γ DORADUS PULSATIONS IN THE ECLIPSING BINARY STAR KIC 6048106

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ABSTRACT

We present the Kepler photometry of KIC 6048106, which is exhibiting the O’Connell effect and multiperiodic pulsations. Including a starspot on either of the components, light-curve synthesis indicates that this system is a semi-detached Algol with a mass ratio of 0.211, an orbital inclination of 73.9°, and a large temperature difference of 2534 K. To examine in detail both the spot variations and pulsations, we separately analyzed the Kepler time-series data at the interval of an orbital period in an iterative way. The results reveal that the variable asymmetries of the light maxima can be interpreted as the changes with time of a magnetic cool spot on the secondary component. Multiple frequency analyses were performed in the outside-eclipse light residuals after removal of the binarity effects from the observed Kepler data. We detected 30 frequencies with signal to noise amplitude ratios larger than 4.0, of which six ($f_2-f_0$ and $f_{00}$) can be identified as high-order ($17 \leq n \leq 25$) low-degree ($\ell = 2$) gravity-mode pulsations that were stable during the observing run of 200 days. In contrast, the other frequencies may be harmonic and combination terms. For the six frequencies, the pulsation periods and pulsation constants are in the ranges of 0.352–0.506 days and 0.232–0.333 days, respectively. These values and the position on the Hertzsprung–Russell diagram demonstrate that the primary star is a γ Dor variable. The evolutionary status and the pulsation nature of KIC 6048106 are discussed.

Key words: binaries: eclipsing – stars: individual (KIC 6048106) – stars: oscillations (including pulsations) – starspots

Supporting material: machine-readable table

1. INTRODUCTION

γ Dor stars are A–F stars of luminosity class IV–V near the red edge of the δ Scy instability strip in the Hertzsprung–Russell (HR) diagram. Their observational properties are very similar to those of δ Scy stars, but they pulsate in high-order gravity ($g$) modes driven by convective blocking (Guzik et al. 2000; Dupret et al. 2004, 2005), with typical periods of 0.4–3 days and pulsation constants of $Q > 0.23$ days (Kaye et al. 1999; Henry et al. 2005). These pulsating stars are of great interest to asteroseismic studies because the g modes assist in probing the deep stellar interiors near the core region. The number of γ Dor-type stars has increased dramatically with space-based missions such as CoRoT (Hareter et al. 2010) and Kepler (Balona et al. 2011; Bradley et al. 2015). Nonetheless, only 13 eclipsing binaries (EBs) are known to contain γ Dor pulsating candidates (Maceroni et al. 2014; Kurtz et al. 2015; Çakirli & Ibanoglu 2016), of which V551 Aur may be a δ Sct star as indicated by its pulsation frequencies (Liu et al. 2012).

Because EBs are a primary source of fundamental stellar properties such as mass and radius, pulsating EBs are ideal targets for the study of the interior structure and evolution of stars due to their binarity and pulsation features. Recently, Çakirli & Ibanoglu (2016) suggested three possible relationships among the pulsation periods of γ Dor components and other parameters (binary orbital periods for 11 EBs, surface gravities for 6 pulsating components, and gravitational forces from companions for 5 EBs). As in the case of EBs with δ Scy components (Soydugan et al. 2006; Liakos et al. 2012), the longer the binary orbital period, the longer the pulsation period: $P_{\text{puls}} = 0.425f_{\text{orb}} - 0.355$. In addition, as the surface gravity of pulsating components and the gravitational force from the companions decrease, their pulsation periods increase.

However, these relationships need further confirmation by new discoveries because the number of such stars remains small. KIC 6048106 (R.A. = 19h34m14.028; decl. = +41° 23'43.26; $K_0$ = +14.091; $g$ = +14.303; $g-r$ = +0.283) was announced to be an EB pulsating at frequencies of 0.43–3.28 day$^{-1}$ by Gaulme & Guzik (2014). In this paper, we demonstrate that the binary system is a semi-detached Algol with a γ Dor-type pulsating component, based on the precise and nearly continuous Kepler data during a period of approximately 200 days. In Section 2, we carry out a light-curve synthesis and present the binary parameters, including the absolute dimensions. Section 3 describes the frequency analysis for the light residuals from each spot model. Finally, we summarize and discuss our conclusion in Section 4.

