Asteroseismology of *Kepler* Algol-type oscillating eclipsing binaries

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ABSTRACT

Context. This research paper contains light curve modelling, spectroscopy, and detailed asteroseismic studies for four out of a total of five semi-detached eclipsing binaries with a δ Scuti component that have been detected to date through *Kepler* mission; these objects are KIC 06669809, KIC 10581918, KIC 10619109, and KIC 11175495.

Aims. The goal is to study the pulsational characteristics of the oscillating stars of the systems and to estimate their absolute parameters and enrich the, thus far, poor sample of such systems.

Methods. Ground-based spectroscopic observations provided the means to estimate the spectral types of the primary components and to model the light curves with higher certainty. The photometric data were analysed using eclipsing binary modelling techniques, while Fourier analysis was applied on their residuals to reveal the pulsation frequency modes.

Results. The results of analyses show that the primaries are pulsating stars of δ Scuti type and that all systems belong to the group of Algol-type binaries that have an oscillating star (oEA stars). The primaries of KIC 06669809, KIC 10581918, and KIC 10619109 pulsate in three, two, and five frequencies, respectively, and more than 200 others are detected as combination frequencies. The pulsator of KIC 11175495 is the youngest and fastest δ Scuti star that has ever been found in a binary system and oscillates in three main non-radial frequencies and in another 153 dependent frequencies. Moreover, comparisons of the properties of these binaries with other systems of the same type and with theoretical models of pulsating stars are also presented and discussed.

Key words. asteroseismology – binaries: eclipsing – stars: variables: δ Scuti – stars: oscillations (including pulsations) – stars: fundamental parameters – binaries: close

1. Introduction

In general, δ Scuti stars are multi-periodic pulsating variables oscillating in radial and non-radial modes. These stars are of A–F spectral types and III–V luminosity classes, their mass values range between $1.4\text{--}3\ M_{\odot}$, and they are located in the classical instability strip. The radial and the low-order non-radial pulsations are excited from κ -mechanism (Balona et al. 2015). Recently, however, it has been proposed that turbulent pressure in the hydrogen convective zone might be the explanation for high-order non-radial modes (Antoci et al. 2014; Grassitelli et al. 2015).

Eclipsing binary systems (EBs) can be considered as the most essential tools for absolute parameters and evolutionary status estimation of stellar components. The combination of light curves (LCs) and radial velocities curves (RVs) provide the means for a very accurate calculation of stellar masses, radii, luminosities, etc. The geometrical status of an EB (i.e. Roche geometry) and its geometrical parameters (e.g. orbital period and inclination) can be extracted directly through analyses of LCs. Moreover, the eclipse timing variations (ETV) method permits the detection of mechanisms (e.g. mass transfer) occurring in the EB. In general, RVs for binaries with orbital periods larger than one to two days cannot be easily obtained. This is mostly because the acquisition of spectroscopic data require large telescopes and different dates of observations, and in many cases, especially for Algol-type EBs, the brighter member dominates the spectrum and makes impossible to detect any spectral lines from its fainter companion. In addition, it is also difficult to obtain data for ETV analysis for recently discovered cases because typical

period changes require decades of observations for photometric minima. However, LCs are generally easier to obtain and it is feasible to derive relatively accurate results and plausible conclusions using fair assumptions based on stellar evolution theory.

The study of δ Scuti stars in EBs can be considered as very important not only because two different stand-alone astrophysical issues (i.e. pulsations and binarity) are combined, but also because the absolute parameters of the pulsator can be derived through the interaction of the members of the binary system. Mkrtichian et al. (2002) first proposed this group as a subclass of EBs. In that paper, a new category of EBs, namely oscillating eclipsing binaries of Algol type (oEA stars), was introduced as the Algol-type mass accreting pulsators of (B)A–F type. Later on, Soyugan et al. (2006a) announced the first connection between orbital (P_{orb}) and dominant pulsation (P_{pul}) periods, while Soyugan et al. (2006b) published lists with candidate EBs with a δ Scuti member. Liakos et al. (2012) after a long-term observational campaign published a catalogue with 74 cases and updated correlations between fundamental parameters. Zhang et al. (2013) made the first theoretical attempt for the $P_{\text{pul}} - P_{\text{orb}}$ correlation. For the first time, Liakos & Niarchos (2015, 2016) noticed that there is a boundary between $P_{\text{pul}} - P_{\text{orb}}$ beyond which these two quantities do not correlate. Finally, Liakos & Niarchos (2017) published the most complete catalogue¹ (204 δ Scuti stars in 199 binary systems) and correlations between fundamental parameters to date.

¹ <http://alexiosliakos.weebly.com/catalogue.html>

The *Kepler* mission provides the means for high precision asteroseismic models of δ Scuti stars because of (a) the unprecedented photometric precision of the data (order of tens of mmag), which makes it feasible to detect frequencies with amplitudes of tens of μmag (e.g. [Murphy et al. 2013](#)); (b) the continuous monitoring of the targets, which eliminates the effect of alias in frequencies detections ([Breger 2000](#)); and (c) the relatively high time resolution of the short-cadence data (~ 1 min). It should be noted that the long-cadence data (i.e. time resolution ~ 30 min) can be also considered extremely valuable for asteroseismology in cases of other pulsating stars such as Cepheids, γ Doradus, etc., which show pulsation periods of the order of several hours to several days. In addition, long-cadence data for targets observed during many quarters of the mission allow the study of short-term pulsation period changes (e.g. of order of a few years). Another very important point is that all the archives of the mission are publicly available and the data can be easily obtained and analysed. Particularly for the EBs, the *Kepler* Eclipsing Binary Catalog² (KEBC; [Prša et al. 2011](#)) is an excellent online database, which provides all the preliminary information (e.g. ephemerides, magnitudes, temperatures) needed for a further and more detailed analysis.

According to the catalogue of [Liakos & Niarchos \(2017\)](#) only 17 cases of *Kepler* EBs with a δ Scuti component have been published so far. In particular, KIC 06220497 ([Lee et al. 2016](#)) and the four presented herein are oEA stars; nine of these are detached systems, while another three are still unclassified regarding their Roche geometry (see [Liakos & Niarchos 2017](#), and references therein).

For the present study, KIC 06669809, KIC 10581918, KIC 10619109, and KIC 11175495 have been selected for detailed analyses for first time. Ground-based spectroscopic observations allowed the estimation of the spectral types of the primary components of the systems and provided the means for a more accurate LCs modelling that led us to estimate the absolute parameters of their components and study in depth the pulsation properties of their δ Scuti stars. The fifth oEA *Kepler* system, KIC 06220497 ([Lee et al. 2016](#)), is not part of the present sample because it was not included in our spectroscopic campaign. The present sample consists of the $\sim 6\%$ of the total known (66) oEA systems with δ Scuti component and the $\sim 7\%$ of those (56 in total) whose absolute parameters are known. Finally, the present research contributes to the least-studied region of the pulsating stars in binaries, namely the *Kepler* oEA stars.

Preliminary results regarding the dominant pulsation frequency and the Roche geometry of the systems have been published by [Liakos & Niarchos \(2016\)](#) for KIC 06669809 and by [Liakos & Niarchos \(2017\)](#) for the remaining three EBs. For all studied systems the respective observations logs are listed in Table 1.

The systems are hereafter abbreviated for easier identification. KIC 06669809 is referred to as KIC 066, KIC 10581918 as KIC 105, KIC 10619109 as KIC 106, and KIC 11175495 as KIC 111 in the whole text.

The system KIC 06669809 (cross ID: TYC 3127-1399-1) has a period of ~ 0.73 d and a LC of β Lyrae type. The first LCs in *V* and *I* filters were obtained by the ASAS survey ([Pigulski et al. 2009](#)). Its temperature is referred as 7239 K ([Christiansen et al. 2012](#); [Pinsonneault et al. 2012](#)), 7150 K in the HIPPARCOS Catalogue ([ESA 1997](#)), 7452 K by [Huber et al. \(2014\)](#), and 7810 K by [Ammons et al. \(2006\)](#). [Conroy et al. \(2014\)](#) presented the ETV diagram of the system, while [Borkovits et al. \(2016\)](#)

Table 1. Log of observations from the *Kepler* mission for all studied systems.

KIC	L-C Q	S-C Q	llc ($\times 10^{-4}$)	Points (S-C)	Days (S-C)	LCs (S-C)
066	1–4; 6–8; 10–12; 14–16	4	5	45 449	31.06	42
105	2–4; 6–8; 10–12; 14–16	7	0	42 700	29.18	16
106	0–6; 8–10; 12–14; 16–17	3	0	38 004	25.97	12
111	0–17	5	0.9	49 145	33.57	15

Notes. The value *Q* denotes the quarters of *Kepler* mission during which long-cadence (L-C) and short-cadence data (S-C) were obtained. The value *llc* denotes the level of light contamination, while the total *points*, the number of consecutive *days* of the S-C data, and the number of the fully covered *LCs* are also given in the last three columns.

analysed this diagram with one periodic and one cubic term. The periodic term was attributed to a possible light-time travel effect due to the presence of a third companion with an orbital period of ~ 194 d and a mass function (i.e. Eq. (3)) of $f(M) \sim 0.0062 M_{\odot}$.

The binary system KIC 10581918 (cross IDs: 2MASS J18521048+4748166; WX Dra) was discovered by [Tsevevich \(1960\)](#) and has an orbital period of ~ 1.8 d. Other than many timings of minima, neither LCs modelling nor spectroscopic studies have been published thus far. The only available LCs come from the ASAS survey ([Pigulski et al. 2009](#)) in *V* and *I* filters and from the Trans-Atlantic Exoplanet Survey ([Devor et al. 2008](#), T-Lyr1-05887) in *R* band. [Christiansen et al. \(2012\)](#) referred the temperature of the system as 7252 K, [Armstrong et al. \(2014\)](#) as 7371 K, [Huber et al. \(2014\)](#) as 7475 K, but the *LAMOST* spectroscopic survey ([Frasca et al. 2016](#)) classified this system as of A7V spectral type (i.e. ~ 7800 K). [Peters & Wilson \(2012\)](#) based on the long and short cadence data of *Kepler* concluded that there is a migrating hot spot on the surface of the primary and that this component pulsates with a dominant frequency of ~ 35.8 cycle d^{-1} . [Wolf et al. \(2015\)](#) and [Zasche et al. \(2015\)](#) analysed the ETV diagram of the system and they found a 14 yr periodic modulation of the orbital period, which they attributed to the possible existence of a third body in an eccentric orbit with a mass function of $f(M) \sim 0.00027 M_{\odot}$. In the latter paper, the model of the *Kepler* LC of the system was presented assuming a mass ratio of 1, but no third light contribution was found.

The system KIC 10619109 (cross ID: TYC 3562-985-1) was identified as an EB with an orbital period of ~ 2 days by the Trans-Atlantic Exoplanet Survey ([Devor et al. 2008](#), T-Cyg1-01956), from which the first LC in *R* passband was obtained. The temperature estimation of the system ranges from 7028 K ([Christiansen et al. 2012](#)) and 7128 K ([Huber et al. 2014](#)) up to 7441 K ([Armstrong et al. 2014](#)). [Gao et al. \(2016\)](#) announced that among 1049 binaries observed by *Kepler* mission, they discovered flare activity in 234 of these binaries including also KIC 106. Based on ~ 3 yr data, they found 14 flares with a frequency of 0.013 d^{-1} and an amplitude of 45 mmag. [Conroy et al. \(2014\)](#) and [Gies et al. \(2015\)](#) performed an ETV analysis, but they found very weak evidence for a potential third star orbiting the system.

KIC 11175495 (cross ID: 2MASS J18501133+4851229) has a period of ~ 2.19 d and was discovered as a high-frequency A-type pulsator ($f_{\text{dom}} \sim 64.44$ cycle d^{-1}) by [Holdsworth et al. \(2014\)](#) using data from the *SWASP* survey. Its temperature is

² <http://keplerebs.villanova.edu/>

Table 2. Spectroscopic observations log of the standard stars used for the comparisons in the A-F spectral types (ST) region.

HIP No	ST	HIP No	ST	HIP No	ST	HIP No	ST
12640	A0V	4436	A5V	194	F0V	5833	F5V
111169	A1V	111259	A6V	19205	F1V	116505	F6V
111242	A2V	12332	A7V	13904	F2V	6711	F7V
92405	A3V	102253	A8V	90345	F3V	109572	F8V
94620	A4V	96286	A9V	10830	F4V	102611	F9V

Table 3. Spectroscopic observations log and results for the primary components of the studied systems.

KIC	Date	E.T. (min)	Φ_{orb}	Spectral type	T_{eff} (K)
066	15/8/16	10	0.35	A9V-F0V	7400(100)
105	6/10/16	15	0.49	A6V-A7V	7900(100)
106	5/10/16	20	0.13	F1V-F2V	7070(75)
111	16/8/16	20	0.66	A8V-A9V	7550(100)

Notes. The columns include the name of the system (KIC), dates of observations (in DD/MM/YY format), exposure time used (E.T.), and orbital phase of the system when the spectrum was obtained (Φ_{orb}). The errors are given in parentheses alongside values and correspond to the last digit(s).

given as 8070 K by Slawson et al. (2011) and Christiansen et al. (2012), and as 8300 K by Huber et al. (2014).

2. Ground-based spectroscopy

Spectroscopic observations were obtained with the 2.3 m Ritchey-Cretien “Aristarchos” telescope at Helmos Observatory in Greece during summer 2016 using the Aristarchos Transient Spectrometer³ (ATS) instrument (Boumis et al. 2004). The ATS is a low- to medium-dispersion fibre spectrometer that consists of 50 fibres (50 μm diameter each) providing a field of view of ~ 10 arcsec on the sky. The U47-MB Apogee CCD camera (Back illuminated, 1024×1024 pixels, $13 \mu\text{m}^2$ pixel size) and the low-resolution grating (600 lines mm^{-1}) were used for the observations. This setup provided a resolution of $\sim 3.2 \text{ \AA pixel}^{-1}$ and a spectral coverage between approximately 4000–7260 $\text{\AA}$, where the first four Balmer (i.e. H_α – H_δ) and many metallic lines (e.g. MgI-triplet, NaI-doublet) are present.

