KIC 8840638: A new Eclipsing Binary Consisting of a $\delta$ Scuti star with multiperiodic pulsations

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ABSTRACT

In this paper, we analyse the light variation of KIC 8840638 using the high-precision time-series data delivered by Kepler mission. The analysis reveals that the target KIC 8840638 is an eclipsing binary with a $\delta$ Scuti component, not a pure single $\delta$ Scuti star previously known. The frequency analysis of the high-precision short cadence light curve reveals 95 significant frequencies, most of them lies in the frequency range of 23–32 d$^{-1}$. Among them, 7 independent frequencies are detected in the typical frequency range of the $\delta$ Scuti variables. In addition, the orbital frequency $f_{\text{orb}}$ (=0.320008 d$^{-1}$) and its harmonic are also detected directly in the frequency spectrum. The binary modeling using the Wilson-Devinney code indicate the binary system is in a semi-detached configures with a mass ratio of 1.6, an inclination angle of 16.9 degree, and a temperature difference of larger than 3000 K between the components. The locations of the components of KIC 8840638 indicate the primary star lies in the $\delta$ Scuti instability region below the terminal-age main-sequence, and the secondary star might be a evolved star.

Subject headings: stars: oscillations; stars: variable: delta Scuti

1. Introduction

Eclipsing binaries (EBs) are often considered as primary source for us to obtain the fundamental stellar parameters precisely, such as the mass and radius for each component. These accurate parameters can be used to improve our knowledge for the stars and test stellar models (Torres et al. 2010). Furthermore, with high-precise and long term photometric time series, the mid-eclipse times can also be determined. These timing measurements can be used to find more components and/or investigate a variety of different physical phenomena causing the orbital period changes of EBs (Hilditch 2001; Kreiner et al. 2001)

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EBs with pulsating components are excellent objects for the study of stellar structure and evolution, as binarity could provide useful information about the components and asteroseismology of the pulsating components could probe into the interiors of stars. Among the pulsating EBs, more than 90 systems have been found to be δ Sct type EB, which was also called as ‘oscillating eclipsing Algol (oEA) stars’ (Mkrtichian et al. 2004; Liakos & Niarchos 2017). δ Sct stars are short-period pulsators with spectral types A and F located in the lower part of the classical Cepheid instability strip. Their oscillating periods are in the range of 0.02-0.25 days and the amplitudes are usually less than 0.1 mag (Breger 2000; Rodríguez & Breger 2001). They usually pulsate in low-order radial/non-radial pressure (p) modes, which are driven by κ mechanism acting in the partial ionization of He II. These modes can be used to probe the envelope of a star. The δ Sct variables in binaries have some pulsation features similar to the single δ Sct stars, but the pulsations of the former might be influenced by mass transfer between both components and gravitational forces from companions. Recently, a threshold in the orbital period of about 13 days was found by Liakos & Niarchos (2015, 2016). Below this threshold the pulsations would be influenced by the binarity. Furthermore, in eccentric-orbit binaries, some pulsations can be excited by tidal interaction, and the resulting excited modes appears as the frequencies at multiples of the orbital frequency (Welsh et al. 2011; Hambleton et al. 2013). Kepler mission (Borucki et al. 2010; Koch et al. 2010) has found more than 2878 eclipsing binaries (Kirk et al. 2016), and at least 2000 δ Sct stars in its main field of view so far (Balona & Dziembowski 2011; Balona 2014; Bowman et al. 2016), however, the sample of the eclipsing binary consisting δ Sct component are still insufficiency, hence more eclipsing δ Sct stars with detailed investigations for needed.

KIC 8840638 (α2000=19h55m35s.03, δ2000=+45°04′45″.4, 2MASS: J19553503+4504454) was classified to be a δ Scuti star by Ramsay et al. (2014) according to the highest peak of the frequency spectra. Its pulsating period was reported as about 49.6 min and this target was considered as a mid-late A type star in that survey (Ramsay et al. 2014). Table I lists some basic parameters of KIC 8840638 collected from the survey and Kepler Input Catalog (KIC; Brown et al. 2011). The Kepler Guest Observer program selected this star as a main target and result a continuous observation for about ten months in both LC and SC for this star. To avoid the Nyquist aliases detected in frequency spectrum, only the SC data was used in this work. The high precision photometric time series data make KIC 8840638 an excellent target to investigate its pulsation behaviour.