2. LIGHT-CURVE SYNTHESIS AND ABSOLUTE DIMENSIONS

KIC 6048106 was observed in a long cadence (LC) mode of 29.42 minutes during Quarters 14 and 15 by the Kepler satellite. The contamination level of the observations by nearby stars is estimated to be 0.028, where a value of 0 implies no contamination and 1 implies all background. For this study, we used the simple aperture photometry data detrended in the Kepler EB catalog (Prša et al. 2011; Slawson et al. 2011). The Kepler data of KIC 6048106 are depicted in the top panel of Figure 1 as the normalized flux versus the orbital phase. The light curve is superficially similar to that of Algols and displays the inverse O’Connell effect whereby Max I (following the primary eclipse) is fainter than Max II by about 0.005 mag. In short-period Algols, this effect is usually interpreted to be due

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to magnetic dynamo-related activity in a cool companion and/or mass transfer between both components if a binary system is in a semi-detached configuration (e.g., KIC 4739791; Lee et al. 2016b).

In order to understand the physical properties of this system, we analyzed simultaneously all Kepler data in a manner almost identical to that for the pulsating EBs V404 Lyr (Lee et al. 2014) and KIC 6220497 (Lee et al. 2016a) using the 2007 version of the Wilson–Devinney binary code (Wilson & Devinney 1971; Van Hamme & Wilson 2007; hereafter W–D) and the so-called $q$-search procedure. In our synthesis, the mean light level at phase 0.75 was set to unity and the surface temperature of the hotter and more massive star was initialized at $T_1 = 7000 \pm 245$ K from the revised Kepler Input Catalog (KIC) properties (Huber et al. 2014). Adjustable parameters include the orbital ephemeris ($T_0$ and $P$), the mass ratio ($q$), the orbital inclination ($i$), the effective temperatures ($T_{1,2}$) and the dimensionless surface potentials ($\Omega_{1,2}$) of the components, and the monochromatic luminosity ($L_1$). Throughout our analyses, a synchronous rotation for both components and a circular orbit were adopted, and the detailed reflection effect was used. In

Figure 1. Light curve of KIC 6048106 with the fitted models. In the top panel, the circles are the individual measurements from the Kepler spacecraft, and the dashed and solid curves represent the synthetic curves computed from the no-spot and the cool-spot models on the secondary star, respectively. The light residuals corresponding to the two models are plotted in the middle and bottom panels, respectively.

Figure 2. Behavior of the $\Sigma$ of KIC 6048106 as a function of mass ratio $q$, showing a minimum value at $q = 0.21$. 

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Lee
was used to estimate the potential

\( L_\text{R} \)

1.0 0.5 1.0 0.5 1.0 0.5

A

0.2097(33) 0.2096(35) 0.2125(40)

i (deg)

73.899(67) 73.879(74) 73.884(78)

T (K)

6999(245) 4473(110) 7015(245) 4472(109) 6997(245) 4472(110)

\( \Omega \)

4.799(32) 2.257 4.816(37) 2.257 4.799(37) 2.264

A

1.0 0.5 1.0 0.5 1.0 0.5

X, Y

0.639, 0.247 0.624, 0.160 0.639, 0.247 0.624, 0.160 0.639, 0.247 0.624, 0.160

x, y

0.592, 0.293 0.737, 0.111 0.592, 0.293 0.737, 0.111 0.593, 0.292 0.737, 0.111

//L_{1}+L_{2}\)

0.8236(22) 0.1764 0.8238(19) 0.1762 0.8227(21) 0.1773

r (pole)