Approximately 45 spectroscopic standard stars, which were suggested by GEMINI Observatory⁴ and range from B0V to K8V spectral types, and the KIC targets were observed with the same instrumental set-up. The objective of these observations was to derive the spectral types of the primary components of the KIC systems. The observations of standard stars took place during three nights in July, five nights in August, and two nights in October 2016. In Table 2 are listed the spectroscopic standards stars (the names are taken from the HIPPARCOS catalogue – Hip No) used for the comparisons in the A-F spectral type region. The spectroscopic observations log for the KIC systems is given in Table 3. The technical calibration of all spectra (bias, dark, and flat-field corrections) was made via MAXIM DL software, while the data reduction (wavelength calibration, cosmic rays removal, spectra normalization, and sky background removal) was performed via RAVERE v.2.2c software (Nelson 2009).

Fig. 1. Spectral type-search plots for all studied KIC systems. The points of KIC 066 and KIC 111 are shifted vertically for better viewing. The arrows show the adopted spectral type for the primary component of each system.

All spectra were calibrated and normalized to enable direct comparisons. The spectra were then shifted, using the Balmer lines as reference, to compensate for the relative Doppler shifts of each standard and the variables. The spectral region between 4000 $\text{\AA}$ and 6800 $\text{\AA}$, where the Balmer and numerous metallic lines are strong, was used for spectral classification. The remaining spectral regions were ignored because they generally lacked sufficient metallic lines with significant signal-to-noise ratios (S/N). The depths of each Balmer and other metallic lines, which are sensitive to the temperature, were calculated in all spectra of the standard stars and variables. The differences of spectral line depths between each standard star and the variables derive sums of squared residuals in each case. These least-squares sums guided us to the closest match between the spectra of variables and standards. In Fig. 1 the Σres^2 against spectral type plot for each variable is shown. The comparison is shown only between A–F spectral types for scaling reasons. In the case of KIC 066 the best match was found with the spectrum of an A9V standard star and, as shown in Fig. 1, the F0V spectral type provides better match than that of an A8V. Thus, in conclusion, KIC 066 is between A9V-F0V spectral types with a formal error of half subclass. Following the same method, it is found that KIC 105 lays between A6V-A7V, KIC 106 between F1V-F2V, and KIC 111 between A8V-A9V spectral types with the same formal error. The spectra of all systems along with those of best-fit standard stars are plotted in Fig. 2. The last two columns of Table 3 host the spectral classification for each system using the aforementioned spectral comparisons and the assigned temperature values (T_{eff}) according to the relations between effective temperatures-spectral types of Cox (2000).

The spectra of all systems, except for KIC 105, were obtained during out-of-eclipse phases; thus, typically, the spectra correspond to the combined spectra of the components. However, in Sect. 3 it is shown that the secondary components of the systems have a very small contribution to the total light and, in addition, the temperature differences between them and their companions are relatively large. Therefore, since the secondaries were found to be cool stars, it can be plausibly assumed that the spectrum of each system practically reflects the spectral type of its primary. For KIC 066 and KIC 106 the present spectral classifications are in relatively good agreement with the results of previous photometry-based methods (see Sect. 1). The primary of KIC 105 is found to be hotter than the estimates from photometry-based methods, but the present result is in excellent agreement with other spectroscopic results (see Sect. 1). Finally, for KIC 111 the present spectroscopic results reveal a

³ <http://helmos.astro.noa.gr/ats.html>

⁴ <http://www.gemini.edu/>

Fig. 2. Comparison spectra of the KIC targets and standard stars with the closest spectral types. The Balmer and some strong metallic lines are also indicated.

cooler spectral type in comparison with those suggested by other photometry-based methods (see Sect. 1).

3. Light curve modelling and absolute parameters calculation

All systems were observed during many quarters of the *Kepler* mission (see Table 1). However, short-cadence data (i.e. time resolution ~ 1 min) were only obtained during one quarter. Since the objective of this research is the study of the asteroseismic behaviour of the pulsating members of the systems, time resolution and continuous recording are very important. Therefore, for the following analyses only the short-cadence data, taken from the online version of the KEBC (Prša et al. 2011), were used. The total number of data points for each system corresponding to a significant number of fully covered LCs (see Table 1) were available and these are plotted in the upper panels of Figs. 3–6. For all systems, the light contamination (see Table 1) is negligible.

The first step of the analysis was to create a mean LC for each system in order to (a) eliminate brightness changes due to pulsations and cool spots (O’Connell effect) and (b) use this LC for faster calculations for the estimation of mass ratio (q) of the EB. For this, the phase diagrams of the LCs folded into the orbital period were used. The ephemerides (T_0 , P_{orb}) for the conversion of the time-dependent LCs into phase folded LCs were taken from the KEBC (Prša et al. 2011) and these are given in Table 4. More specifically, by taking averages every ~ 80 data points, one single LC with ~ 600 mean points was derived for each system and used only for the q -search method as described below.

The LCs analyses were made using the PHOEBE v.0.29d software (Prša & Zwitter 2005) that is based on the 2003 version of the Wilson-Devinney (W-D) code (Wilson & Devinney 1971; Wilson 1979, 1990). In the absence of spectroscopic mass ratios, the “ q -search” method (for details see Liakos & Niarchos 2012) was applied in modes 2 (detached system), 4 (semi-detached system with the primary component filling its Roche lobe) and 5 (conventional semi-detached binary) to find feasible (“photometric”) estimates of the mass ratio. The step of q change

during the search was 0.05–0.1 starting from $q = 0.05$ –0.1. The effective temperatures of the primaries (T_1) were given the values derived from the spectral classification (see Sect. 2) and were kept fixed during the analysis, while the temperatures of the secondaries T_2 were adjusted. The Albedos, A_1 and A_2 , and gravity darkening coefficients, g_1 and g_2 , were set to generally adopted values for the given spectral types of the components (Rucinski 1969; von Zeipel 1924; Lucy 1967). The (linear) limb darkening coefficients, x_1 and x_2 , were taken from the tables of van Hamme (1993). The dimensionless potentials Ω_1 and Ω_2 , the fractional luminosity of the primary component L_1 , and the orbital inclination of the system i were set as adjustable parameters. At this point it should be noted that since the *Kepler*’s photometer has a spectral response range between approximately 410–910 nm with a peak at ~ 588 nm, the R filter (Bessell photometric system-range between 550–870 nm and with a transmittance peak at 597 nm) was selected as the best representative for the filter depended parameters (i.e. x and L). Moreover, there is evidence of maxima brightness changes in all of the systems, therefore parameters of photospheric spots on the surface of the secondary were also adjusted. The selection of the magnetically active component was based on the effective temperatures of the members of the systems. In all cases the secondaries are clearly cooler than the primaries (i.e. large minima difference), therefore, they host a convective envelope that better suits a magnetically active star. In addition, the hotter stars are candidates for δ Sct type pulsations and it is rather rare to present magnetic activity also. For all EBs, except for KIC 111, the third light parameter (l_3) was also adjusted because the systems are candidates for triplicity (see Sect. 1). However, during the iterations it resulted in unrealistic values, therefore, it was omitted in the final analysis. Finally, all systems were found to have the minimum $\sum \text{res}^2$ in mode 5. KIC 066 and KIC 111 have a minimum at $q = 0.3$, while KIC 105 and KIC 106 at $q = 0.15$. In Fig. 7 the respective q -search plots are shown.

The analyses of the systems confronted three main problems: (a) the spot migration over time, which did not allow us to create one simple LC model using all the available points; (b) the widely known “unrealistic” error estimation of PHOEBE;

Fig. 3. Upper panel: short cadence LCs for KIC 06669809. Lower panel: LCs residuals after the subtraction of the binary models.

Fig. 4. Same as Fig. 3, but for KIC 10581918.

and (c) the LC asymmetries due to pulsations. We point out that the objectives of the LC modelling are the estimation of the parameters of the systems (geometrical and absolute) and also the elimination of the binarity influence to the data points to be used later for a frequency analysis. A plausible solution to the first two problems was to solve each LC separately, while for the third problem we used mean points again but this time for each LC. Thus, for all systems ~ 500 normal points per LC were used. For each LC model as input parameters were used those derived from the “ q -search” method and following exactly the

same assumptions as before and with the addition of q as adjustable parameter, the iterations began. The iterations finished once the parameters could not converge to a solution with less $\sum \text{res}^2$. This method provides one model per LC, i.e. 42, 16, 12, and 15 models for KIC 066, KIC 105, KIC 106, and KIC 111, respectively.

In these cases, the changes of spot parameters over time is interesting. Although the spots are not subject of this study, it was considered useful to show how they migrated and changed during the duration of observations in Appendix B. In the cases

Fig. 5. Same as Fig. 3, but for KIC 10619109.

Fig. 6. Same as Fig. 3, but for KIC 11175495.

of KIC 066 and KIC 111, one cool photospheric spot was assumed, while two cool spots were used to describe the brightness changes of KIC 105. For KIC 106 two bright spots were assumed on the surface of the secondary because the system presents flare activity (Gao et al. 2016) and wide bright regions are expected. In Table B.1 all the spot parameters are given, namely co-latitude (co-lat.), longitude (long.), radius, and temperature factor (T_f) for each LC. As the representative beginning time of the spot migration is the half value of the period of the EB. Then, every

successive timing is derived from the previous timing plus the period of the EB. The upper sections of Figs. B.1–B.6 show the changes of the parameters of all spots over time for each system, while the lower parts show the spot on the surfaces of the secondaries during the first and last days of observations.

Each value of the final LC model presented in Table 4 is the mean value of the same parameters of the individual LC models, while the errors are the standard deviation of them. The upper sections of Figs. 8–11 show the fits to the observed points of an

Table 4. Light curve and absolute parameters for all studied systems.

System	KIC 06669809		KIC 10581918		KIC 10619109		KIC 11175495	
System parameters								
K_{p}^a (mag)	10.76		12.80		11.70		12.97	
T_0^a (BJD)	2 454 953.998571		2 455 139.362915		2 454 955.136772		2 454 954.005791	
P_{orb}^a (days)	0.733738		1.801863		2.045183		2.191027	
q (m_2/m_1)	0.31(1)		0.12(1)		0.14(1)		0.29(1)	
i ($^\circ$)	67.5(1)		89.0(2)		75.0(1)		68.6(2)	
Components parameters								
	Prim.	Sec.	Prim.	Sec.	Prim.	Sec.	Prim.	Sec.
T_{eff} (K)	7400(100) ^b	4898(57)	7900(100) ^b	4954(51)	7070(75) ^b	3949(31)	7550(100) ^b	3600(55)
Ω	3.04(2)	2.61(1)	4.83(2)	2.03(1)	4.32(1)	2.07(2)	7.4(2)	2.41(1)
A^c	1	0.5	1	0.5	1	0.5	1	0.5
g^c	1	0.32	1	0.32	1	0.32	1	0.32
x	0.442	0.637	0.394	0.627	0.414	0.689	0.500	0.646
$L/(L_{\text{P}} + L_{\text{S}})$	0.905(1)	0.095(3)	0.843(4)	0.157(1)	0.934(7)	0.066(2)	0.870(9)	0.130(1)
r_{pole}	0.385(1)	0.264(1)	0.212(1)	0.201(1)	0.239(1)	0.208(1)	0.141(4)	0.259(3)
r_{point}	0.423(1)	0.383(1)	0.214(1)	0.298(1)	0.242(1)	0.308(1)	0.141(4)	0.377(4)
r_{side}	0.400(1)	0.275(1)	0.214(1)	0.209(1)	0.241(1)	0.217(1)	0.141(4)	0.270(4)
r_{back}	0.411(1)	0.308(1)	0.214(1)	0.241(1)	0.241(1)	0.248(1)	0.141(4)	0.303(4)
Absolute parameters								
M ($M_{\odot}$)	1.65(17) ^c	0.51(5)	1.87(19) ^c	0.22(3)	1.54(15) ^c	0.22(3)	1.70(17) ^c	0.49(5)
R ($R_{\odot}$)	1.81(2)	1.21(1)	1.74(3)	1.66(3)	2.01(3)	1.79(3)	1.33(5)	2.48(8)
L ($L_{\odot}$)	8.6(5)	0.76(6)	10.5(6)	1.51(8)	9.0(5)	0.70(6)	5.2(8)	0.93(1)
$\log g$ (cm s ⁻²)	4.14(4)	3.98(5)	4.23(5)	3.35(6)	4.02(5)	3.27(6)	4.42(8)	3.34(5)
a ($R_{\odot}$)	1.07(3)	3.46(2)	0.87(7)	7.29(4)	1.03(7)	7.34(4)	2.12(6)	7.32(4)
M_{bol} (mag)	2.4(3)	5.1(3)	2.2(3)	4.3(3)	2.4(3)	5.1(3)	3.0(4)	4.8(5)

Notes. The errors are given in parentheses alongside values and correspond to the last digit(s). ^(a) Taken from the KEBC (Prša et al. 2011), ^(b) results from spectroscopy, ^(c) assumed, Prim. = primary; Sec. = secondary component.

Fig. 7. q -search method for all systems. The points of KIC 11175495 are shifted vertically for better viewing.

individual observed LC for each system, while their Roche models are illustrated in the lower sections. The residuals of each LC were derived after the subtraction of the respective model from all the observed points of the particular LC. The LC residuals are plotted against time in the lower sections of Figs. 3–6 for each system.