2. Observations and Data Reduction

KIC 8840638 was observed by Kepler space telescope in short (integration time of 58.8 s) cadence from BJD 2456139.15 to 2456414.59, which spans 275.44 days. There are 4 quarters
Table 1. Basic properties of KIC 8840638.

| Parameters | KIC 8840638 | References |
|------------|-------------|------------|
| $K_P$      | 14.262      | a          |
| $P$        | 49.6 min    | b          |
| $g_{SDSS}$ | 14.671      | a          |
| $i_{SDSS}$ | 14.086      | a          |
| $z_{SDSS}$ | 13.938      | a          |
| D51        | 14.489      | a          |
| $J_{2MASS}$| 13.053      | a          |
| $H_{2MASS}$| 12.708      | a          |
| $K_{2MASS}$| 12.582      | a          |
| $g$        | 14.63       | c          |
| $U-g$      | 0.52        | c          |
| $g-r$      | 0.54        | c          |
| $T_{Gaia}$ | 5736 ± 250 K| d          |
| $T_{KIC}$  | 6310 ± 250 K| a          |
| $T_{GTC}$  | 7860 ± 120 K| b          |
| log $g$    | 3.8 ± 0.25 dex| a          |

Note. — (a) KIC Brown et al. 2011; (b) Ramsay et al. 2014; (c) Greiss et al. 2012.
(Q14.2, Q15.2, Q16.2 and Q17.1) of the short cadence data, containing 165143 points in total. The short cadence photometric flux data of KIC 8840638 is available in Kepler Asteroseismic Science Operations Center (KASOC) data base\textsuperscript{1} (Kjeldsen et al. 2010) with two types: the first is labeled as ‘raw’ data which was produced by the NASA Kepler Science pipeline, and the second is the flux data corrected by KASOC Working Group 4 (WG#4: δ Scuti targets). We use the latter and perform corrections eliminating outliers, as well as the possible linear trends in some quarters. The flux data are converted to magnitude scale, then the mean value of each quarter is subtracted, and the rectified time series is obtained. The light curve of SC data is shown in Figure 1. From the zoom in light curves (middle and bottom panels of Figure 1), the brightness of KIC 8840638 clearly show pulsations.

3. Pulsational Characteristics

To investigate the pulsating behavior, we used the software PERIOD04\textsuperscript{2} (Lenz & Breger 2005) to perform Fourier analysis for the rectified data. To detect more significant frequencies in the SC data, we chose a frequency range of $0 < \nu < 80 \, \text{d}^{-1}$, a little wider than the typical pulsation frequency range of the δ Scuti stars.

During the extraction of significant frequency, the highest peak in the frequency spectrum was considered as a significant frequency, then a multi-frequency least-squares fit using formula:

$$ m = m_0 + \sum A_i \sin(2\pi(f_i t + \phi_i)) $$

($m_0$ is the zero-point, $A_i$ is the amplitude, $f_i$ is the frequency, and $\phi_i$ is the corresponding phase) was conducted to the light curve with all the significant frequencies detected, resulting to the solutions of all the significant frequencies. A constructed light curve using the above solutions was subtracted from the data, and the residual was obtained to search for significant frequency in next step. Then, the above steps were repeated until there was no significant peak in the residual. The criterion (S/N $> 4.0$) suggested by Breger et al. (1993) was adopted to judge the significant peaks. The uncertainties of frequencies were calculated following Kallinger et al. (2008).

A total of 95 significant frequencies were extracted and they were listed in Table\textsuperscript{2}. As shown in Figure\textsuperscript{2} and Table\textsuperscript{2}, most of the detected frequencies lies in a region between 23 and 32 d\textsuperscript{-1}. Among these frequencies, seven strong frequencies, i.e. $f_2$, $f_4$ to $f_8$, and $f_{19}$ are considered to be independent frequencies, as they are neither any combinations nor harmonics of other frequencies, these seven frequencies are marked with ‘independent’ in the last column of Table\textsuperscript{2}.