0.2177(18) 0.2361(12) 0.2169(20) 0.2360(13) 0.2178(20) 0.2370(15)

r (point)

0.2199(18) 0.3458(17) 0.2191(21) 0.3457(18) 0.2201(21) 0.3469(20)

r (side)

0.2190(18) 0.2456(13) 0.2182(21) 0.2456(14) 0.2192(21) 0.2465(16)

r (back)

0.2197(18) 0.2780(13) 0.2189(21) 0.2780(14) 0.2198(21) 0.2790(16)

r (volume)\(^a\)

0.2188(18) 0.2540(14) 0.2180(21) 0.2540(15) 0.2190(21) 0.2549(16)

Spot parameters:

Colatitude (deg) ... ... 45.5(4.9) ... ... 83.4(5.6)

Longitude (deg) ... ... 94.5(1.5) ... ... 64.3(1.5)

Radius (deg) ... ... 12.4(2.2) ... ... 12.0(2.9)

\( T_{\text{spot}}/T_{\text{local}} \)

... ... 1.041(10) ... ... 0.896(46)

\( \Sigma \)

0.00360 0.00317 0.00316

Absolute parameters:

\( M (M_{\odot}) \)

1.50(8) 0.31(2) 1.50(8) 0.31(2) 1.50(8) 0.32(2)

\( R (R_{\odot}) \)

1.51(4) 1.75(4) 1.50(4) 1.75(4) 1.51(4) 1.76(4)

log g (gps)

4.26(3) 3.45(4) 4.26(3) 3.45(4) 4.26(3) 3.45(4)

L (L_{\odot})

4.89(73) 1.10(12) 4.90(73) 1.10(12) 4.90(73) 1.11(12)

M_{\text{bol}} (mag)

3.01(16) 4.63(12) 3.00(16) 4.63(12) 3.00(16) 4.62(12)

BC (mag)

0.03(1) -0.62(8) 0.03(1) -0.62(8) 0.03(1) -0.62(8)

M_{V} (mag)

2.98(16) 5.25(15) 2.97(16) 5.25(14) 2.97(16) 5.24(15)

Note.

\(^a\) Mean volume radius computed from the tables given by Mochnacki (1984).

this paper, we refer to the primary and secondary stars as those being eclipsed at Min I (phase 0.0) and Min II, respectively.

First, because there is no light-curve solution for KIC 6048106, we conducted an extensive \( q \)-search for various modes of the W–D code to obtain binary parameters. The behavior of the weighted sum of the squared residuals (\( \Sigma W (O - C)^2 \); hereafter \( \Sigma \)) was used to estimate the potential reality of each model. This procedure showed acceptable indications that the optimal solution is around \( q = 0.21 \), which was adopted as the initial value and adjusted to derive all subsequent photometric solutions. The unsotted solution is listed in the second and third columns of Table 1 and appears as a dashed curve in the top panel of Figure 1. The light residuals from this solution are plotted in the middle panel of Figure 1, wherein it can be seen that the unsotted model does not describe the observed \textit{Kepler} data satisfactorily. In this and subsequent syntheses, the errors for the adjustable parameters were established following the procedure described by Koo et al. (2014). For this procedure, the observed \textit{Kepler} data were split into 10 subsets.

The light asymmetries in KIC 6048106 may be attributed to either a magnetic cool spot located on the surface of the late-type secondary star or a hot spot on the detached primary as a result of the impact of the gas stream due to mass transfer from the lobe-filling companion. The two possible spot models were applied to fit the asymmetrical light curve, and the results are given in columns (4)–(7) of Table 1. The synthetic curve from the cool-spot model is displayed as the solid curve in the top panel of Figure 1, and the residuals from the spot model are plotted in the bottom panel. From the table and figure, we can see that the spot models improve the light-curve fitting and give smaller values of \( \Sigma \) than the unsotted model. Although there are no \( \Sigma \) differences between the two spot models, it may be more reasonable to regard the main cause of the spot activity to be a magnetized cool spot on the secondary star, because the \textit{Kepler} data showed the variable asymmetries of the light maxima with time.