Although no RV curves exist for these systems, fair estimates of their absolute parameters can be formed. The mass of each primary was inferred from its spectral type according to the spectral type-mass correlations of Cox (2000) for main-sequence stars. Mass values of $1.65 M_\odot$, $1.87 M_\odot$, $1.54 M_\odot$, and $1.7 M_\odot$ were assigned for the primaries of KIC 066, KIC 105, KIC 106, and KIC 111, respectively, while a fair error value of 10% was also adopted. The masses of the secondaries follow

from the determined mass ratios. The semi-major axes a , which fix the absolute mean radii, can then be derived from Kepler's third law. The luminosities (L), gravity acceleration ($\log g$), and bolometric magnitudes values (M_{bol}) were calculated with the standard definitions. For the calculation of the absolute parameters the software ABSPAREB (Liakos 2015) was used in mode 3 and the results are shown in the lower section of Table 4.

4. Pulsation frequencies analyses

According to the results of the spectroscopic the LC analyses (Sects. 2 and 3), only the primary components of the studied systems have stellar characteristics similar to the δ Sct type stars (i.e. mass and temperature), therefore the following analyses and results concern only the primaries. Frequency analysis was performed with the software PERIOD04 v.1.2 (Lenz & Breger 2005), which is based on classical Fourier analysis. Given that typical frequencies for δ Sct stars range between 4–80 cycle d^{-1} (Breger 2000), the analysis should be made for this range. However, given that δ Sct stars in binary systems may present g -mode pulsations that are connected to their P_{orb} or present hybrid behaviour of γ Dor- δ Sct type the search was extended to 0–80 cycle d^{-1} .

According to the method followed for the LC modelling (see Sect. 3), the binarity influence (e.g. proximity effects) and the light variations due to the cool spot existence in both systems were eliminated from the LC residuals. However, given that the total luminosity of a binary varies during the eclipses causing changes to the pulsations as well, and, in addition, because the

Fig. 8. Upper panel: theoretical (solid line) over observed (points) LC for KIC 06669809. Lower panel: three-dimensional representation of the Roche geometry of the system at orbital phase 0.75.

Fig. 9. Same as Fig. 8, but for KIC 10581918.

LC fitting is never perfect, only the out-of-eclipse data were used in the subsequent analysis. In particular, the range of orbital phases (Φ_{orb}) of the data that were excluded from the analysis are listed in Table 5.

Before the pulsation frequency search, another significant problem had to be confronted, which in general arises when very accurate photometric data such as those of *Kepler* are analysed. Because of the high accuracy signals, frequencies can be found very close to each other and very often the calculation of their S/N may be problematic and unrealistic. More specifically, the software calculates the S/N of a given frequency based on its amplitude and background noise around it. The problem is the calculation of the background noise itself. In particular, in data

Fig. 10. Same as Fig. 8, but for KIC 10619109.

Fig. 11. Same as Fig. 8, but for KIC 11175495.

Table 5. Pulsation analysis parameters.

System	Excluded (Φ_{orb})	bgd (μmag)	4σ (mmag)	$Nyq.$	δf (cycle d^{-1})
KIC066	0.90–0.10; 0.40–0.60	8.4	0.034	727.1	0.0483
KIC105	0.93–0.07; 0.44–0.56	12.2	0.049	720.9	0.0518
KIC106	0.93–0.07; 0.44–0.57	7.1	0.028	721.9	0.0581
KIC111	0.97–0.03; 0.43–0.57	9.4	0.038	723.6	0.0487

Notes. The columns contain the orbital phases (Φ_{orb}) of the excluded data, background noise (bgd) of each data set, 4σ detection threshold, Nyquist number ($Nyq.$) and frequency resolutions (δf). See text for further details.

Table 6. Independent oscillation frequencies for the pulsating components of all systems.

i	f_i (cycle d ⁻¹)	A (mmag)	Φ (°)	S/N	Q (d)	$P_{\text{pul}}/P_{\text{orb}}^a$	l -degree	Mode
KIC 06669809								
2	35.28312(7)	0.829(3)	260.9(2)	102.3	0.0150(14)	0.0386	2	NR p_4
3	23.54355(9)	0.687(3)	317.9(3)	84.7	0.0225(21)	0.0579	1	NR p_2
8	38.61245(13)	0.448(3)	300.7(4)	55.3	0.0173(13)	0.0353	2	NR p_5
KIC 10581918								
1	34.0784(1)	1.194(6)	14.0(3)	98.1	0.0175(16)	0.0163	2	NR p_3
2	36.4615(1)	1.048(6)	160.0(3)	86.1	0.0164(15)	0.0152	3	NR p_3
KIC 10619109								
1	42.8022(1)	0.661(4)	135.3(3)	93.7	0.0103(9)	0.0114	0	R $7H$
2	32.0947(2)	0.509(4)	15.5(4)	72.1	0.0137(12)	0.0152	1	NR p_5
3	31.1941(3)	0.273(4)	343.0(8)	38.6	0.0141(13)	0.0157	3	NR p_4
6	35.7549(3)	0.238(4)	212.7(9)	33.7	0.0123(11)	0.0137	3	NR p_5
7	45.9953(3)	0.232(4)	109.8(9)	32.8	0.0096(9)	0.0106	3	NR p_7
KIC 11175495								
1	64.44272(3)	3.151(5)	129.0(1)	336.2	0.0132(45)	0.0071	1	NR p_5
4	57.73592(9)	0.947(5)	48.7(3)	101	0.0147(50)	0.0079	2	NR p_2
5	56.68742(14)	0.643(5)	98.3(5)	68.6	0.0150(51)	0.0081	2	NR p_2

Notes. The columns include for each system the frequency values f_i (where i is an increasing number), semi-amplitudes A , phases Φ , S/N , pulsation constants Q , and pulsation-orbital period ratios ($P_{\text{pul}}/P_{\text{orb}}$). The errors are given in parentheses alongside values and correspond to the last digit(s).
^(a) Error values are of 10^{-7} – 10^{-8} order of magnitude; R = radial, NR = non radial pulsation.

from *Kepler* there might be many other frequencies of lower amplitudes around a given frequency. Although it is possible to increase the window for the background noise calculation around the detected frequency to minimize the contribution of the closest frequencies, the results remain unrealistic since frequencies of multi-periodic pulsators very often occupy wide bands in the periodogram. This problem is more obvious when reaching the last significant frequencies. In order to solve this problem and provide more realistic S/N for the detected frequencies, the background noise (b_{gd}) of each data set was calculated and listed in Table 5 in regions where no frequencies seem to exist with a spacing of 2 cycle d⁻¹ and a box size of 2. The software has a critical limit of 4σ (i.e. $S/N > 4$) to detect reliable frequencies, thus the same threshold was adopted and is given for each system in Table 5. In the same table, the Nyquist number ($Nyq.$) and the frequency resolutions (δf) according to the Rayleigh-Criterion (i.e. $1.5/T$, where T is the observations time range in days) are also given for each data set. Finally, after the first frequency computation the residuals were subsequently pre-whitened for the next computation until the detected frequency had $S/N \sim 4$. Table 6 contains the values of only the independent frequencies found for each system. The errors of all values listed in Tables 6, and A.1–A.4 were calculated via analytical simulations (for details see Lenz & Breger 2005).

4.1. KIC 06669809

KIC 066 was found to pulsate in three independent frequencies, namely f_2 , f_3 , and f_8 in the range 23–38 cycle d⁻¹, while the corresponding frequency to the orbital period of the system is $f_{\text{orb}} = 1.36288$ cycle d⁻¹. The most powerful frequency (f_1) is the second harmonic of f_{orb} . In total, 255 frequencies were detected, but 252 of these (listed in Table A.1) are either combinations or harmonics of the others. The Fourier fit on individual data points is shown in Fig. 12, while the periodogram, in which

the level of significance and independent frequencies are indicated, is illustrated in Fig. 16. In the periodogram it is clear that the distribution of frequencies show uniformity in all over the spectrum, but there are two main bands between 0–15 cycle d⁻¹ and 23–45 cycle d⁻¹, where their majority is concentrated. The slowest frequency is the $f_{54} \sim 0.037$ cycle d⁻¹ and the fastest is the $f_{187} \sim 68.145$ cycle d⁻¹, but both of these are combinations of other frequencies.

4.2. KIC 10581918

Two independent oscillation frequencies (see Table 6) between 34–36.5 cycle d⁻¹ and another 205 dependent frequencies, listed in Table A.2, were detected for KIC 105. As shown in the periodogram (Fig. 17), the majority of the frequencies spread in the range 18–55 cycle d⁻¹, while the range 0–5 cycle d⁻¹ is dominated by the frequencies that are connected to the orbital period ($f_{\text{orb}} = 0.55498$ cycle d⁻¹). In Fig. 13 is illustrated the Fourier fit on a selected data set.

4.3. KIC 10619109

The pulsating star of KIC 106 pulsates in 208 frequencies. In particular, f_1 , f_2 , f_3 , f_6 , and f_7 are the five independent frequencies, lie in the range 31–46 cycle d⁻¹ (see Table 6), while the other 203 are combined frequencies and are listed in Table A.3. The periodogram (Fig. 18) shows four main frequency concentration ranges; the first is between 22–38 cycle d⁻¹, the second between 41–48 cycle d⁻¹, a third between 50–54 cycle d⁻¹, and the fourth between 0–6 cycle d⁻¹. The latter range has the highest peak at 3.9135 cycle d⁻¹, which corresponds to the eighth harmonic of the $f_{\text{orb}} (=0.48895$ cycle d⁻¹) of the system. In Fig. 14 is shown the Fourier fit on individual observations.

Fig. 12. Fourier fit (solid line) on various data points for KIC 06669809.

Fig. 13. Same as Fig. 12, but for KIC 10581918.

Fig. 14. Same as Fig. 12, but for KIC 10619109.

Fig. 15. Same as Fig. 12, but for KIC 11175495.

4.4. KIC 11175495

The periodogram of KIC 111 (Fig. 19) clearly shows two main frequencies concentrations: one between 0–12 cycle d^{-1} and a second between 55–70 cycle d^{-1} , with only one frequency to be detected in the range 12–55 cycle d^{-1} , namely f_{156} . The dominant frequency is the $f_1 \sim 64.44$ cycle d^{-1} with an amplitude of ~ 3.1 mmag, while the other two independent frequencies (f_4 , f_5) were found in the range 56.5–57.7 cycle d^{-1} (see Table 6). The remaining 153 detected frequencies are either combinations or harmonics of the others and these frequencies are

listed in Table A.4. The Fourier fit on a selected day of observations is given in Fig. 15.

In order to check the most possible oscillations modes for the independent frequencies, the pulsation constants (Q), based on the equation of Breger (2000) were calculated as

$$\log Q = -\log f + 0.5 \log g + 0.1 M_{\text{bol}} + \log T_{\text{eff}} - 6.456, \quad (1)$$

where f is the frequency of the pulsation, and $\log g$, M_{bol} , and T_{eff} denote the standard quantities (see Sect. 3). Together with the Q values, the $P_{\text{pul}}/P_{\text{orb}}$ ratios were also calculated and all of these values are listed in Table 6. We note that the quantity P_{pul}

Fig. 16. Periodogram for KIC 06669809. The independent frequencies, the strong frequencies that are connected to the P_{orb} , and the significance level are also indicated.

Fig. 17. Same as Fig. 16, but for KIC 10581918.

refers to the dominant pulsation mode (i.e. the frequency with the highest amplitude). Firstly, according to [Zhang et al. \(2013\)](#) if $P_{\text{pul}}/P_{\text{orb}}$ of a frequency is less than 0.07, then this frequency potentially belongs to the p -mode region. For all independent frequencies it was found that their $P_{\text{pul}}/P_{\text{orb}}$ ratios are indeed smaller than this value. Secondly, the Q of each frequency was compared with the theoretical models of [Fitch \(1981\)](#) for $M = 1.5 M_{\odot}$ for all stars except for the primary of KIC 105, whose Q values were compared with the models for $M = 2 M_{\odot}$. The l -degrees and the type of each oscillation frequency are listed in Table 6. All stars were found to pulsate in non-radial p -modes, except for the primary of KIC 106, which pulsates in both radial and non-radial modes. In addition, for the latter, the ratio f_2/f_1 is ~ 0.75 , that is the typical ratio for the radial fundamental to the first overtone mode ([Stellingwerf 1979](#); [Ooster et al. 2006](#)), and this can be an alternative explanation for its first two pulsating modes. Finally, the range of Q errors also allow other possible mode determinations, but the closest to the mean values were finally chosen.

The frequency search results of all stars show that the dominant independent pulsations occur in frequency ranges that are typical for the δ Sct type stars. Therefore, and in combination with the spectroscopic results regarding their spectral types (Sect. 2), they can be plausibly considered to be of this type of pulsators. However, the distributions of their frequencies in the periodograms (Figs. 16–19), i.e. existence of slow ($< 5 \text{ cycle d}^{-1}$) and fast pulsations, may reveal the possibility of potential δ Sct- γ Dor hybrid behaviour. This issue is discussed in the last section.

5. Discussion and conclusions

In this paper, detailed LCs and frequency analyses for four *Kepler* EBs were presented. Spectroscopic observations of the

Fig. 18. Same as Fig. 16, but for KIC 10619109.

Fig. 19. Same as Fig. 16, but for KIC 11175495.

systems permitted the estimation of the spectral types of their primaries with an error of half subclass. The absolute parameters of the components of the systems and their evolutionary stages were also estimated, while the pulsational characteristics of their primaries were determined.