In the low frequency region of $0 < \nu < 1 \, \text{d}^{-1}$, three frequencies, $f_1(=0.320008 \, \text{d}^{-1})$, $f_3(=0.639945 \, \text{d}^{-1})$,

\textsuperscript{1}KASOC data base: http://kasoc.phys.au.dk
Fig. 1.— The light curves of KIC 8840638 in short cadence. Top panel: the whole light curve of Q14.2. Middle panel: the zoom in light curve of Q14.2 with 4.4 days. Bottom panel: the zoom in light curve of Q14.2 with 1 day.
Fig. 2.— Amplitude spectra for the rectified SC data of KIC 8840638 up to 80 d$^{-1}$. The top-left insert figure: a zoom-in amplitude spectra in the low frequency region of $0 < \nu < 4$ d$^{-1}$. The top-right insert figure: a zoom-in amplitude spectra in the high frequency region of $50 < \nu < 65$ d$^{-1}$. 
\(d^{-1}\) and \(f_{62}(=0.959744 \text{ d}^{-1})\) are interesting peaks. We examined these frequencies and found \(f_3\) and \(f_{62}\) are harmonics of \(f_1\). The lowest frequency \(f_1\) might be due to the orbital motion of binary. In the frequency region of \(35 \leq \nu \leq 80 \text{ d}^{-1}\), only several peaks were detected and they mainly concentrate in a narrow region of \(52 < \nu < 58 \text{ d}^{-1}\). These frequencies are combinations and harmonics of the independent terms and the orbital frequencies.
Table 2. All frequencies detected in SC data.

| $f_i$ | Frequency (d$^{-1}$) | Amplitude (mmag) | S/N  | Identification | Note          |
|-------|----------------------|------------------|------|----------------|---------------|
| 1     | 0.320008 ± 0.000001  | 7.989            | 42.2 | $f_{orb}$      |               |
| 2     | 29.024570 ± 0.000001 | 7.697            | 85.0 | independent    |               |
| 3     | 0.639945 ± 0.000003  | 4.252            | 77.3 | independent    |               |
| 4     | 25.843653 ± 0.000003 | 3.780            | 36.3 | independent    |               |
| 5     | 24.985826 ± 0.000005 | 2.441            | 30.3 | independent    |               |
| 6     | 28.925876 ± 0.000005 | 2.205            | 35.0 | independent    |               |
| 7     | 24.110686 ± 0.000006 | 2.032            | 45.6 | independent    |               |
| 8     | 27.365182 ± 0.000008 | 1.408            | 13.5 | independent    |               |
| 9     | 25.625751 ± 0.000008 | 1.401            | 39.0 | f5+2$f_{orb}$ |               |
| 10    | 28.286089 ± 0.000009 | 1.218            | 18.8 | f6-2$f_{orb}$ |               |
| 11    | 28.225151 ± 0.000011 | 1.074            | 17.8 | f4+f8-f5      |               |
| 12    | 26.725303 ± 0.000018 | 0.652            | 9.5  | f8-2$f_{orb}$ |               |
| 13    | 27.639707 ± 0.000018 | 0.652            | 11.5 | 2f2+f4-2f6+5$f_{orb}$ |          |
| 14    | 27.215143 ± 0.000018 | 0.651            | 12.8 | f6+2f5-2f4    |               |
| 15    | 28.865007 ± 0.000021 | 0.541            | 16.2 | f4+f8-f5+2$f_{orb}$ |          |
| 16    | 26.934483 ± 0.000022 | 0.521            | 10.6 | f2+2f4+f8-2f5-f6-7$f_{orb}$ |      |
| 17    | 24.099312 ± 0.000022 | 0.520            | 20.5 | independent    |               |
| 18    | 27.254431 ± 0.000025 | 0.467            | 9.8  | f2+2f4+f8-2f5-f6-6$f_{orb}$ |          |
| 19    | 26.637981 ± 0.000029 | 0.390            | 8.5  | 3f4+f8-f6-2f5+2$f_{orb}$ |          |
| 20    | 26.415518 ± 0.000031 | 0.369            | 9.0  | f2+2f4-2f5-4f6+4f8+6$f_{orb}$ |          |
| 21    | 26.997106 ± 0.000037 | 0.307            | 8.3  | 2f2+f4-2f6+3$f_{orb}$ |               |
| 22    | 24.520008 ± 0.000040 | 0.290            | 14.7 | 3f2+4f4+f7-4f6+10$f_{orb}$ |          |
| 23    | 23.459362 ± 0.000044 | 0.262            | 18.1 | f4+f5-f8      |               |
| 24    | 27.205488 ± 0.000049 | 0.236            | 6.6  | f4+2f8-f2-f5+2$f_{orb}$ |          |
| 25    | 25.676200 ± 0.000055 | 0.211            | 8.0  | 3f4+f8-f6-2f5-7$f_{orb}$ |          |
| 26    | 30.494036 ± 0.000057 | 0.203            | 12.8 | 2f6+f8-f2-f19-5$f_{orb}$ |          |
| 27    | 26.553998 ± 0.000058 | 0.198            | 6.0  | f6+f7-f4-2$f_{orb}$ |               |
| 28    | 28.395747 ± 0.000064 | 0.181            | 6.1  | f2-f4-f5+f7+f8-4$f_{orb}$ |          |
| 29    | 26.351489 ± 0.000068 | 0.170            | 5.7  | f7+7$f_{orb}$ |               |
| 30    | 27.277842 ± 0.000069 | 0.167            | 5.0  | 3f4+f8-f6-2f5+4$f_{orb}$ |          |
| 31    | 23.845839 ± 0.000071 | 0.163            | 11.4 | 2f4+f7+f8-f2-2f5-7$f_{orb}$ |          |
Table 2—Continued

