in *B*-band and the phased light curves at two frequencies' (24.175 c/d) and (18.681 c/d) periods are presented in Figure 2.

The light curve was fitted by using two frequencies (24.321 and 18.377) with residuals = 0.009 and 0.007, respectively, as shown (upper and lower plots) in Figure 3. More time series photometric and spectroscopic observations are needed to determine a more accurate spectral type and to study the multi-periodic nature of the pulsation and amplitude variations.

We carried out detailed frequency analysis of the available data, and we obtained improved frequencies f_1 (24.321) and f_2 (18.377) and detected oscillations corresponding to the interaction between f_1 and f_2, (f_1+f_2) and (f_1-f_2). The period ratio, $P_1/P_0=0.756$, is a little higher than the mean canonical value of the range 0.75–0.79, with the minimum value corresponding to metal-strong stars (Z ~ 0.01), while the maximum value corresponds to metal-poor stars (Z ~ 0.001) (Poretti *et al.* 2005).

5. Pulsating mode identification of KAO-EGYPT J064512.06+341749.2

In order to obtain the global physical parameters of KAO-EGYPT J064512.06+341749.2 we used the following relations for the pulsating stars. We attempted to identify the observed frequencies of pulsation with pulsation modes. The basic solar parameters were T_{eff} = 5777 K, log g = 4.44, and M_{bol} = 4.75, which we used in the following equations. We also used the effective temperature of our system from the Gaia web site (http://sci.esa.int/gaia/), T_{eff} = 7776 K.

The absolute magnitude of the star was calculated in *V*-band in a recent paper by McNamara (2011):

$$M_v = (-2.89 \pm 0.13) \log (p) - (1.31 \pm 0.10). \tag{1}$$

The bolometric correction (BC) relation was evaluated by Reed (1998):

$$BC = -8.499\,[\log(T)-4]^4 + 13.421\,[\log(T)-4]^3 \\ -8.131\,[\log(T)-4]^2 - 3.901\,[\log(T)-4] - 0.438. \tag{2}$$

The bolometric magnitude, M_{bol}, is further given by $M_\lambda = M_{bol} - BC$.

By using the last equations, the absolute magnitude of the star was calculated in *V-filter* as M_V = 2.696 ± 0.078 mag. We found that BC = – 0.127 ± 0.003, M_{bol} = 2.823 ± 0.078.

Using the mass relation by Cox (2000) for δ Scuti stars, *Log M = 0.46 – 0.10* M_{bol}, the stellar mass of the system equals M = 1.506 ± 0.072$M_\odot$.

The stellar radius was calculated from a polynomial fit to the temperature/radius relation by using Gray (1992, equation 3), or from the formulae by Tsvetkov (1988), $\log R = 8.472 - 2\log T_{eff} - 0.2\,M_{bol}$. The results are $R/R_\odot = 1.330 \pm 0.012$ and 1.259 ± 0.053, respectively.

We can use the following equation to calculate stellar luminosity:

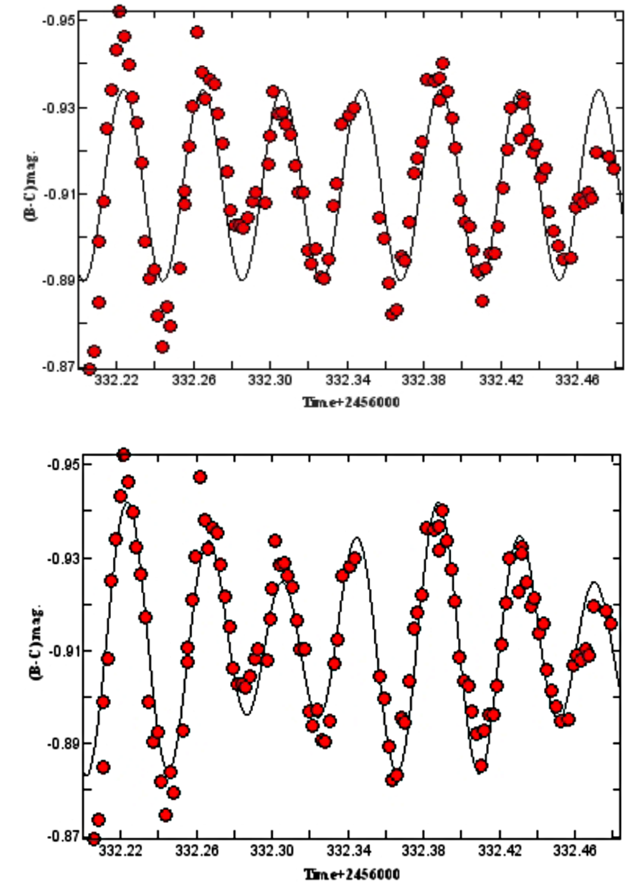

Figure 3. Observed *B*-band light curve (dots) of the present observations together with the fitted two frequencies (solid line). The upper plot is the fit by using the first frequency (residual = 0.0088) and the lower plot is the fit by using the second frequency (residual = 0.0066).