All systems were found to be in a conventional semi-detached configuration, with their less massive components filling their Roche lobes; therefore, these systems can be categorized as classical Algol-type stars regarding their evolutionary status. The positions of the components of the systems in the mass-radius (M-R) and Hertzsprung-Russell (H-R) evolutionary diagrams are given in Figs. 20 and 21, respectively. Zero and terminal age (ZAMS and TAMS, respectively) main-sequence lines (for solar metallicity composition, i.e. $Z = 0.019$) for these diagrams were taken from [Girardi et al. \(2000\)](#), while the positions of the other δ Scuti stars of oEA systems were taken from [Liakos & Niarchos \(2017\)](#). The secondaries of all systems have left the main sequence and they are in the subgiant evolutionary phase. Moreover, these components were found to be magnetically active, in that their spots migrated in both latitude and longitude and, in addition, they changed radii in only ~ 30 days. On the other hand, all primaries, except for that of KIC 111, are well inside the main-sequence boundaries. In particular, the primaries of KIC 066 and KIC 105 are closer to the ZAMS, while that of KIC 106 is approximately in the middle of main-sequence band. The primary of KIC 111 was found to evolve slightly before ZAMS and it is currently the youngest of all other stars of the same type.

Although none of the systems exhibit total eclipses, which can be potentially used for the determination of the pulsating component (i.e. occurrence/absence of pulsations during the flat-phase part of the total eclipse), the primaries of all systems are A–F type stars according to the present spectral classification; thus, they fit better to a profile of a δ Scuti star in comparison with the secondaries, which are much cooler. Therefore, it

Fig. 20. Location of the primary (filled symbols) and secondary (empty symbols) components of KIC 06669809 (square), KIC 10581918 (circle), KIC 10619109 (triangle), and KIC 11175495 (diamond) within the mass-radius diagram. Crosses denote the δ Sct components of other oEA stars, while the solid lines the boundaries of main sequence.

Fig. 21. Location of the components of all studied systems within the H-R diagram. Symbols and lines have the same meaning as in Fig. 20.

is plausibly concluded that, in combination with the previous results for their evolutionary stages, all systems can be considered by definition as oEA stars. Three independent p -mode frequencies in the range $23\text{--}38\text{ cycle d}^{-1}$ were found for the primary of KIC 066 with the dominant at $35.283\text{ cycle d}^{-1}$ and an amplitude of $\sim 0.83\text{ mmag}$, while the primary of KIC 105 pulsates in two main non-radial pressure modes in the range $34\text{--}36.5\text{ cycle d}^{-1}$. The main component of KIC 106 exhibits five independent oscillation frequencies, where the dominant frequency (42.8 cycle d^{-1}) is radial mode and the other four are non radial p -modes. The primary of KIC 111 was also found to oscillate in three frequencies in the range $56\text{--}65\text{ cycle d}^{-1}$ and it is the fastest pulsator in binary systems that has ever been found (cf. Liakos & Niarchos 2017).

A direct comparison between the pulsators of these systems and the δ Scuti components of other oEA stars is presented in the $P_{\text{orb}} - P_{\text{pul}}$ diagram (Fig. 22). Although the present analysis for these systems is much more detailed than the preliminary analysis of Liakos & Niarchos (2017), the new derived dominant frequencies are close enough to the previous values. Therefore, and given that these systems are the $\sim 6\%$ of the total available sample of oEA stars with δ Scuti component, the current correlation (Liakos & Niarchos 2017, Eq. (1)) remains as it is. The primary of KIC 066 is among the first five oEA stars with the shortest P_{orb} values and is very close to the empirical fit. The pulsators of KIC 105 and KIC 106 follow well the empirical fit and the distribution of the other stars. On the other hand, the δ Scuti component of KIC 111 is the fastest pulsator of the sample but is also one of the cases that deviates most from the fit. However,

Fig. 22. Location of the pulsating components of all studied systems among other δ Sct stars (crosses) of oEA systems within the $P_{\text{orb}} - P_{\text{pul}}$ diagram. The dashed line represents the empirical relation for oEA stars of Liakos & Niarchos (2017). Symbols have the same meaning as in Fig. 20.

Fig. 23. Location of the pulsating components of all studied systems within the $\log g - P_{\text{pul}}$ diagram. Symbols have the same meaning as in Fig. 20 and the line denotes the present empirical correlation for oEA stars with a δ Sct component.

the latter cannot characterize it as an extreme case since, as mentioned by Liakos & Niarchos (2017), there is a large scatter between $1.2\text{ d} < P_{\text{orb}} < 2.6\text{ d}$ (i.e. $0.08 < \log P_{\text{orb}} < 0.42$) and $6.4\text{ cycle d}^{-1} < f_{\text{dom}} < 64.5\text{ cycle d}^{-1}$ (i.e. $-1.81 < \log P_{\text{pul}} < -0.81$) for unknown reasons so far.

In Fig. 23 the locations of the primaries of the studied systems and other of oEA stars within the $\log g - \log P_{\text{pul}}$ diagram are also shown. Contrary to the previous empirical fit, in this case the contribution of the systems to a new empirical relation between $\log g - \log P_{\text{pul}}$ is very significant. The previous fit (Liakos & Niarchos 2017, Eq. (7)) included all the known systems with a δ Scuti component, whose absolute parameters are known, regardless their Roche geometry. In the present study and for the following empirical correlation, only the oEA stars are taken into account. The four studied systems consist of the $\sim 7\%$ of the whole sample of oEA stars (56 in total) and they contribute for the first time in this fit with updated and more accurate absolute parameters (Table 4). Therefore, the new empirical correlation between $\log g - \log P_{\text{pul}}$ for the semi-detached EBs with a δ Scuti component (i.e. oEA stars) is the following:

$$\log g = 3.5(1) - 0.40(9) \log P_{\text{pul}} \quad (2)$$

and is represented in Fig. 23 as well. In this case, all the studied stars are relatively close enough to the empirical fit. This diagram also shows that the δ Scuti member of KIC 111 is the youngest of the sample, while the remaining three cases are among the 20 youngest stars of this type.

Possible hybrid δ Sct- γ Dor scenarios may arise because of the frequency distributions of all of the systems. It is clear from Figs. 16–19 that there are bands of frequencies of high and low values. In order to decide whether a star presents a hybrid behaviour, the criteria proposed by Uytterhoeven et al. (2011) should be checked. According to that work, the δ Sct- γ Dor hybrids have to fulfil the following: (a) present frequencies in both δ Sct and γ Dor domains, (b) the amplitudes in the two domains must be either comparable or the amplitudes should not differ by more than a factor of 5–7, and (c) at least two independent frequencies are detected in both regimes with amplitudes higher than 100 ppm. For all systems except for KIC 111, no independent pulsation frequencies were detected in the γ -Dor regime, thus the hybrid scenario can be directly rejected for these three EBs. On the other hand, for KIC 111 two separate concentrations of frequencies exist (Fig. 19): one in the δ Sct frequency range and another in the γ Dor region (i.e. <5 cycle d^{-1}). The first frequency found in the latter region is the $f_6 = 0.8668$ cycle d^{-1} . In this case, the first and second criteria are indeed satisfied, i.e. there are many frequencies in both regions and the amplitude of f_6 (0.59 mmag) is ~ 5.3 times less than the amplitude of f_1 . Regarding the third criterion, no other independent frequencies exist in the γ Dor region. However, if we compare the f_6 with the second harmonic of the orbital frequency ($2f_{\text{orb}} = 0.9128$ cycle d^{-1}), they only differ by 0.046 cycle d^{-1} , where the frequency resolution for this sample is 0.049 cycle d^{-1} . Therefore, it can be plausibly assumed that f_6 is probably the $2f_{\text{orb}}$. Moreover, another possible reason for declining f_6 as a true γ Dor frequency is its $P_{\text{pul}}/P_{\text{orb}}$ ratio, which has a value 0.526. By comparing this value with other values of known hybrids (e.g. Zhang et al. 2013), it could be seen that it is outside their $P_{\text{pul}}/P_{\text{orb}}$ ratio range. Therefore, it is concluded that f_6 is probably the second harmonic of f_{orb} instead of an independent frequency and that the pulsator of KIC 111 is not a hybrid δ Sct- γ Dor star.

The ETV analysis for KIC 066 by Borkovits et al. (2016) suggested the presence of a third body with a minimum mass of $m_{3,\text{min}} \sim 0.32 M_{\odot}$, based on the assumption that the total mass of the binary is $2 M_{\odot}$. For reasons of completeness, the $m_{3,\text{min}}$ value is recalculated according to the currently derived mass values (Table 4) and the formula of the mass function of a third body (Mayer 1990) is written as

$$f(m_3) = \frac{(m_3 \sin i_3)^3}{(m_1 + m_2 + m_3)^2}, \quad (3)$$

where m are the masses of the components and i_3 is the inclination of the orbit of the tertiary body. For $i_3 = 90^\circ$ the orbits of the EB and the third body are coplanar and the minimum mass of the third component $m_{3,\text{min}}$ can be derived. The above calculation results in $m_{3,\text{min}} \sim 0.34 M_{\odot}$. Assuming that the potential third body is a main-sequence star and by following the formalism of Liakos et al. (2011), the luminosity contribution to the total light, using the INPEVEB software (Liakos 2015), is found to be $\sim 0.25\%$. Therefore, the absence of a third light in the LC solution seems very reasonable. For KIC 105 the orbital period analyses of Wolf et al. (2015) and Zasche et al. (2015) resulted in a cyclic modulation of the P_{orb} with a period of ~ 14 yr, which was attributed as presence of a third companion with a mass function of $f(m_3) = 0.00027(9) M_{\odot}$. Following the same method as in the previous case, a minimum mass of $m_{3,\text{min}} \sim 0.1 M_{\odot}$ and a luminosity contribution of less than 0.05% are derived. Therefore, also in this case, the light of the potential third body is too weak to be detected either spectroscopically or photometrically.

Both systems host magnetically active components, therefore the Applegate mechanism (Applegate 1992) has to be tested as a potential orbital period modulator. The quadrupole moment variation ΔQ is calculated based on the formula of Lanza & Rodonò (2002) via the INPEVEB software (Liakos 2015),

$$\Delta Q = -\frac{1}{9} \frac{\Delta P_{\text{orb}}}{P_{\text{orb}}} M a^2, \quad (4)$$

where ΔP_{orb} is the period of the variation of P_{orb} , M the mass of the star, and a the semi-major axis of the orbit. The ΔQ values are found to be less than 10^{51} g cm^2 for both systems, thus, according to the criterion of Lanza & Rodonò (2002), the magnetic activity cannot stand as possible explanation for the cyclic changes of their orbital periods. However, the amplitudes of the periodic terms of the ETV fitting functions are very small (~ 0.0014 d and ~ 0.0021 d for KIC 066 and KIC 105, respectively) and given that the secondary components are magnetically active stars, these cyclic variations of the P_{orb} could be caused by the visibility of the spot (Kalimeris et al. 2002; Tran et al. 2013). It seems that the ETV diagrams of KIC 106 and KIC 111 (Conroy et al. 2014; Gies et al. 2015) cannot provide any other useful information for the systems thus far, except for some irregularities that are probably due to the presence of pulsations and spots.

Regarding any future studies on these systems, it could be mentioned that RV measurements will certify or modify the values of the absolute parameters. To accomplish this, high-resolution spectrographs in telescopes with diameters of more than ~ 2 m for KIC 066 and more than ~ 4 m for the remaining three systems are needed to detect signals from both components, given that the primaries dominate (more than 84%) the spectra especially in bluer wavelength bands. In any case, the pulsation models, which were the objectives of this study, are not expected to be dramatically changed. Follow-up observations for minima timings are also welcome because many years from now they may offer the opportunity to study the ETV diagrams for any possible orbital period modulating mechanisms in detail. In general, detailed LCs and pulsation analyses of other *Kepler* oEA stars are highly recommended, since the sample of these systems is still very small but at the same time it is very promising in regards to our knowledge of pulsations in binary systems.

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Appendix A: Lists of combined frequencies

Tables A.1–A.4 contain the values f_i (where i is an increasing number), semi-amplitudes A , phases Φ , S/N, and the

combinations of the depended frequencies of the systems. Details can be found in Sect. 4.