| \( f_i \) | Frequency (d\(^{-1} \)) | Amplitude (mmag) | S/N | Identification | Note |
|---|---|---|---|---|---|
| 34 | 25.890555 ± 0.000070 | 0.164 | 7.0 | 3f2+2f5+f7-3f6-2f4+10f orb | |
| 35 | 27.574478 ± 0.000072 | 0.160 | 5.0 | 2f4+f2+f8-2f5-f6-5f orb | |
| 36 | 25.036422 ± 0.000077 | 0.150 | 8.5 | 3f4+f8-f6-2f5-3f orb | |
| 37 | 27.05648 ± 0.000078 | 0.148 | 6.0 | f2+2f4-2f5-4f6+4f8+8f orb | |
| 38 | 26.669568 ± 0.000078 | 0.147 | 5.5 | f7+8f orb | |
| 39 | 27.95661 ± 0.000081 | 0.142 | 5.0 | 2f2+f4-2f5-f6-5f orb | |
| 40 | 27.907678 ± 0.000077 | 0.149 | 5.7 | f4+8f-f5-f orb | |
| 41 | 27.208304 ± 0.000082 | 0.141 | 5.6 | f4+2f8-f5-f2+2f orb | |
| 42 | 26.476246 ± 0.000082 | 0.140 | 6.3 | 2f5+2f6-2f4-f2-2f orb | |
| 43 | 58.049048 ± 0.000082 | 0.140 | 17.3 | 2f2 | |
| 44 | 56.152527 ± 0.000088 | 0.130 | 10.5 | f5+f6+7f orb | |
| 45 | 28.715414 ± 0.000095 | 0.121 | 5.4 | f2-f4-f5+f7+f8-3f orb | |
| 46 | 24.165708 ± 0.000094 | 0.122 | 8.9 | 2f4+f7+f8-f2-2f5 | |
| 47 | 27.316678 ± 0.000095 | 0.121 | 5.7 | 2f2+f4-2f6+4f orb | |
| 48 | 25.250567 ± 0.000096 | 0.120 | 7.5 | 3f2+2f5+f7-3f6-2f4+8f orb | |
| 49 | 54.868095 ± 0.000101 | 0.114 | 9.6 | f2+f4 | |
| 50 | 23.387329 ± 0.000101 | 0.114 | 11.1 | 3f4+f7-f6-2f5+2f orb | |
| 51 | 23.525758 ± 0.000106 | 0.108 | 11.3 | 2f4+f7+f8-f2-2f5-2f orb | |
| 52 | 27.309647 ± 0.000107 | 0.107 | 5.2 | f7+10f orb | |
| 53 | 27.550568 ± 0.000114 | 0.101 | 5.0 | f5+8f orb | |
| 54 | 28.670572 ± 0.000114 | 0.101 | 5.0 | f2+3f4+f8-2f5-f6+7f orb | |
| 55 | 28.998015 ± 0.000117 | 0.098 | 5.9 | 2f5+3f6-f2-8f4+f orb | |
| 56 | 27.109034 ± 0.000121 | 0.095 | 5.6 | f4+f6+2f8-f5-2f2-2f orb | |
| 57 | 26.148543 ± 0.000125 | 0.092 | 5.2 | f6+f5-f4-6f orb | |
| 58 | 28.030988 ± 0.000128 | 0.090 | 4.4 | f2+3f4+f8-2f5-f6+f7-f9 f orb | |
| 59 | 26.910598 ± 0.000129 | 0.089 | 5.3 | f5+6f orb | |
| 60 | 26.089366 ± 0.000135 | 0.085 | 5.8 | f8-4f orb | |
| 61 | 26.530479 ± 0.000135 | 0.085 | 5.2 | 3f2+2f5+f7-3f6-2f4+12f orb | |
| 62 | 0.959744 ± 0.000140 | 0.082 | 4.1 | 3f orb | |
| 63 | 23.927733 ± 0.000140 | 0.082 | 7.7 | 2f5-f6+9f orb | |
| 64 | 25.711425 ± 0.000140 | 0.082 | 5.7 | f7+5f orb | |
| 65 | 28.293114 ± 0.000140 | 0.082 | 4.6 | f6-2f orb | |
| 66 | 29.033747 ± 0.000146 | 0.079 | 4.2 | f2-f4-f5+f7+f8-2f orb | |
Table 2—Continued