Considering its error, the effective temperature of the primary component corresponds to a normal main-sequence star with a spectral type of approximately F0±1. We assumed the primary’s mass to be \( M_1 = 1.50 \pm 0.08 M_{\odot} \), from Harmanec’s (1988) established relationship between spectral type and stellar mass. The absolute dimensions for KIC 6048106 can be roughly estimated from our photometric solutions and \( M_1 \). These are given in the bottom of Table 1, where the luminosity (\( L \)) and bolometric magnitudes (\( M_{\text{bol}} \)) were computed by adopting \( T_{\text{eff}} = 5780 \text{K} \) and \( M_{\text{bol}} = +4.73 \) for solar values. For the absolute visual magnitudes (\( M_{V} \)), we used the bolometric corrections (BCs) appropriate for the temperature of each
component from the relation between log $T_{\text{eff}}$ and BC given by Torres (2010).

3. STARSPOT ACTIVITY AND PULSATIONAL CHARACTERISTICS

The time-series data for 20 days for the Kepler observations are displayed as cyan circles in Figure 3. As shown in the figure, the brightness of KIC 6048106 has varied visibly with time, which might be a result of spot variations and pulsations. In order to study in detail the spot behavior and obtain more reliable frequency analyses, we divided the light curve of KIC 6048106 into 113 segments at intervals of an orbital period and analyzed them separately. First, we obtained the light residuals after subtracting the cool-spot model from the observed Kepler data and applied a multiple frequency analysis.

Table 2

| Epoch (BJD) | Longitude (deg) | Angular Radius (deg) | Temp. Factor |
|-------------|-----------------|----------------------|--------------|
| 2,456,108.55095 | 71.43           | 12.01                | 0.896        |
| 2,456,110.11031 | 65.16           | 12.11                | 0.919        |
| 2,456,111.66947 | 54.39           | 12.35                | 0.899        |
| 2,456,113.22906 | 28.63           | 12.01                | 0.913        |
| 2,456,114.78847 | 68.44           | 12.81                | 0.927        |
| 2,456,116.34724 | 75.33           | 12.46                | 0.924        |
| 2,456,117.90699 | 70.22           | 12.27                | 0.914        |
| 2,456,119.46643 | 75.40           | 12.85                | 0.942        |
| 2,456,121.02539 | 86.17           | 12.01                | 0.939        |
| 2,456,122.58213 | 80.56           | 11.93                | 0.924        |

(This table is available in its entirety in machine-readable form.)
only to the outside-eclipse residuals using the PERIOD04 program (Lenz & Breger 2005). The frequency analysis was performed on the range from 0 to the Nyquist limit of \( f_{Ny} = 24.47 \text{ day}^{-1} \). As in the case of V404 Lyr (Lee et al. 2014), the successive prewhitening of each frequency peak was carried out by applying the light residuals to the equation

\[
Z = Z_0 + A_i \sin(2\pi f_i t + \phi_i).
\]

Here, \( Z \) and \( Z_0 \) denote the calculated magnitude and zero point, respectively, \( A_i \) and \( f_i \) are the amplitude and phase of the \( i \)th frequency, respectively, and \( t \) is the time of each measurement. We detected the frequencies with signal to noise amplitude (S/N) ratios larger than 4.0 (Breger et al. 1993). Second, we removed the pulsation signatures from the observed data, and each pulsation-subtracted light curve was solved by using the cool-spot model parameters as initial values and adjusting the epoch and spot parameters, with the exception of the colatitude. Third, we removed the spot solution from each light curve in the original data and performed frequency analysis for the entire set of residuals, excluding the data around the primary and secondary minima.