Table A.1. Combined frequencies of KIC 06669809.

i	f_i (cycle d ⁻¹)	A (mmag)	Φ (°)	S/N	Combination	i	f_i (cycle d ⁻¹)	A (mmag)	Φ (°)	S/N	Combination
1	2.72399(4)	1.529(3)	280.7(1)	188.6	$2f_{\text{orb}}$	76	24.54653(77)	0.078(3)	101.7(2.5)	9.6	$2f_{62}$
4	37.98941(10)	0.605(3)	122.8(3)	74.6	$f_1 + f_2$	77	24.45155(76)	0.079(3)	119.7(2.5)	9.7	$f_{11} - f_1$
5	6.80998(10)	0.578(3)	345.4(3)	71.3	$5f_{\text{orb}}$	78	24.85403(78)	0.077(3)	87.8(2.5)	9.5	$f_{63} + f_7$
6	1.36683(11)	0.548(3)	258.8(4)	67.6	$f_5 - 2f_1 (\sim f_{\text{orb}})$	79	1.48918(78)	0.076(3)	137.9(2.5)	9.4	$f_{12} - f_{31}$
7	5.44799(11)	0.537(3)	53.3(4)	66.2	$2f_1 (\sim 4f_{\text{orb}})$	80	29.79167(79)	0.076(3)	233.5(2.6)	9.3	$\sim f_{47}$
9	32.56879(14)	0.438(3)	123.3(4)	54.1	$f_2 - f_1$	81	31.50785(79)	0.076(3)	85.4(2.5)	9.3	$f_9 - f_{73}$
10	29.99935(16)	0.373(3)	203.4(5)	46.1	$2f_5 + 3f_7$	82	30.56443(80)	0.075(3)	101.0(2.6)	9.3	$f_{21} + f_{79}$
11	27.19164(19)	0.310(3)	268.9(6)	38.2	$4f_5$	83	40.39625(80)	0.075(3)	198.5(2.6)	9.2	$f_{25} - f_1$
12	35.05613(20)	0.302(3)	271.5(6)	37.3	$2f_{10} - f_3 - f_6$	84	18.56727(82)	0.073(3)	116.4(2.6)	9	$f_{45} - f_7$
13	29.44715(21)	0.291(3)	34.9(7)	35.9	$2f_{12} - f_1 - f_4$	85	32.60099(83)	0.072(3)	88.5(2.7)	8.9	$\sim f_9$
14	35.28151(24)	0.245(3)	100.9(8)	30.2	$\sim f_2$	86	28.00787(83)	0.072(3)	72.6(2.7)	8.9	$f_{27} - f_{61}$
15	35.34108(25)	0.242(3)	132.2(8)	29.9	$f_1 + f_9$	87	1.31370(85)	0.071(3)	273.4(2.7)	8.7	$\sim f_{18}$
16	35.22517(24)	0.252(3)	125.4(8)	31.1	$f_4 - f_1$	88	14.41849(85)	0.071(3)	200.0(2.7)	8.7	$f_4 - f_3$
17	28.37654(25)	0.236(3)	5.8(8)	29.1	$f_{16} - f_5$	89	25.66704(86)	0.070(3)	212.5(2.8)	8.6	$f_{17} - f_1$
18	1.36039(28)	0.217(3)	82.2(9)	26.8	$\sim f_6 (\sim f_{\text{orb}})$	90	22.86094(86)	0.070(3)	88.4(2.8)	8.6	$f_{71} - f_1$
19	2.75136(28)	0.217(3)	30.6(9)	26.8	$\sim f_1 (\sim 2f_{\text{orb}})$	91	23.03803(82)	0.073(3)	146.5(2.6)	9	$f_{44} - f_1$
20	39.39326(28)	0.210(3)	125.3(9)	25.9	$f_4 + f_6$	92	19.98239(85)	0.070(3)	51.7(2.8)	8.7	$f_{51} - f_1$
21	29.08974(29)	0.205(3)	261.9(9)	25.3	$f_8 - f_1 - f_5$	93	39.31599(86)	0.069(3)	123.0(2.8)	8.6	$f_4 + f_6$
22	35.83855(30)	0.199(3)	31.8(1.0)	24.6	$f_8 - f_{19}$	94	38.60762(89)	0.067(3)	151.7(2.9)	8.3	$\sim f_8$
23	13.63285(32)	0.187(3)	345.4(1.0)	23.1	$2f_5$	95	31.02970(89)	0.067(3)	77.1(2.9)	8.3	$f_{67} - f_5$
24	25.89887(34)	0.177(3)	0.9(1.1)	21.8	$f_1 + f_{10} - f_5$	96	38.02000(90)	0.067(3)	63.9(2.9)	8.2	$\sim f_4$
25	43.12346(36)	0.164(3)	240.0(1.2)	20.3	$f_{13} + f_{23}$	97	40.88406(90)	0.067(3)	263.2(2.9)	8.2	$f_{39} - f_1$
26	8.18325(37)	0.163(3)	53.2(1.2)	20.2	$f_1 + f_7$	98	23.80275(91)	0.066(3)	24.1(2.9)	8.1	$f_{55} + f_7$
27	32.09547(38)	0.158(3)	334.6(1.2)	19.5	$f_3 + f_4 - f_{13}$	99	29.25717(86)	0.069(3)	104.7(2.8)	8.6	$f_{35} + f_6$
28	27.15783(39)	0.154(3)	168.9(1.2)	19.1	$\sim f_{11}$	100	24.34046(91)	0.066(3)	38.3(2.9)	8.2	$f_4 - f_{23}$
29	41.34127(39)	0.152(3)	348.3(1.3)	18.8	$f_1 + f_8$	101	35.98183(94)	0.064(3)	215.1(3.0)	7.9	$f_{64} + f_7$
30	19.87614(40)	0.151(3)	113.6(1.3)	18.6	$f_{13} - f_1 - f_5$	102	11.28880(94)	0.064(3)	184.0(3.0)	7.8	$f_2 - f_{45}$
31	33.60880(40)	0.150(3)	11.5(1.3)	18.5	$f_{25} - f_1 - f_5$	103	34.26565(94)	0.063(3)	4.1(3.0)	7.8	$f_1 + f_{81}$
32	16.35684(40)	0.150(3)	226.4(1.3)	18.4	$2f_{26}$	104	1.15110(96)	0.062(3)	265.6(3.1)	7.7	$f_1 - f_{60}$
33	18.92306(41)	0.144(3)	20.8(1.3)	17.8	$f_2 - f_{32}$	105	42.46017(97)	0.061(3)	115.1(3.1)	7.6	$f_3 + f_{33}$
34	33.08719(42)	0.143(3)	16.4(1.3)	17.7	$f_{22} - f_1$	106	59.96972(97)	0.061(3)	247.1(3.1)	7.6	$2f_{10}$
35	27.89357(42)	0.142(3)	49.6(1.4)	17.5	$f_3 + f_4 - f_{31}$	107	19.57025(99)	0.061(3)	324.5(3.2)	7.5	$f_{25} - f_3$
36	17.68664(43)	0.138(3)	100.9(1.4)	17.1	$f_{32} + f_6$	108	16.15721(99)	0.060(3)	352.9(3.2)	7.4	$f_{33} - f_1$
37	22.97203(43)	0.138(3)	291.2(1.4)	17.1	$f_{17} - f_7$	109	38.31944(99)	0.060(3)	253.7(3.2)	7.4	$f_5 + f_{81}$
38	18.99390(43)	0.138(3)	21.9(1.4)	17.0	$f_{11} - f_{26}$	110	1.70008(100)	0.060(3)	207.3(3.2)	7.4	$\sim f_{46}$
39	43.61771(45)	0.133(3)	30.3(1.5)	16.4	$f_{10} + f_{23}$	111	21.49250(100)	0.060(3)	120.4(3.2)	7.4	$f_{90} - f_6$
40	24.10058(45)	0.132(3)	247.7(1.5)	16.3	$f_{25} - f_{38}$	112	0.96274(100)	0.060(3)	273.9(3.2)	7.4	$f_{76} - f_3$
41	24.90716(48)	0.126(3)	125.0(1.5)	15.5	$f_3 + f_6$	113	6.48317(100)	0.060(3)	52.9(3.2)	7.4	$f_{10} - f_3$
42	20.24159(49)	0.123(3)	92.1(1.6)	15.1	$f_{37} - f_1$	114	26.63300(101)	0.059(3)	68.2(3.3)	7.3	$f_{27} - f_7$
43	20.81956(49)	0.122(3)	95.0(1.6)	15.0	$f_3 - f_1$	115	47.14345(103)	0.058(3)	49.7(3.3)	7.2	$f_{13} + f_{36}$
44	25.77008(51)	0.118(3)	329.8(1.6)	14.6	$f_9 - f_5$	116	6.79710(104)	0.058(3)	255.5(3.4)	7.1	$\sim f_5$
45	24.03136(52)	0.115(3)	21.8(1.7)	14.2	$f_{13} - f_7$	117	32.19690(104)	0.057(3)	41.9(3.4)	7.1	$\sim f_{56}$
46	1.66788(53)	0.113(3)	160.1(1.7)	14.0	$f_2 - f_{31}$	118	33.20310(105)	0.057(3)	47.8(3.4)	7	$f_8 - f_7$
47	29.82709(53)	0.112(3)	153.5(1.7)	13.8	$f_9 - f_1$	119	39.12602(105)	0.057(3)	93.7(3.4)	7	$2f_{107}$
48	37.95882(55)	0.109(3)	141.1(1.8)	13.5	$\sim f_4$	120	31.24865(106)	0.056(3)	134.9(3.4)	6.9	$f_9 - f_6$
49	41.79205(56)	0.108(3)	267.0(1.8)	13.3	$f_{25} - f_6$	121	33.93562(106)	0.056(3)	23.2(3.4)	6.9	$f_2 - f_6$
50	19.71193(57)	0.106(3)	83.4(1.8)	13.0	$f_8 - f_{33}$	122	12.64274(106)	0.056(3)	121.7(3.4)	7	$f_{63} - f_5$
51	22.70961(59)	0.102(3)	255.3(1.9)	12.6	$f_{40} - f_6$	123	13.62641(105)	0.057(3)	17.8(3.4)	7	$\sim f_{23}$
52	35.89812(60)	0.100(3)	321.1(1.9)	12.4	$f_8 - f_1$	124	21.79678(99)	0.061(3)	249.5(3.2)	7.5	$f_{76} - f_1$
53	38.09727(61)	0.099(3)	286.9(2.0)	12.2	$f_1 + f_{15}$	125	18.60913(106)	0.056(3)	117.9(3.4)	7	$\sim f_{84}$
54	0.03703(62)	0.096(3)	36.5(2.0)	11.9	$f_{19} - f_1$	126	25.53342(107)	0.056(3)	185.3(3.4)	6.9	$\sim f_{71}$
55	18.33866(63)	0.096(3)	87.7(2.0)	11.8	$f_{50} - f_6$	127	25.12611(108)	0.056(3)	120.9(3.5)	6.8	$f_{35} - f_1$
56	32.17436(64)	0.094(3)	98.3(2.1)	11.6	$f_1 + f_{13}$	128	1.85946(108)	0.055(3)	85.0(3.5)	6.8	$f_{21} - f_{11}$
57	40.72145(64)	0.094(3)	147.4(2.1)	11.5	$f_1 + f_4$	129	47.98866(109)	0.055(3)	40.5(3.5)	6.8	$f_3 + f_{77}$
58	17.42583(65)	0.093(3)	332.4(2.1)	11.4	$f_1 + f_{17} - f_{23}$	130	5.37232(109)	0.055(3)	106.3(3.5)	6.8	$2f_{72}$
59	32.70724(65)	0.092(3)	72.7(2.1)	11.3	$2f_{32}$	131	41.97397(110)	0.055(3)	100.0(3.5)	6.7	$f_{17} + f_{23}$
60	1.55036(67)	0.090(3)	208.9(2.2)	11.1	$f_{13} - f_{35}$	133	18.14708(110)	0.055(3)	116.1(3.5)	6.7	$f_4 - f_{30}$
61	4.11658(67)	0.089(3)	244.8(2.2)	11.0	$f_5 - f_1$	134	16.61926(112)	0.053(3)	322.8(3.6)	6.6	$f_{16} - f_{84}$
62	12.26763(68)	0.088(3)	238.4(2.2)	10.9	$f_5 + f_7$	135	4.36934(113)	0.053(3)	171.6(3.6)	6.6	$f_1 + f_{46}$
63	19.44790(71)	0.084(3)	146.3(2.3)	10.3	$f_{41} - f_7$	136	4.18420(110)	0.054(3)	193.1(3.5)	6.7	$f_1 + f_{79}$
64	30.49843(73)	0.082(3)	269.7(2.4)	10.1	$f_{21} + f_6$	137	20.44605(113)	0.053(3)	249.6(3.6)	6.5	$f_1 + f_{36}$

Notes. The errors are given in parentheses alongside values and correspond to the last digit(s).

Table A.1. continued.