| $f_i$ | Frequency (d$^{-1}$) | Amplitude (mmag) | S/N | Identification | Note |
|-------|---------------------|------------------|-----|---------------|------|
| 67    | 56.106080 ± 0.000149| 0.077            | 6.6 | 2f2+2f4-3f5+2f8-f6-14 $f_{orb}$ |
| 68    | 24.610641 ± 0.000158| 0.073            | 5.9 | f2+f4-f8-9 $f_{orb}$ |
| 69    | 54.571444 ± 0.000164| 0.070            | 6.2 | f4+3f8-f5-f2+2 $f_{orb}$ |
| 70    | 29.132862 ± 0.000164| 0.070            | 4.2 | 2f5-2f4+f6+6 $f_{orb}$ |
| 71    | 26.788611 ± 0.000169| 0.068            | 4.4 | f4+f6+2f8-f5-2f2+ $f_{orb}$ |
| 72    | 24.805965 ± 0.000169| 0.068            | 5.5 | 2f4+f7+f8-f2-2f5+2 $f_{orb}$ |
| 73    | 25.305529 ± 0.000177| 0.065            | 5.5 | f5+$f_{orb}$ |
| 74    | 22.674102 ± 0.000198| 0.058            | 7.8 | f4+f8-f5+f7-2 $f_{orb}$-f2 |
| 75    | 52.622924 ± 0.000202| 0.057            | 5.4 | 2f2+f4+f5-2f6+5 $f_{orb}$ |
| 76    | 55.923463 ± 0.000205| 0.056            | 4.9 | f2+f4+f6-f5-9 $f_{orb}$ |
| 77    | 29.453077 ± 0.000205| 0.056            | 4.1 | 2f5-2f4+f6+7 $f_{orb}$ |
| 78    | 25.342924 ± 0.000209| 0.055            | 4.8 | 2f2+3f5-2f4-f6-f8+ $f_{orb}$ |
| 79    | 53.911772 ± 0.000209| 0.055            | 4.9 | f5+f6 |
| 80    | 54.634252 ± 0.000221| 0.052            | 4.7 | 4f2+2f4-4f6-8 $f_{orb}$ |
| 81    | 52.385486 ± 0.000225| 0.051            | 5.0 | f6+f4+f5-f8 |
| 82    | 4.815395 ± 0.000225 | 0.051            | 6.7 | f6-f7 |
| 83    | 54.009898 ± 0.000230| 0.050            | 4.7 | f2+f5 |
| 84    | 55.650909 ± 0.000235| 0.049            | 4.5 | f6+f8-2 $f_{orb}$ |
| 85    | 3.181020 ± 0.000235 | 0.049            | 5.0 | f2-f4 |
| 86    | 19.483597 ± 0.000235| 0.049            | 6.9 | 2f4+f7+f8-2f2-f5-2 $f_{orb}$ |
| 87    | 24.027238 ± 0.000235| 0.049            | 5.4 | 3f4+f7-f6-2f5+4 $f_{orb}$ |
| 88    | 52.660710 ± 0.000250| 0.046            | 4.3 | 2f5+2f6-2f2+9 $f_{orb}$ |
| 89    | 57.950430 ± 0.000256| 0.045            | 5.0 | f2+f6 |
| 90    | 25.186838 ± 0.000256| 0.045            | 4.2 | f6+f5-f4-9 $f_{orb}$ |
| 91    | 55.556078 ± 0.000267| 0.043            | 4.1 | 4f2+2f5+f7-3f6-2f4+12 $f_{orb}$ |
| 92    | 56.702608 ± 0.000274| 0.042            | 4.3 | 2f2+6f4+2f8-4f5-2f6-2f7-16 $f_{orb}$ |
| 93    | 56.028777 ± 0.000274| 0.042            | 4.0 | 2f2-2f5+f7+f8-11 $f_{orb}$ |
| 94    | 52.560506 ± 0.000274| 0.042            | 4.4 | f2+2f4+f8-f5-f6-5 $f_{orb}$ |
| 95    | 11.278539 ± 0.000280| 0.041            | 5.6 | 3f12-3f13 |
4. Binary Modeling