This procedure was repeated five times until the detected frequencies were unchanged. In the first iteration, very low-frequency signals such as 0.00635 day\(^{-1}\) and 0.03706 day\(^{-1}\) were detected, but they disappeared in subsequent analyses. The final epochs and spot parameters are listed in Table 2, and the pulsation-subtracted data and spot models for each light curve are plotted as plus symbols and solid curves, respectively, in Figure 3. The light residuals from the detailed analysis are displayed in the upper panel of Figure 4 as magnitude versus BJD, whereas the lower panel presents a short section of the residuals. In Figure 5, we show the amplitude spectra for KIC 6048106 before and after prewhitening the first 6 frequencies and all 30 frequencies. The synthetic curve obtained from the 30-frequency fit is displayed in the lower panel of Figure 4. The result for the multiple frequency analysis is given in Table 3, where the frequencies are listed in order of detection, and the noises are calculated in the range of 5 day\(^{-1}\) around each frequency. We can see that all signals lie in the low-frequency \( g \)-mode region. The uncertainties in the table were derived according to Kallinger et al. (2008).

In order to examine the frequency variations with time, we analyze the out-of-eclipse residuals at intervals of \(~50\) days. The results from the analyses are not much different from each other, and more than 11 frequencies were detected at each subset with the same criterion of S/N > 4.0. We plotted the stability of the eight frequencies repeatedly detected in Figure 6. Among these, the frequencies of \( f_2, f_3, f_8, f_9, f_{10} \), and \( f_{16} \) varied significantly. The unstable frequencies might result from alias effects caused...
by the orbital frequency ($f_{orb} = 0.64129 \text{ day}^{-1}$). Within the frequency resolution of 0.008 day$^{-1}$ (Loumos & Deeming 1978), we searched for possible harmonic and combination frequencies. As listed in the last column of Table 3, six ($f_2 - f_6, f_{10}$) are pulsation frequencies, and $f_6$ and $f_{15}$ appear to be the sidelobes split from the orbital frequency $f_{orb}$ by $\sim 0.011 \text{ day}^{-1}$. The other frequencies may come from orbital harmonics and combination frequencies, some of which could be partially attributed to the imperfect removal of the binary effects in the observed light curve.

The *Kepler* LC data were integrated over 270 exposures with a sampling rate of 6.54 s (including readout) to form 29.42 min observations. The merging effect reduces the amplitude of peaks in the power spectrum, which increases with higher frequencies (Murphy 2012; Lee et al. 2016b). On the other hand, some signals near the Nyquist frequency can be reflections of real frequencies ($2f_{Ny} - f_i$) (Murphy et al. 2013). However, because KIC 6048106 exhibit frequencies much lower than the Nyquist limit, the possibility of reflections in the detected frequencies seems very unlikely.

4. DISCUSSION AND CONCLUSIONS

In this paper, we studied both the binarity and pulsation of KIC 6048106 from detailed analyses of the *Kepler* observations obtained during Quarters 14 and 15. The *Kepler* time-series data display mutiperiodic pulsations and the O’Connell effect with unequal light levels at the quadratures (Max I and Max II). The asymmetric light curve was modeled by applying a single spot to either of the components: a hot spot on the primary star and a cool spot on the secondary. Our light-curve synthesis indicates that KIC 6048106 is a classical Algol-type system with parameters of $q = 0.211$, $i = 73.9^\circ$, and $(T_1 - T_2) = 2534 \text{ K}$; the primary component fills about 52% of its limiting lobe and is slightly smaller than the lobe-filling secondary. The locations of the components in the HR diagram are shown in Figure 7, together with those of other well-studied semi-detached Algols (Ibañoglu et al. 2006) and the $\gamma$ Dor stars in nine EBs (Maceroni et al. 2014; Çakırlı & Ibañoglu 2016). Here, the dashed and dashed–dotted lines are the instability strips of the $\gamma$ Dor and $\delta$ Sct stars, respectively. The pulsating primary star of KIC 6048106 resides within the $\gamma$ Dor region on the zero-age main sequence (ZAMS), and the secondary lies in a location where the secondary components of other Algols exist.