<i>i</i>	<i>f_i</i> (cycle d ⁻¹)	<i>A</i> (mmag)	Φ (°)	<i>S/N</i>	Combination	<i>i</i>	<i>f_i</i> (cycle d ⁻¹)	<i>A</i> (mmag)	Φ (°)	<i>S/N</i>	Combination
65	30.45818(73)	0.082(3)	189.0(2.4)	10.1	$\sim f_{64}$	138	25.62196(114)	0.053(3)	142.9(3.7)	6.5	$\sim f_{89}$
66	33.69574(73)	0.082(3)	222.9(2.3)	10.1	$f_{12} - f_6$	139	13.75359(115)	0.052(3)	96.1(3.7)	6.4	$f_8 - f_{41}$
67	37.84452(73)	0.082(3)	62.8(2.4)	10.1	$2f_{33}$	140	32.01498(115)	0.052(3)	208.6(3.7)	6.4	$f_1 + f_{99}$
68	14.26394(74)	0.081(3)	111.8(2.4)	9.9	$f_{50} - f_7$	141	21.65511(115)	0.052(3)	272.3(3.7)	6.4	$f_1 + f_{33}$
69	24.16176(74)	0.081(3)	324.4(2.4)	9.9	$f_{25} - f_{33}$	142	2.86889(113)	0.053(3)	46.0(3.6)	6.5	$f_1 - f_{28}$
70	15.78854(74)	0.081(3)	77.7(2.4)	9.9	$f_2 - f_{63}$	143	3.00895(114)	0.053(3)	85.8(3.7)	6.5	$2f_{79}$
71	25.57205(75)	0.080(3)	324.4(2.4)	9.9	$f_6 + f_{69}$	144	43.32792(116)	0.052(3)	101.9(3.7)	6.4	$2f_{41}$
72	2.67087(75)	0.080(3)	184.6(2.4)	9.8	$f_4 - f_2$	145	50.63859(116)	0.051(3)	30.1(3.7)	6.4	$f_{122} + f_4$
73	1.02069(75)	0.079(3)	321.9(2.4)	9.8	$f_1 - f_{46}$	146	19.48815(117)	0.051(3)	146.8(3.8)	6.3	$\sim f_{63}$
74	35.42963(76)	0.079(3)	311.1(2.5)	9.7	$f_{10} + f_7$	147	16.73195(114)	0.053(3)	96.3(3.7)	6.5	$f_3 - f_5$
75	34.59569(77)	0.078(3)	90.9(2.5)	9.6	$f_{34} + f_{60}$	148	17.39524(115)	0.052(3)	61.1(3.7)	6.4	$\sim f_{58}$
149	34.32039(117)	0.051(3)	89.0(3.8)	6.3	$f_2 - f_{112}$	203	36.28289(146)	0.041(3)	116.4(4.7)	5.1	$2f_{133}$
150	32.45127(118)	0.051(3)	7.6(3.8)	6.3	$f_{16} - f_{19}$	204	22.06242(146)	0.041(3)	33.6(4.7)	5.0	$f_3 - f_{79}$
151	2.12832(119)	0.050(3)	11.8(3.8)	6.2	$f_4 - f_{22}$	205	5.63152(147)	0.041(3)	46.8(4.7)	5.0	$f_{12} - f_{13}$
152	2.17340(118)	0.051(3)	56.5(3.8)	6.3	$\sim f_{151}$	206	13.29798(148)	0.040(3)	152.1(4.8)	5.0	$f_{113} + f_5$
153	45.45785(120)	0.050(3)	21.9(3.9)	6.2	$2f_{51}$	207	2.22814(147)	0.041(3)	110.5(4.8)	5.0	$f_2 - f_{34}$
154	43.52111(120)	0.050(3)	260.9(3.9)	6.2	$f_{53} + f_7$	208	37.09590(150)	0.040(3)	357.2(4.9)	4.9	$2f_{84}$
155	26.06147(120)	0.050(3)	148.7(3.9)	6.2	$f_{81} - f_7$	209	28.74361(151)	0.040(3)	228.6(4.9)	4.9	$f_{81} - f_1$
156	3.44363(120)	0.050(3)	282.4(3.9)	6.2	$2f_{110}$	210	3.60301(151)	0.040(3)	35.4(4.9)	4.9	$f_{11} - f_3$
157	37.27460(122)	0.049(3)	320.5(3.9)	6.1	$f_8 - f_6$	211	44.05883(152)	0.039(3)	74.5(4.9)	4.9	$f_7 + f_8$
158	57.50331(122)	0.049(3)	166.8(3.9)	6.0	$f_{33} + f_8$	212	19.09854(153)	0.039(3)	253.0(4.9)	4.8	$f_1 + f_{32}$
159	4.64141(122)	0.049(3)	131.1(3.9)	6.0	$f_3 - f_{33}$	213	22.94627(153)	0.039(3)	133.5(4.9)	4.8	$\sim f_{37}$
160	4.74606(122)	0.049(3)	283.8(3.9)	6.1	$f_2 - f_{64}$	214	4.39993(154)	0.039(3)	78.3(5.0)	4.8	$\sim f_{135}$
161	4.69293(120)	0.050(3)	160.7(3.9)	6.1	$f_2 - f_{82}$	215	11.69933(156)	0.038(3)	164.4(5.0)	4.7	$f_2 - f_3$
162	12.91804(122)	0.049(3)	162.6(3.9)	6.0	$2f_{113}$	216	28.33147(156)	0.038(3)	211.1(5.0)	4.7	$\sim f_{17}$
163	23.14751(124)	0.048(3)	174.4(4.0)	6.0	$f_{24} - f_1$	217	47.60227(156)	0.038(3)	309.9(5.0)	4.7	$2f_{98}$
164	23.53711(125)	0.048(3)	1.8(4.0)	5.9	$\sim f_3$	218	7.23178(157)	0.038(3)	178.1(5.1)	4.7	$2f_{210}$
165	17.51438(127)	0.047(3)	5.7(4.1)	5.8	$f_{42} - f_1$	219	19.03254(159)	0.038(3)	190.9(5.1)	4.7	$\sim f_{38}$
166	30.26821(127)	0.047(3)	66.5(4.1)	5.8	$f_7 + f_{78}$	220	42.10599(159)	0.038(3)	225.9(5.1)	4.6	$f_2 + f_5$
167	29.66931(127)	0.047(3)	123.5(4.1)	5.8	$f_5 + f_{90}$	221	25.47707(160)	0.037(3)	227.4(5.2)	4.6	$f_1 + f_{51}$
168	44.52571(128)	0.047(3)	315.7(4.1)	5.8	$f_1 + f_{49}$	222	2.30863(163)	0.037(3)	104.4(5.3)	4.5	$2f_{104}$
169	17.62546(128)	0.047(3)	105.7(4.1)	5.8	$f_2 - f_{36}$	223	24.40969(163)	0.037(3)	152.6(5.3)	4.5	$\sim f_{77}$
170	5.00687(128)	0.047(3)	259.9(4.1)	5.8	$f_8 - f_{31}$	224	12.54454(165)	0.036(3)	304.0(5.3)	4.5	$f_2 - f_{51}$
171	40.77297(128)	0.047(3)	189.4(4.1)	5.8	$f_2 + f_7$	225	25.04400(166)	0.036(3)	95.2(5.3)	4.5	$2f_{224}$
172	26.72315(129)	0.047(3)	105.8(4.1)	5.7	$f_{13} - f_1$	226	29.76108(165)	0.036(3)	307.3(5.3)	4.5	$\sim f_{80}$
173	30.19737(129)	0.047(3)	10.3(4.2)	5.7	$f_{11} + f_{143}$	227	13.47508(165)	0.036(3)	255.9(5.3)	4.5	$f_{108} - f_1$
174	1.39903(129)	0.046(3)	202.5(4.2)	5.7	$\sim f_6$	228	32.23715(165)	0.036(3)	45.3(5.3)	4.5	$\sim f_{117}$
175	31.33559(129)	0.046(3)	327.7(4.2)	5.7	$f_{10} + f_6$	229	33.65871(166)	0.036(3)	79.5(5.4)	4.4	$\sim f_{69}$
176	16.99759(132)	0.045(3)	190.9(4.3)	5.6	$f_{50} - f_1$	230	36.91237(167)	0.036(3)	233.8(5.4)	4.4	$f_2 + f_{46}$
177	40.07426(133)	0.045(3)	181.8(4.3)	5.5	$f_7 + f_{75}$	231	39.48181(168)	0.036(3)	19.4(5.4)	4.4	$f_{53} + f_6$
178	30.60629(134)	0.045(3)	343.8(4.3)	5.5	$\sim f_{82}$	232	4.83300(169)	0.035(3)	125.2(5.4)	4.4	$f_{17} - f_3$
179	3.48871(135)	0.044(3)	68.3(4.3)	5.5	$\sim f_{156}$	233	4.58990(164)	0.037(3)	44.7(5.3)	4.5	$2f_{222}$
180	29.41495(135)	0.044(3)	160.9(4.4)	5.5	$\sim f_{13}$	234	35.53588(170)	0.035(3)	350.8(5.5)	4.3	$f_{143} + f_9$
181	34.81625(133)	0.045(3)	330.3(4.3)	5.6	$2f_{58}$	235	26.21602(170)	0.035(3)	54.8(5.5)	4.3	$f_1 + f_{164}$
182	5.18879(136)	0.044(3)	281.1(4.4)	5.4	$f_{16} - f_{10}$	236	8.17198(170)	0.035(3)	74.5(5.5)	4.3	$\sim f_{26}$
183	38.46273(136)	0.044(3)	349.4(4.4)	5.4	$f_{102} + f_{11}$	237	48.65195(170)	0.035(3)	150.7(5.5)	4.3	$2f_{100}$
184	40.49284(136)	0.044(3)	359.1(4.4)	5.4	$2f_{42}$	238	52.42561(170)	0.035(3)	100.8(5.5)	4.3	$2f_{235}$
185	65.41932(136)	0.044(3)	182.7(4.4)	5.4	$2f_{59}$	239	6.09840(169)	0.035(3)	309.6(5.5)	4.4	$f_{29} - f_2$
186	57.24090(125)	0.048(3)	30.1(4.0)	5.9	$f_{106} - f_1$	240	5.24031(171)	0.035(3)	37.5(5.5)	4.3	$f_2 - f_{10}$
187	68.14492(135)	0.044(3)	59.5(4.4)	5.5	$f_1 + f_{185}$	241	51.50634(171)	0.035(3)	248.9(5.5)	4.3	$2f_{44}$
188	41.37830(137)	0.044(3)	257.0(4.4)	5.4	$\sim f_{29}$	242	15.93343(174)	0.034(3)	286.6(5.6)	4.2	$f_{125} - f_1$
189	23.71098(138)	0.044(3)	234.8(4.4)	5.4	$f_4 - f_{68}$	243	5.11956(174)	0.034(3)	28.0(5.6)	4.2	$f_{25} - f_4$
190	3.93466(139)	0.043(3)	53.7(4.5)	5.3	$f_7 - f_{60}$	244	9.57262(175)	0.034(3)	201.9(5.7)	4.2	$f_1 + f_5$
191	23.39544(138)	0.043(3)	239.5(4.5)	5.3	$f_{134} + f_5$	245	33.02923(176)	0.034(3)	127.2(5.7)	4.2	$f_1 + f_{166}$
192	32.34018(140)	0.043(3)	287.8(4.5)	5.3	$f_{12} - f_1$	246	13.41712(177)	0.034(3)	214.8(5.7)	4.2	$f_{108} - f_1$
193	56.82232(139)	0.043(3)	198.1(4.5)	5.3	$f_{111} + f_2$	247	20.38005(178)	0.034(3)	259.6(5.8)	4.1	$f_1 + f_{36}$
194	43.42774(141)	0.043(3)	34.4(4.5)	5.3	$f_4 + f_7$	248	21.00792(178)	0.034(3)	309.3(5.7)	4.1	$f_2 - f_{68}$
195	47.38171(141)	0.043(3)	177.3(4.5)	5.3	$2f_{189}$	249	31.56581(179)	0.033(3)	146.1(5.8)	4.1	$2f_{70}$
196	37.53219(141)	0.042(3)	323.6(4.5)	5.2	$f_{27} + f_7$	250	34.78566(179)	0.033(3)	215.3(5.8)	4.1	$\sim f_{181}$
197	43.12346(141)	0.042(3)	60.1(4.5)	5.2	$\sim f_{25}$	251	1.52621(180)	0.033(3)	73.8(5.8)	4.1	$\sim f_{60}$
198	17.96838(142)	0.042(3)	340.3(4.6)	5.2	$f_4 - f_{92}$	252	14.72599(181)	0.033(3)	195.1(5.8)	4.1	$f_{58} - f_1$
199	28.47797(142)	0.042(3)	218.0(4.6)	5.2	$f_2 - f_5$	253	56.35222(182)	0.033(3)	201.8(5.9)	4.1	$f_4 + f_{55}$
200	32.67505(145)	0.041(3)	195.7(4.7)	5.1	$\sim f_{59}$	254	47.79707(182)	0.033(3)	318.7(5.9)	4.0	$f_2 + f_{224}$
201	31.75256(144)	0.041(3)	236.2(4.7)	5.1	$f_{26} + f_3$	255	33.74082(183)	0.033(3)	145.6(5.9)	4.0	$\sim f_{66}$
202	21.24297(145)	0.041(3)	0.9(4.7)	5.1	$f_1 + f_{84}$						

Table A.2. Combined frequencies of KIC 10581918.