As listed in Table 1, it is clear that the temperature discrepancy of KIC 8840638 collected from KIC, GTC and Gaia2 is greater than 1500 K. Such a large inconsistency in the spectrum over a short time is puzzling for a δ Scuti star.

As shown in the top and middle panels of Figure 1, the light variation of KIC 8840638 exhibit the typical shape of light curve shown in eclipsing binaries, which indicate KIC 8840638 might be an eclipsing binary containing a δ Scuti star. It is obviously that the depth of the primary and secondary eclipses are different, which indicate a large temperature difference between both components.

To clearly show the light variation due to the orbital motion from binary, the light curve is folded with the detected low frequency \( f_1 \). The phase of SC data is shown in Figure 4. There are 100 time bins in the phase. From this figure, the orbital phase of KIC 8840638 is clearly shown, so we marked the lowest frequency \( f_1 \) as orbital frequency in Table 2.

In order to obtain the physical and geometrical parameters of this binary system, the 2013 version of the Wilson-Devinney (W-D) code (Wilson & Devinney 1971; Wilson 1979; Wilson 2012) was used to analyze the rectified SC data. Considering the multiperiodic pulsations and eclipsing of binary could both affect the solutions of observed light curves, the removal of pulsating signals will be more conducive to the solution of parameters of binary by W-D code. Thus, the pulsation signals from the Kepler data was smoothed out, leaving behind the light variations due to the binarity effects.

The initial effective temperature of the hotter and less massive component was set to be 7860 ± 120 K from GTC while the other's is 5736 ± 250 K which is released by Gaia2 (Andrae et al. 2018). We defined parameters of the hotter component with subscript 1 and the cooler one with subscript 2. Based on the initial temperature of two components of KIC 8840638, the gravity darkening coefficients and the bolometric albedos are fixed at standard values of \( g_1 = 1.0, g_2 = 0.32 \) (Lucy 1967), \( A_1 = 1.0 \) and \( A_2 = 0.5 \) (Ruciński 1969). The bolometric (X and Y) and the monochromatic (x and y) limbdarkening coefficients in logarithmic form were taken from van Hamme (1993). The adjustable parameters are: the orbit inclination \( i \), the mean surface temperature of primary \( T_1 \), the mean surface temperature of secondary \( T_2 \), the mass ratio \( q \), the bandpass luminosity of primary \( L_1 \) and the modified dimensionless surface potential, \( \Omega_1 \) and \( \Omega_2 \).