The *Kepler* data indicated that the light curve of KIC 6048106 varied due to the combination of both spot and pulsation. To explore in detail the light variations, we individually analyzed the *Kepler* light curve at the interval of an orbital period using the iterative method described in the
previous section. The variable asymmetries of the light maxima can be explained by the changes of the cool spot with time, which may be formed from magnetic dynamo-related activity because the system is rotating rapidly, and the secondary component should be a deep convective envelope as surmised from its temperature. In order to understand the pulsational characteristics of the system, multiple frequency analyses were applied to the whole outside-eclipse light residuals, removing the binarity effects from the observed *Kepler* data. Thirty frequencies with S/N ratios larger than 4.0 were found in the range of 0.31–5.78 day\(^{-1}\) with amplitudes between 0.14 and 3.29 mmag. Among these, six \((f_5, f_6, f_8, f_{10}, f_{11}, f_{12})\) may be pulsation frequencies in the g-mode region, which were stable during the observational interval of about 200 days. We computed the pulsation constants from the cool-spot model parameters in Table 1 and the well-known relation of $\log Q_1 = -\log f_1 + 0.5 \log g + 0.1 M_{\text{bol}} + \log T_{\text{eff}} - 6.456$ (Petersen & Jørgensen 1972). The results are listed in the third column of Table 4. The Q values and the position of KIC 6048106 on the HR diagram demonstrate that the detached primary component would be a δ Sct-type pulsating star. On the other hand, all but the six frequencies appear to be harmonic and combination terms, some of which might arise from starspot activity or from alias effects caused by the orbital frequency. The orbital harmonics \((f_7, f_8, f_{11}, f_{12}, f_{19}, f_{20})\) can be stellar pulsations excited by the tidal forces of the secondary component (Welsh et al. 2011; Hambleton et al. 2013; Lee et al. 2016a).

As binary stars are generally supposed to reach synchronization before their semi-detached phases, the pulsating primary component of KIC 6048106 may have a synchronized rotation of approximately 50 km s\(^{-1}\). Thus, we can make a possible identification of the radial order \((n)\) and spherical degree \((\ell)\) for the observed frequencies using the Frequency Ratio Method (Moya et al. 2005; Suárez et al. 2005), which is useful for γ Dor stars with rotational velocities of $v \sin i \lesssim 70$ km s\(^{-1}\) and at least three g-mode frequencies. Furthermore, it is possible to obtain the corresponding value for the integral of the Brunt–Väisälä frequency \((\mathcal{J})\). Following the procedure described by Lee et al. (2014), we determined that the model frequency ratios \((f_{n}/f_{\ell})_{\text{model}}\) were best-fitted to the observed ratios \((f_{n}/f_{\ell})_{\text{obs}}\), and identified the pulsation modes of the six frequencies. As listed in Table 4, the $f_2, f_3, f_4, f_5, f_{10}$, and $f_{11}$ frequencies are identified as degree $\ell = 2$ for radial orders of $n = 25, 22, 24, 17, 21$, and 18, respectively. The observed average value of $\mathcal{J}_{\text{obs}} = 742.2 \pm 5.3$ for the six frequencies is close to the theoretical integral of $\mathcal{J}_{\text{theo}} = 700$ μHz for a model of $\log T_{\text{eff}} = 3.845, 1.5 M_{\odot}$, and [Fe/H] = 0.0 in the $\mathcal{J} - \log T_{\text{eff}}$ diagram given by Moya et al. (2005).