i	f_i (cycle d ⁻¹)	A (mmag)	Φ (°)	S/N	Combination	i	f_i (cycle d ⁻¹)	A (mmag)	Φ (°)	S/N	Combination
3	1.6666(1)	0.906(6)	288.2(0.4)	74.4	$3f_{\text{orb}}$	16	52.0507(3)	0.362(6)	197.3(0.9)	29.7	$2f_1 - f_5$
4	1.1111(1)	0.857(6)	89.0(0.4)	70.4	$2f_{\text{orb}}$	17	0.5366(3)	0.353(6)	193.6(1.0)	29.0	$f_3 - f_4$ ($\sim f_{\text{orb}}$)
5	39.9446(1)	0.807(6)	248.3(0.4)	66.3	$f_4 + 2f_2 - f_1$	18	37.7467(3)	0.339(6)	107.5(1.0)	27.8	$2f_1 - f_{10}$
6	2.7742(2)	0.682(6)	300.2(0.5)	56.0	$f_3 + f_4$ ($\sim 5f_{\text{orb}}$)	19	21.2481(3)	0.337(6)	137.0(1.0)	27.7	$f_1 + f_{14} - f_{11}$
7	46.0158(2)	0.600(6)	148.1(0.6)	49.2	$f_5 + f_6 + 2f_3$	20	31.6962(4)	0.307(6)	350.6(1.1)	25.2	$2f_1 - f_2$
8	29.6242(2)	0.579(6)	213.1(0.6)	47.6	$f_1 - f_3 - f_6$	21	35.0967(4)	0.289(6)	283.7(1.2)	23.7	$f_{13} + f_2 - f_1$
9	19.1709(2)	0.549(6)	229.6(0.6)	45.1	$f_6 + f_7 - f_8$	22	40.7590(4)	0.288(6)	23.5(1.2)	23.7	$f_1 + f_2 - f_{14}$
10	30.4058(2)	0.455(6)	14.8(0.7)	37.4	$f_2 + f_5 - f_7$	23	44.5666(4)	0.268(6)	288.1(1.3)	22.0	$f_1 + f_8 - f_9$
11	42.5618(3)	0.428(6)	48.6(0.8)	35.2	$f_2 + f_7 - f_5$	24	40.9298(4)	0.265(6)	314.6(1.3)	21.8	$f_{11} - f_3$
12	35.0398(3)	0.419(6)	241.4(0.8)	34.4	$2f_9 - 2f_3$	25	43.8506(4)	0.260(6)	1.3(1.3)	21.4	$f_{15} + f_5$
13	32.7383(3)	0.403(6)	45.5(0.8)	33.1	$f_{10} + f_2 - f_1$	26	0.5711(4)	0.258(6)	276.6(1.3)	21.2	$\sim f_{17}$
14	29.7795(3)	0.382(6)	137.9(0.9)	31.4	$2f_1 - 2f_9$	27	19.0968(5)	0.240(6)	187.1(1.4)	19.7	$f_5 - f_3 - f_9$
15	3.8835(3)	0.374(6)	180.1(0.9)	30.7	$f_4 + f_6$ ($\sim 7f_{\text{orb}}$)	28	1.1266(5)	0.224(6)	97.7(1.5)	18.4	$\sim f_4$ ($\sim 2f_{\text{orb}}$)
29	38.5144(5)	0.221(6)	247.0(1.5)	18.2	$2f_1 - f_8$	103	26.6016(12)	0.094(6)	232.7(3.6)	7.7	$f_{102} + f_4$
30	0.7574(5)	0.217(6)	246.8(1.6)	17.8	$f_{10} - f_8$	104	49.9494(13)	0.089(6)	342.8(3.8)	7.3	$\sim f_{45}$
31	0.5003(5)	0.206(6)	143.3(1.7)	16.9	$\sim f_{17}$	105	3.1572(13)	0.088(6)	136.9(3.9)	7.2	$2f_{56}$
32	28.8582(6)	0.203(6)	256.8(1.7)	16.7	$f_{13} - f_{15}$	106	44.5321(13)	0.088(6)	226.5(3.9)	7.2	$\sim f_{23}$
33	3.3004(6)	0.200(6)	78.0(1.7)	16.4	$2f_3$ ($\sim 6f_{\text{orb}}$)	107	60.6200(13)	0.086(6)	219.2(3.9)	7.1	$f_{36} + f_9$
34	24.3294(6)	0.191(6)	230.5(1.8)	15.7	$2f_1 - f_{25}$	108	24.4157(13)	0.085(6)	96.8(4.0)	7.0	$f_{102} - f_4$
35	0.6090(6)	0.190(6)	335.0(1.8)	15.6	$\sim f_{26}$	109	29.5604(13)	0.085(6)	168.9(4.0)	7.0	$f_4 + f_{57}$
36	41.4629(6)	0.190(6)	200.2(1.8)	15.6	$f_{11} - f_4$	110	0.3554(13)	0.085(6)	173.3(4.0)	7.0	$\sim f_{37}$
37	0.3226(6)	0.187(6)	323.4(1.8)	15.3	$f_4 - f_{30}$	111	13.3172(13)	0.084(6)	314.9(4.0)	6.9	$f_7 - f_{13}$
38	1.2939(6)	0.184(6)	15.8(1.9)	15.1	$f_1 - f_{13}$	112	18.5861(14)	0.084(6)	204.4(4.1)	6.9	$f_9 - f_{17}$
39	28.9531(6)	0.180(6)	110.4(1.9)	14.8	$f_{20} - f_6$	113	1.4302(14)	0.083(6)	286.5(4.1)	6.8	$f_2 - f_{12}$
40	0.8264(6)	0.176(6)	169.5(1.9)	14.5	$f_{10} - f_8$	114	48.6830(14)	0.083(6)	111.6(4.1)	6.8	$2f_{34}$
41	0.0983(6)	0.175(6)	239.3(1.9)	14.4	$f_9 - f_{27}$	115	48.6295(14)	0.082(6)	327.4(4.1)	6.7	$2f_{34}$
42	1.0024(6)	0.180(6)	169.6(1.9)	14.8	$2f_{31}$	116	54.9181(14)	0.081(6)	306.0(4.2)	6.7	$2f_{70}$
43	4.9980(7)	0.170(6)	23.1(2.0)	14.0	$f_{15} + f_4$	117	49.7009(14)	0.079(6)	223.1(4.3)	6.5	$f_{46} + f_8$
44	16.0586(7)	0.167(6)	156.4(2.0)	13.8	$f_1 + f_4 - f_9$	118	53.0220(14)	0.080(6)	294.9(4.3)	6.5	$\sim f_{75}$
45	49.9217(7)	0.164(6)	237.6(2.1)	13.5	$f_{15} + f_7$	119	35.1864(14)	0.079(6)	65.3(4.3)	6.5	$f_1 + f_4$
46	20.0560(7)	0.162(6)	182.4(2.1)	13.3	$f_{27} + f_{42}$	120	42.5929(14)	0.078(6)	289.0(4.3)	6.4	$\sim f_{11}$
47	18.7207(7)	0.160(6)	91.3(2.1)	13.2	$f_5 - f_{19}$	121	4.4201(15)	0.078(6)	312.9(4.4)	6.4	$\sim f_{76}$
48	1.9996(7)	0.160(6)	304.8(2.1)	13.1	$2f_{42}$	122	46.6041(15)	0.078(6)	324.3(4.4)	6.4	$f_{25} + f_6$
49	0.2484(7)	0.159(6)	184.1(2.1)	13.1	$f_4 - f_{40}$	123	22.8751(15)	0.076(6)	24.8(4.5)	6.3	$f_{19} + f_3$
50	2.2877(7)	0.156(6)	110.6(2.2)	12.8	$2f_{28}$	124	0.7281(15)	0.076(6)	271.3(4.5)	6.2	$\sim f_{30}$
51	2.2204(8)	0.149(6)	129.6(2.3)	12.2	$2f_4$ ($\sim 4f_{\text{orb}}$)	125	39.4909(15)	0.075(6)	320.0(4.5)	6.2	$f_5 - f_{31}$
52	3.3297(8)	0.149(6)	32.5(2.3)	12.2	f_{33} ($\sim 6f_{\text{orb}}$)	126	28.8979(15)	0.074(6)	183.5(4.6)	6.1	$\sim f_{32}$
53	30.7715(8)	0.141(6)	22.6(2.4)	11.6	$f_4 + f_8$	127	1.3336(15)	0.074(6)	223.5(4.6)	6.0	$\sim f_{38}$
54	2.0737(8)	0.141(6)	255.3(2.4)	11.6	$f_{29} - f_2$	128	43.6695(16)	0.073(6)	256.9(4.7)	6.0	$f_{11} + f_4$
55	34.0219(8)	0.140(6)	322.0(2.4)	11.5	$f_{21} - f_4$	129	40.7866(16)	0.073(6)	204.4(4.7)	6.0	$\sim f_{22}$
56	1.5613(8)	0.139(6)	192.7(2.4)	11.4	$2f_{30}$	130	2.0996(16)	0.072(6)	224.7(4.7)	5.9	$\sim f_{54}$
57	28.4994(8)	0.137(6)	246.7(2.5)	11.3	$f_8 - f_4$	131	55.9273(16)	0.071(6)	45.1(4.8)	5.9	$f_{15} + f_{16}$
58	37.5707(8)	0.137(6)	35.1(2.5)	11.3	$f_2 + f_4$	132	56.5208(16)	0.072(6)	209.0(4.7)	5.9	$f_2 + f_{46}$
59	37.6225(8)	0.144(6)	88.8(2.4)	11.8	$\sim f_{58}$	133	53.1549(16)	0.071(6)	253.4(4.8)	5.8	$2f_{103}$
60	24.2777(8)	0.137(6)	285.2(2.5)	11.2	$f_{34} - f_{41}$	134	17.7614(16)	0.070(6)	119.8(4.9)	5.8	$f_2 - f_{47}$
61	17.1559(8)	0.135(6)	155.2(2.5)	11.1	$f_4 + f_{44}$	135	26.6395(16)	0.070(6)	180.6(4.8)	5.8	$\sim f_{103}$
62	2.8398(8)	0.136(6)	95.6(2.5)	11.1	$f_{28} + f_3$	136	34.2893(16)	0.070(6)	312.2(4.9)	5.7	$2f_{61}$
63	1.6304(8)	0.136(6)	90.4(2.5)	11.2	$\sim f_3$ ($\sim 3f_{\text{orb}}$)	137	32.8315(16)	0.069(6)	292.3(4.9)	5.7	$f_{20} + f_4$
64	1.0265(9)	0.133(6)	179.8(2.6)	10.9	$\sim f_{42}$	138	25.8839(16)	0.069(6)	179.8(4.9)	5.7	$f_{14} - f_{15}$
65	36.6322(9)	0.132(6)	80.9(2.6)	10.8	$f_{18} - f_4$	139	0.6780(16)	0.069(6)	250.1(4.9)	5.7	$\sim f_{124}$
66	58.0373(9)	0.128(6)	308.4(2.7)	10.5	$f_{24} + f_{61}$	140	19.9163(16)	0.069(6)	143.8(4.9)	5.7	$f_5 - f_{46}$
67	46.7059(9)	0.127(6)	221.2(2.7)	10.4	$f_{25} + f_{62}$	141	2.9433(17)	0.068(6)	53.9(5.0)	5.6	$\sim f_{99}$
68	1.7563(9)	0.126(6)	23.0(2.7)	10.3	$f_{34} + f_4$	142	7.2133(17)	0.067(6)	334.2(5.1)	5.5	$f_5 - f_{13}$
69	1.9064(9)	0.130(6)	187.9(2.6)	10.7	$f_{30} + f_4$	143	56.7727(17)	0.067(6)	168.2(5.1)	5.5	$f_{59} + f_9$
70	27.4677(9)	0.121(6)	68.7(2.8)	10.0	$f_{14} - f_{50}$	144	50.0684(17)	0.067(6)	178.5(5.1)	5.5	$f_{19} + f_{32}$
71	2.1859(9)	0.121(6)	185.5(2.8)	10.0	$\sim f_{51}$	145	49.9890(17)	0.067(6)	53.4(5.1)	5.5	f_{104}
72	36.3889(9)	0.121(6)	94.0(2.8)	9.9	$f_1 + f_{50}$	146	38.4782(17)	0.065(6)	351.5(5.2)	5.4	$\sim f_{29}$
73	21.0394(10)	0.118(6)	5.5(2.9)	9.7	$f_{69} + f_9$	147	5.6605(17)	0.065(6)	61.3(5.2)	5.4	$2f_{62}$
74	2.4153(10)	0.113(6)	183.6(3.0)	9.3	$f_2 - f_1$	148	41.0540(17)	0.065(6)	312.1(5.2)	5.3	$f_4 + f_5$
75	53.0721(10)	0.112(6)	261.2(3.0)	9.2	$f_{16} + f_{42}$	149	22.0038(18)	0.064(6)	26.5(5.3)	5.3	$f_{62} + f_9$
76	4.4598(10)	0.112(6)	250.0(3.0)	9.2	$2f_{51}$ ($\sim 8f_{\text{orb}}$)	150	8.8798(18)	0.064(6)	93.2(5.3)	5.3	$2f_{76}$
77	3.3556(10)	0.117(6)	344.3(2.9)	9.6	$\sim f_{52}$ ($\sim 6f_{\text{orb}}$)	151	45.6828(18)	0.064(6)	114.5(5.3)	5.3	$f_{23} + f_4$
78	0.5711(10)	0.110(6)	299.2(3.1)	9.1	$\sim f_{17}$ ($\sim f_{\text{orb}}$)	152	5.9003(18)	0.064(6)	345.0(5.3)	5.2	$f_5 - f_1$
79	18.7500(10)	0.109(6)	206.3(3.1)	9.0	$\sim f_{47}$	153	29.6691(18)	0.063(6)	255.6(5.4)	5.1	$\sim f_8$
80	3.4522(10)	0.110(6)	5.4(3.1)	9.1	$f_5 - f_2$	154	3.7852(18)	0.062(6)	348.5(5.5)	5.1	$2f_{69}$
81	51.9575(11)	0.107(6)	54.3(3.2)	8.8	$f_{13} + f_9$	155	24.5848(18)	0.062(6)	321.8(5.5)	5.1	$f_8 - f_{43}$
82	3.0709(11)	0.107(6)	69.7(3.2)	8.8	$f_{13} - f_8$	156	8.3243(18)	0.061(6)	204.2(5.5)	5.1	$f_{70} - f_9$

Notes. The errors are given in parentheses alongside values and correspond to the last digit(s).