The mass ratio \( q \) is usually a crucial parameter for the light curve analysis, but there is no one for KIC 8840638 at present, so we utilize a method called mass ratio search (q-search) to search for a reliable mass ratio \( q \). In this search, \( q \) was fixed as a series of values and the weighted sum of squared deviations \( \sum W(O-C)^2 \) (hereafter \( \sum \) ) of each solution generated by W-D code was used to estimate the potential reality of \( q \). For each assumed mass ratio, q-search was applied for
various modes which represent different solution constraints for binary stars, however, the results showed that only the Mode 5, which represents a semi-detached binaries where the secondary component fills its limiting lobe, could derive an acceptable photometric solution. Figure 3 shows the minimum value of $\sum$ is achieved at $q = 1.40$ in the q-search procedure. Then, the value of $q (=1.40)$ was set as an initial value and an adjustable parameter to perform the differential corrections. The solutions derived from the phase-folded light curve, which excludes the pulsational variations, are listed as Form 1 in Table 2 and the synthetic light curve is shown in upper part of Figure 4.

To investigate the influence of pulsation on the orbital parameters of the binary system, the observed Kepler light curve was also solved using W-D code, and the solutions (given as Form 2) are listed in the fourth and fifth columns of Table 2. From Table 2 we found the binary parameters from Form 2 are in good agreement with those from Form 1, which implies the photometric solutions of KIC 8840638 might not be influenced by the pulsation. Figure 4 shows the synthetic light curves from these two forms respectively, they match well with the corresponding observed phase-folded light curves.

For the primary component of KIC 8840638, its effective temperature ($T = 7968$ K) corresponds to a normal main-sequence star with a spectral type of about A6V according to the relationship by Harmanec (1988). Based on the empirical relation between spectral type and the stellar mass, the mass of the primary component was estimated to be $M_1 = 1.83 \pm 0.18 M_\odot$, assuming an error 10 %. Then the luminosity of the primary component of KIC 8840638 can be derived from the photometric solutions and $M_1$ as to be $L = 56 \pm 4 L_\odot$. The location of the primary component of KIC 8840638 in H-R diagram is shown in Figure 5 together with those of other well-studied semi-detached Algol binary systems collected by İbanoğlu et al. (2006). From Figure 5 the pulsating primary star of KIC 8840638 lies in the $\delta$ Scuti instability region and below the terminal-age main-sequence (TAMS).

5. DISCUSSION AND CONCLUSIONS

In this paper, we analyzed the light variation of KIC 8840638 using the Kepler SC observations obtained from Quarter 14 to 17. The light curve of this target exhibited both eclipses and oscillations, suggesting this object is a new pulsating EB, rather than a single star.

The binary light curve was satisfactorily modelled in two cases: including and removing the light variations due to the pulsations. The results indicate that the binary parameters are not affected by the pulsations and the binary system is in a semi-detached configuration with $q=1.6$. In this semi-detached model, the primary component fill $F_1= 85 \%$ of their inner critical lobe. Here, the fill-out factor $F_1= \Omega_{\text{in}} / \Omega_1$, where $\Omega_{\text{in}}$ is the potential of the inner Roche surface. With
Fig. 3.— Behavior of $\Sigma$ (the weighted sum of the residuals squared) of KIC 8840638 as a function of mass ratio $q$, showing a minimum value at $q=1.4$. The open circles represent the $q$-search results for the semi-detached configurations.
Fig. 4.— Comparison of binary light curves after (up) and before (down) removing the pulsation signals from the observed Kepler data. The red and blue solid curves are theoretical light curves, which calculated by W-D code with the Form 1 and Form 2 parameters in Table 2, respectively.
Table 2. Photometric solutions of KIC 8840638.