Classical Algols are semi-detached interacting systems in which one type of interaction is mass transfer from the lobe-filling secondary to the detached primary component via the inner Lagrange $L_1$ point. The semi-detached configuration of KIC

| Frequency (day\(^{-1}\)) | Amplitude (mmag) | Phase (rad) | S/N ratio | Remark |
|--------------------------|------------------|-------------|-----------|--------|
| $f_1$                     | 0.63775 ± 0.00002 | 3.29 ± 0.06 | 6.00 ± 0.06 | $f_{1\varnothing}$ |
| $f_2$                     | 1.97655 ± 0.00003 | 1.77 ± 0.05 | 4.58 ± 0.09 | $f_{2\varnothing}$ |
| $f_3$                     | 2.21165 ± 0.00004 | 1.50 ± 0.05 | 2.69 ± 0.10 | $f_{3\varnothing}$ |
| $f_4$                     | 2.04610 ± 0.00004 | 1.39 ± 0.05 | 2.81 ± 0.11 | $f_{4\varnothing}$ |
| $f_5$                     | 2.84140 ± 0.00004 | 1.27 ± 0.05 | 1.03 ± 0.10 | $f_{5\varnothing}$ |
| $f_6$                     | 2.30595 ± 0.00005 | 1.07 ± 0.05 | 5.53 ± 0.14 | $f_{6\varnothing}$ |
| $f_7$                     | 2.56510 ± 0.00009 | 0.54 ± 0.05 | 4.49 ± 0.26 | $4f_{\varnothing}$ |
| $f_8$                     | 3.20665 ± 0.00004 | 1.04 ± 0.04 | 1.57 ± 0.12 | $5f_{\varnothing}$ |
| $f_9$                     | 0.65200 ± 0.00013 | 0.48 ± 0.06 | 0.67 ± 0.38 | $f_{\varnothing} + 0.01071$ |
| $f_{10}$                  | 2.72325 ± 0.00008 | 0.60 ± 0.05 | 6.04 ± 0.23 | 22.02 |
| $f_{11}$                  | 4.84925 ± 0.00005 | 0.65 ± 0.03 | 2.68 ± 0.13 | 38.12 |
| $f_{12}$                  | 1.28360 ± 0.00007 | 0.85 ± 0.06 | 1.97 ± 0.20 | 24.66 |
| $f_{13}$                  | 1.27415 ± 0.00011 | 0.54 ± 0.06 | 4.16 ± 0.32 | 15.62 |
| $f_{14}$                  | 0.64590 ± 0.00011 | 0.60 ± 0.06 | 1.90 ± 0.31 | $f_{\varnothing}$ |
| $f_{15}$                  | 0.63005 ± 0.00012 | 0.53 ± 0.06 | 5.69 ± 0.35 | 14.36 |
| $f_{16}$                  | 3.03275 ± 0.00010 | 0.44 ± 0.04 | 3.06 ± 0.29 | 17.51 |
| $f_{17}$                  | 2.79950 ± 0.00017 | 0.27 ± 0.05 | 3.93 ± 0.50 | 10.09 |
| $f_{18}$                  | 1.30860 ± 0.00025 | 0.24 ± 0.06 | 3.32 ± 0.72 | 6.94 |
| $f_{19}$                  | 1.27985 ± 0.00019 | 0.32 ± 0.06 | 6.17 ± 0.54 | 9.32 |
| $f_{20}$                  | 5.77215 ± 0.00007 | 0.29 ± 0.02 | 4.67 ± 0.22 | 23.11 |
| $f_{21}$                  | 2.82475 ± 0.00020 | 0.23 ± 0.05 | 6.25 ± 0.57 | 8.75 |
| $f_{22}$                  | 2.41375 ± 0.00024 | 0.21 ± 0.05 | 3.72 ± 0.69 | 7.31 |
| $f_{23}$                  | 1.85800 ± 0.00026 | 0.22 ± 0.06 | 6.07 ± 0.74 | 6.75 |
| $f_{24}$                  | 1.26435 ± 0.00030 | 0.20 ± 0.06 | 4.48 ± 0.85 | 5.87 |
| $f_{25}$                  | 0.31565 ± 0.00032 | 0.20 ± 0.06 | 2.68 ± 0.94 | 5.34 |
| $f_{26}$                  | 2.68710 ± 0.00026 | 0.18 ± 0.05 | 2.33 ± 0.75 | 6.64 |
| $f_{27}$                  | 1.11995 ± 0.00033 | 0.19 ± 0.06 | 2.19 ± 0.95 | 5.30 |
| $f_{28}$                  | 2.65335 ± 0.00029 | 0.17 ± 0.05 | 2.31 ± 0.83 | 6.06 |
| $f_{29}$                  | 2.11240 ± 0.00032 | 0.17 ± 0.05 | 1.64 ± 0.92 | 5.45 |
| $f_{30}$                  | 1.69665 ± 0.00042 | 0.14 ± 0.06 | 4.10 ± 1.21 | 4.15 |
6048106 permits some mass transfer between the component stars by means of a gas stream. Just as with the mass-accreting $\delta$ Sct components of semi-detached Algols (Mkrtichian et al. 2004; the so-called oEA stars), the secondary to primary mass transfer could at least be partly responsible for the $\gamma$ Dor-type oscillations detected in this paper. In addition, the pulsations may be influenced by the tidal and gravitational forces from the secondary component. As mentioned in the Introduction, Çakırlı & İbanoğlu (2016) presented three empirical relations for the $\gamma$ Dor stars in EBs, where the equation and figure between the pulsation period $P_{\text{pul}}$ and the gravitational force $\log(F/M_i)$ are not consistent with each other. We think that their Equation (9) should be $\log(F/M_i) = -2.021 \log P_{\text{pul}} + 2.093$. The physical properties of KIC 6048106 match well the relationships of the orbital periods, surface gravities, and gravitational forces against the pulsation periods. However, because only 13 stars, including KIC 6048106, have been identified as EBs containing $\gamma$ Dor-type components, additional discoveries and follow-up observations will help reveal more accurate properties of the pulsating EBs.