$$M_* = M_\Theta - 2.5\log(L_*/L_\Theta). \tag{3}$$

Surface gravity can be evaluated by using the following equation and its range should be between 3.4 and 4.4 for δ Scuti stars (Alcock *et al.* 2000):

$$\frac{g}{g_\Theta} = \left(\frac{M_*}{M_\Theta}\right) \frac{(T_*/T_\Theta{}^4)}{(L_*/L_\Theta)} \tag{4}$$

The luminosity ratio $L/L_\odot$ is found to equal 5.899 and $\log g = 4.363 \pm 0.111$.

The pulsation constant (Q) can be determined using the following equation (Breger and Bregman 1975):

$$\log Q = 0.5 \log g + 0.1\,M_{bol} + \log T_{eff} + \log P - 6.456, \tag{5}$$

where Q depends on the physical parameters of the star. The pulsation frequency of 24.321 c/d has a Q value corresponding to 0.0325, and 0.0277 for frequency 18.377 c/d.

6. Discussion and conclusion

With the *BVRI* photometric observations obtained using the 1.88-m KAO telescope, we discovered the variability of KAO-EGYPT J064512.06+341749.2 (Essam 2013) as a δ Scuti pulsating variable. The present analysis shows that KAO-EGYPT J064512.06+341749.2 is clearly a double-mode variable star with two radial modes. Photometric analysis conducted by the authors yields a period of 0.0425 day and a peak-to-peak amplitude of 0.014 magnitude. There are two clear frequencies: the first overtone mode ($f_1 = 24.3212678 \pm 0.081$ c/d with amplitude = 0.022 ± 0.001 mag., S / N = 07.862) and the fundamental mode ($f_0 = 18.681 \pm 0.227$ c/d with amplitude = 0.008 mag., S / N = 10.732), with the ratio $f_0 / f_1 = 0.768$. The frequency ratio of 0.77 seen in the confirmed double mode stars indicates that they are pulsating primarily in the fundamental and first overtone modes, suggesting that this star must lie nearer the red edge of the instability strip. The physical parameters of this newly discovered pulsating star KAO-EGYPT J064512.06+341749.2 are determined as: $M_{bol} = 2.823 \pm 0.078$, $M / M_\odot = 1.506 \pm 0.072$, $R / R_\odot = 1.330 \pm 0.012$, $L / L_\Theta = 5.899$, $\log g = 4.363 \pm 0.111$, and Q values of 0.032 d ± 0.002 for the pulsation frequency 24.321 c/d and 0.0277 d ± 0.001 for the pulsation frequency 18.377 c/d. All values are based on solar units and a bolometric correction of -0.127 ± 0.003 mag. Typical values of pulsation constants of the fundamental, first, and second overtone radial p modes in δ Sct stars are $0.022 \leq Q \leq 0.033$ d (Breger and Bregman 1975), thus the Q values indicate overtone radial or non-radial pulsation ($k \geq 0$) (Breger 1990).

Our results show a good agreement with the work thesis by Bowman (2016, figure 4.12) for low-frequency pulsations ($\nu \leq 25\,d - 1$), and physical evolution with that expounded by Flower (1996), as seen in Table 3. From the study of the evolution status of KAO-EGYPT J064512.06+341749.2 we found that its age (τ) is equal to $6.6 \pm 4.5 \times 10^8$ years by using the database of stellar evolutionary tracks and isochrones of Mowlavi *et al.* (2012). Also, we predict that this pulsating star is in the red edge of the instability strip as compared with theoretical results by Baglin *et al.* (1973) and Christiansen *et al.* (2007). More photometric and spectroscopic observations are needed to confirm the possible variation in amplitude and period found in the present analysis of this pulsating star.

7. Acknowledgement

The authors are very grateful to Dr. Luis Balona (South African Astronomical Observatory) for his very helpful discussion.

Table 3. Frequency ratio as detected in the *B*-band.

Mode	*Frequency (c/d)*	*Amplitude (magnitude)*	*Phase*	*Epoch 2456000+*
f_1	24.321 ± 0.081	0.0213	0.657	331.963
f_0	18.377 ± 0.206	0.0086	0.402	331.964
$f_1 + f_0$	42.698 ± 0.915	0.0020	0.553	331.981
$f_1 - f_0$	5.944 ± 1.525	0.0016	0.684	331.843

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