| Parameters | Form 1<sup>a</sup> | Form 2<sup>b</sup> |
|------------|----------------------|----------------------|
|            | Primary | Secondary | Primary | Secondary |
| $g$ (deg)  | 1.00    | 0.50      | 1.00    | 0.50      |
| $A$ (deg)  | 0.50    | 0.32      | 0.50    | 0.32      |
| $X$        | 0.670   | 0.640     | 0.670   | 0.640     |
| $Y$        | 0.200   | 0.170     | 0.200   | 0.170     |
| $x$        | 0.585   | 0.715     | 0.585   | 0.715     |
| $y$        | 0.253   | 0.212     | 0.253   | 0.212     |
| $i$ (deg)  | 16.94(7)|          | 16.67(81)|          |
| $q = M_2/M_1$ | 1.598(16) |          | 1.624(200) |          |
| $T$ (K)    | 7968(10)| 4879(4)   | 7966(126)| 4880(53)  |
| $\Omega_{in}$ | 4.67   | 4.67     | 4.71    | 4.71      |
| $\Omega_{out}$ | 4.09   | 4.09     | 4.13    | 4.13      |
| $\Omega$  | 5.50(1) | 4.67      | 5.50(12)| 4.71      |
| $L_1/(L_1+L_2)$ | 0.758(1) |          | 0.759(3) |          |
| $r$(pole)  | 0.2530(4)| 0.3955(8)| 0.2546(50)| 0.3969(103) |
| $r$(side)  | 0.2585(5)| 0.4183(10)| 0.2603(59)| 0.4198(117) |
| $r$(back)  | 0.2689(7)| 0.4474(9)| 0.2712(84)| 0.4488(112) |
| $r$(volume)| 0.2601(6)| 0.4204(9)| 0.2637(84)| 0.4218(110) |
| $\sum W(O-C)^2$ | 0.000052 |          | 0.0023   |          |

Absolute parameters:

|          | Form 1<sup>a</sup> | Form 2<sup>b</sup> |
|----------|----------------------|----------------------|
| $M$ ($M_\odot$) | 1.83 ± 0.18 | 2.93 ± 0.29 | 1.83 ± 0.18 | 2.93 ± 0.29 |
| $R$ ($R_\odot$) | 3.93 ± 0.13 | 6.35 ± 0.21 | 3.93 ± 0.13 | 6.35 ± 0.21 |
| $\log g$ (cgs) | 3.52 ± 0.08 | 3.30 ± 0.07 | 3.52 ± 0.08 | 3.30 ± 0.07 |
| $L$ ($L_\odot$) | 56 ± 4     | 21 ± 1     | 56 ± 4     | 21 ± 1     |
| $M_{bol}$ (mag) | 0.36 ± 0.08 | 1.42 ± 0.06 | 0.36 ± 0.08 | 1.42 ± 0.06 |

Note. — a: Result for the light curve removing the pulsations. b: Result from the observed *Kepler* light curve.
Fig. 5.— Location of the primary (’blue diamond’) component of KIC 8840638 in the H-R diagram. The filled and open circles represent the primary and secondary components taken from İbanoğlu et al. (2006). The zero-age main-sequence (ZAMS) and terminal-age main-sequence (TAMS) are taken from the models in Pols et al. (1998). The blue and red solid lines represent the blue and red edge of δ Scuti instability strip (Soydugan et al. 2006).
the derived effective temperature (= 7968 K) and luminosity (= 56 $L_{\odot}$), the primary components of KIC 8840638 lies in the intersection of the δ Scuti strip and the main sequence in the H-R diagram.

In order to understand the pulsational characteristic of KIC 8840638, multiple-frequency analyses was applied to the observed Kepler SC time-series data. We detected 7 significant independent frequencies in the typical frequency range of δ Scuti stars. The period ratios of these independent frequencies to orbital periods were calculated to be $P_{\text{pul}}/P_{\text{orb}} = 0.011 - 0.013$, which is within the upper limit of 0.09 for δ Scuti stars in binaries (Zhang et al. 2013). These values and the location on the H-R diagram reveal that the primary component of KIC 8840638 might be a δ Scuti star.

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