Figure 6. Variability of the main frequencies detected in the four subsets at intervals of $\sim$50 days. In all panels, the $y$-axes are scaled to 0.04 day$^{-1}$, and the tick intervals are 0.01 day$^{-1}$.

| Frequency (day$^{-1}$) | $Q$ (days) | $(f_i/f_5)_{\text{obs}}$ | mode $(n, \ell)$ | $(f_i/f_5)_{\text{model}}$ | $\Delta(f_i/f_5)_{\text{obs-model}}$ | $\mathcal{Z}_{\text{obs}}$ ($\mu$Hz) |
|------------------------|------------|------------------------|-----------------|----------------------------|----------------------------------|--------------------------|
| $f_2$                  | 1.97655    | 0.333                  | 0.6956          | (25, 2)                    | 0.6863                           | +0.0094                  | 748.2                    |
| $f_3$                  | 2.21165    | 0.298                  | 0.7784          | (22, 2)                    | 0.7778                           | +0.0006                  | 738.7                    |
| $f_4$                  | 2.04610    | 0.322                  | 0.7201          | (24, 2)                    | 0.7143                           | +0.0058                  | 744.1                    |
| $f_5$                  | 2.84140    | 0.232                  | ...             | (17, 2)                    | ...                              | ...                      | 738.1                    |
| $f_6$                  | 2.30595    | 0.286                  | 0.8116          | (21, 2)                    | 0.8140                           | -0.0024                  | 735.9                    |
| $f_{10}$               | 2.72325    | 0.242                  | 0.9584          | (18, 2)                    | 0.9459                           | +0.0125                  | 747.9                    |
| Average                |            |                        |                 |                            | +0.0052 $\pm$ 0.0061            | 742.2 $\pm$ 5.3          |

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Lee
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Figure 7. Position on the HR diagrams of KIC 6048106 (star symbols) and other Algol EBs. The filled and open circles refer to the primary and secondary components of the semi-detached Algols, respectively, and the squares are the nine γ Dor stars in EBs with known parameters. The solid line denotes the ZAMS for solar metallicity from Tout et al. (1996). The dashed and dashed–dotted lines represent the instability strips of γ Dor (Warner et al. 2003; Çakirli 2015) and δ Sct stars (Rolland et al. 2002; Soydugan et al. 2006), respectively.