Table A.2. continued.

i	f_i (cycle d ⁻¹)	A (mmag)	Φ (°)	S/N	Combination	i	f_i (cycle d ⁻¹)	A (mmag)	Φ (°)	S/N	Combination
83	3.8559(11)	0.107(6)	55.3(3.2)	8.8	$\sim f_{15}$	157	42.7033(19)	0.061(6)	25.2(5.6)	5.0	$f_5 + f_6$
84	2.5810(11)	0.103(6)	230.5(3.3)	8.5	$2f_{38}$	158	25.2421(19)	0.061(6)	100.2(5.6)	5.0	$f_1 - f_{150}$
85	33.3145(11)	0.103(6)	88.7(3.3)	8.5	$f_{20} + f_3$	159	50.6998(19)	0.061(6)	58.6(5.6)	5.0	$f_{73} + f_8$
86	1.3647(11)	0.103(6)	103.2(3.3)	8.4	$f_1 - f_{13}$	160	3.6472(19)	0.061(6)	17.2(5.6)	5.0	$f_1 - f_{10}$
87	2.3843(11)	0.103(6)	76.3(3.3)	8.4	$\sim f_{74}$	161	1.1542(19)	0.059(6)	24.8(5.7)	4.9	$\sim f_4$
88	0.0656(11)	0.101(6)	275.7(3.4)	8.3	$\sim f_{41}$	162	30.7267(19)	0.059(6)	149.3(5.8)	4.9	$\sim f_{53}$
89	22.0728(11)	0.101(6)	87.0(3.4)	8.3	$f_{19} + f_{40}$	163	18.6689(19)	0.059(6)	286.0(5.8)	4.8	$f_5 - f_{19}$
90	24.0793(11)	0.099(6)	98.0(3.4)	8.1	$f_{19} + f_{62}$	164	39.7186(19)	0.058(6)	66.5(5.8)	4.8	$f_2 + f_{33}$
91	2.5068(11)	0.099(6)	69.2(3.4)	8.1	$f_3 + f_{40}$	165	58.0649(19)	0.058(6)	66.6(5.9)	4.8	$\sim f_{66}$
92	31.8550(12)	0.098(6)	285.4(3.5)	8.0	$f_1 - f_{51}$	166	58.2236(19)	0.058(6)	178.5(5.8)	4.8	$f_{132} + f_3$
93	28.2078(12)	0.096(6)	358.6(3.5)	7.9	$f_{15} + f_{34}$	167	2.8001(19)	0.058(6)	60.0(5.9)	4.8	$\sim f_6 (\sim 5f_{\text{orb}})$
94	52.7546(12)	0.095(6)	37.7(3.6)	7.8	$f_1 + f_{47}$	168	45.8622(19)	0.058(6)	12.2(5.9)	4.8	$f_{11} + f_{33}$
95	3.5506(12)	0.094(6)	323.9(3.6)	7.8	$2f_{68}$	169	31.5185(20)	0.057(6)	209.3(5.9)	4.7	$f_{10} + f_4$
96	0.8954(12)	0.096(6)	171.3(3.5)	7.9	$f_3 - f_{30}$	170	36.5149(20)	0.056(6)	235.9(6.0)	4.6	$f_2 + f_{41}$
97	4.0146(12)	0.095(6)	2.5(3.6)	7.8	$2f_{48}$	171	23.4823(20)	0.056(6)	57.8(6.0)	4.6	$f_{11} - f_{27}$
98	39.8170(12)	0.095(6)	106.5(3.6)	7.8	$f_{11} - f_6$	172	40.6865(20)	0.056(6)	266.3(6.0)	4.6	$f_{30} + f_5$
99	2.9830(12)	0.093(6)	22.3(3.6)	7.7	$f_3 + f_{38}$	173	5.8193(20)	0.056(6)	206.3(6.1)	4.6	$f_5 - f_1$
100	53.6655(12)	0.092(6)	179.0(3.7)	7.5	$f_2 + f_{61}$	174	3.7334(20)	0.056(6)	338.8(6.1)	4.6	$f_2 - f_{13}$
101	47.1303(12)	0.091(6)	169.5(3.7)	7.5	$f_4 + f_7$	175	2.1324(20)	0.056(6)	173.8(6.1)	4.6	$\sim f_{130}$
102	25.4767(13)	0.090(6)	113.7(3.8)	7.4	$f_{34} + f_4$	176	19.8628(20)	0.055(6)	124.0(6.2)	4.5	$f_4 + f_{47}$
177	25.6061(21)	0.055(6)	141.3(6.2)	4.5	$f_8 - f_{97}$	193	23.3115(22)	0.052(6)	357.1(6.5)	4.3	$f_{23} - f_{19}$
178	1.7235(21)	0.055(6)	113.2(6.2)	4.5	$\sim f_{68}$	194	5.5484(21)	0.054(6)	336.2(6.3)	4.4	$2f_6 (\sim 10f_{\text{orb}})$
179	1.8063(20)	0.057(6)	244.2(6.0)	4.6	$\sim f_{68}$	195	5.1119(21)	0.053(6)	340.3(6.5)	4.3	$2f_{84}$
180	5.1947(21)	0.055(6)	77.7(6.2)	4.5	$2f_{84}$	196	6.8216(22)	0.052(6)	139.0(6.5)	4.3	$f_2 - f_8$
181	58.6722(21)	0.055(6)	347.5(6.2)	4.5	$f_{47} + f_5$	197	59.0086(22)	0.052(6)	70.2(6.5)	4.3	$f_{27} + f_5$
182	36.4527(21)	0.054(6)	232.1(6.3)	4.4	$\sim f_2$	198	40.8953(22)	0.052(6)	273.2(6.5)	4.3	$\sim f_{24}$
183	33.4853(21)	0.054(6)	357.8(6.3)	4.4	$f_1 - f_{26}$	199	55.0354(22)	0.052(6)	281.4(6.6)	4.3	$f_{112} + f_2$
184	52.7839(21)	0.054(6)	16.4(6.4)	4.4	$\sim f_{94}$	200	47.0044(22)	0.051(6)	89.8(6.6)	4.2	$2f_{171}$
185	60.5527(21)	0.054(6)	71.4(6.3)	4.4	$f_2 + f_{90}$	201	37.7450(22)	0.051(6)	313.1(6.7)	4.2	$\sim f_{18}$
186	30.3764(21)	0.053(6)	196.3(6.4)	4.4	$\sim f_{10}$	202	56.6157(22)	0.051(6)	194.2(6.7)	4.2	$f_{116} + f_3$
187	3.1986(21)	0.053(6)	117.8(6.4)	4.3	$\sim f_{105}$	203	54.6610(22)	0.050(6)	129.6(6.7)	4.1	$f_{118} + f_3$
188	1.9340(21)	0.053(6)	33.3(6.4)	4.4	$\sim f_{69}$	204	32.1207(23)	0.050(6)	286.4(6.8)	4.1	$2f_{44}$
189	21.0083(21)	0.053(6)	64.1(6.4)	4.3	$\sim f_{73}$	205	1.2094(23)	0.050(6)	4.1(6.8)	4.1	$2f_{35}$
190	35.0536(22)	0.053(6)	180.3(6.5)	4.3	$\sim f_{124}$	206	42.3945(23)	0.049(6)	210.6(6.9)	4	$f_{22} + f_3$
191	17.2438(22)	0.053(6)	138.5(6.5)	4.3	$f_2 - f_9$	207	5.4242(23)	0.049(6)	124.3(7.0)	4	$f_{12} - f_8$
192	33.9287(22)	0.052(6)	6.2(6.5)	4.3	$f_{12} - f_4$						

Table A.3. Combined frequencies of KIC 10619109.

i	f_i (cycle d ⁻¹)	A (mmag)	Φ (°)	S/N	Combination	i	f_i (cycle d ⁻¹)	A (mmag)	Φ (°)	S/N	Combination
4	3.9135(3)	0.255(4)	358.7(0.8)	36.2	$8f_{\text{orb}}$	56	41.4925(10)	0.079(4)	359.3(2.7)	11.2	$f_1 - f_{32}$
5	52.3919(3)	0.246(4)	250.7(0.9)	34.8	$2f_2 - 3f_4$	57	30.4380(10)	0.079(4)	54.2(2.7)	11.2	$f_2 - f_{24}$
8	1.7930(4)	0.218(4)	92.2(1.0)	31.0	$2f_2 - 2f_3$	58	22.4908(10)	0.078(4)	197.1(2.8)	11.1	$f_{17} - f_4$
9	45.6890(4)	0.209(4)	288.0(1.0)	29.7	$f_7 + 2f_8 - f_4$	59	40.7268(10)	0.078(4)	9.9(2.8)	11.1	$f_1 - f_{33}$
10	2.9347(4)	0.207(4)	166.1(1.0)	29.3	$f_9 - f_1 (\sim 6f_{\text{orb}})$	60	25.2452(10)	0.078(4)	115.8(2.8)	11.1	$f_{17} - f_{47}$
11	33.2060(4)	0.205(4)	132.8(1.1)	29.0	$2f_1 - f_5$	61	45.0164(10)	0.077(4)	146.6(2.8)	11.0	$2f_{58}$
12	2.2814(4)	0.204(4)	205.4(1.1)	28.9	$2f_{10} - f_8$	62	1.3142(11)	0.076(4)	166.6(2.8)	10.8	$\sim f_{32}$
13	29.4611(4)	0.199(4)	273.1(1.1)	28.2	$f_4 + 2f_6 - f_7$	63	0.3121(11)	0.075(4)	135.3(2.9)	10.6	$f_1 - f_{16}$
14	34.6016(4)	0.199(4)	7.3(1.1)	28.2	$f_2 + f_6 - f_{11}$	64	3.1537(11)	0.074(4)	19.2(2.9)	10.4	$2f_{22}$
15	1.0913(4)	0.189(4)	71.3(1.1)	26.9	$f_{11} - f_2$	65	35.2645(11)	0.074(4)	318.3(2.9)	10.4	$f_2 + f_{64}$
16	42.4655(4)	0.188(4)	1.9(1.1)	26.7	$f_1 + f_9 - f_7$	66	32.2310(11)	0.072(4)	156.1(3.0)	10.3	$f_{15} + f_3$
17	26.3946(4)	0.181(4)	167.1(1.2)	25.7	$f_2 - f_4 - f_8$	67	55.3634(11)	0.072(4)	143.7(3.0)	10.2	$f_{10} + f_5$
18	2.1884(4)	0.180(4)	98.2(1.2)	25.5	$2f_{15}$	68	20.8684(11)	0.072(4)	282.4(3.0)	10.1	$f_{38} - f_{22}$
19	1.4848(5)	0.177(4)	5.5(1.2)	25.0	$f_{16} + f_8 - f_1 (\sim 3f_{\text{orb}})$	69	30.9401(11)	0.071(4)	203.8(3.0)	10.1	$f_2 - f_{47}$
20	38.4570(5)	0.163(4)	40.8(1.3)	23.1	$f_2 + f_5 - f_7$	70	3.7449(11)	0.070(4)	40.6(3.1)	10.0	$f_{11} - f_{13}$
21	0.9827(5)	0.163(4)	104.7(1.3)	23.0	$f_4 - f_{10} (\sim 2f_{\text{orb}})$	71	31.0254(12)	0.068(4)	47.9(3.2)	9.7	$f_2 - f_{15}$
22	1.5759(5)	0.159(4)	124.3(1.4)	22.5	$f_4 - f_{12}$	72	0.1531(12)	0.066(4)	16.3(3.2)	9.4	$f_{66} - f_2$
23	33.0781(5)	0.155(4)	150.7(1.4)	22.0	$f_2 + f_{21}$	73	1.8356(12)	0.066(4)	311.3(3.3)	9.3	$\sim f_8$
24	1.6844(5)	0.148(4)	196.9(1.5)	21.0	$f_3 - f_{13}$	74	0.4768(12)	0.065(4)	187.5(3.3)	9.3	$f_{12} - f_8 (\sim f_{\text{orb}})$
25	0.5389(5)	0.151(4)	158.1(1.4)	21.4	$f_{12} - f_8$	75	2.8959(13)	0.064(4)	151.1(3.4)	9.1	$\sim f_{10} (\sim 6f_{\text{orb}})$
26	1.9946(6)	0.133(4)	288.2(1.6)	18.8	$2f_{21} (\sim 4f_{\text{orb}})$	76	0.1027(13)	0.064(4)	308.8(3.4)	9.1	$\sim f_{72}$
27	1.9306(6)	0.142(4)	307.8(1.5)	20.1	$2f_{21} (\sim 4f_{\text{orb}})$	77	3.8438(13)	0.064(4)	40.3(3.4)	9.1	$2f_{27}$

Notes. The errors are given in parentheses alongside values and correspond to the last digit(s).

Table A.3. continued.

i	f_i (cycle d ⁻¹)	A (mmag)	Φ (°)	S/N	Combination	i	f_i (cycle d ⁻¹)	A (mmag)	Φ (°)	S/N	Combination
28	0.7812(6)	0.136(4)	216.8(1.6)	19.2	$f_{10} - f_{18}$	78	47.8290(13)	0.064(4)	173.7(3.4)	9.0	$f_7 + f_8$
29	36.1833(6)	0.133(4)	353.1(1.6)	18.8	$f_{10} + f_{11}$	79	19.8565(13)	0.063(4)	288.2(3.4)	8.9	$f_{68} - f_{21}$
30	35.2006(6)	0.145(4)	222.1(1.5)	20.5	$f_6 - f_{25}$	80	24.7701(13)	0.064(4)	62.3(3.4)	9.1	$f_{17} - f_{22}$
31	36.5768(6)	0.128(4)	336.6(1.7)	18.1	$f_{28} + f_6$	81	4.0105(14)	0.059(4)	270.0(3.6)	8.4	$2f_{26}$
32	1.2716(6)	0.127(4)	116.3(1.7)	18.0	$f_{12} - f_{21}$	82	23.0430(14)	0.058(4)	307.4(3.7)	8.3	$f_{60} - f_{18}$
33	2.1244(6)	0.129(4)	319.5(1.7)	18.2	$f_4 - f_8$	83	39.5753(14)	0.057(4)	171.5(3.8)	8.1	$f_{16} - f_{10}$
34	0.8626(6)	0.129(4)	237.0(1.7)	18.3	$f_2 - f_3$	84	5.1890(14)	0.057(4)	341.4(3.8)	8.1	$f_{10} + f_{12}$
35	1.7465(6)	0.129(4)	107.9(1.7)	18.3	$\sim f_8$	85	0.7773(14)	0.056(4)	243.4(3.8)	8.0	$\sim f_{28}$
36	4.8885(7)	0.123(4)	127.3(1.7)	17.5	$f_{21} + f_4 (\sim 10f_{\text{orb}})$	86	46.0261(14)	0.057(4)	42.3(3.8)	8.0	$\sim f_7$
37	1.6263(7)	0.118(4)	72.0(1.8)	16.8	$\sim f_{22}$	87	49.1934(14)	0.056(4)	231.5(3.9)	7.9	$f_{49} - f_{12}$
38	2.4966(7)	0.119(4)	20.9(1.8)	16.9	$2f_{32}$	88	3.1227(14)	0.056(4)	50.3(3.9)	7.9	$\sim f_{64}$
39	3.4154(7)	0.110(4)	138.1(2.0)	15.6	$2f_{24} (\sim 7f_{\text{orb}})$	89	2.2349(14)	0.056(4)	237.7(3.8)	8.0	$\sim f_{12}$
40	2.4481(7)	0.118(4)	346.4(1.8)	16.7	$\sim f_{38} (\sim 5f_{\text{orb}})$	90	48.2165(14)	0.057(4)	63.4(3.8)	8.1	$f_{18} + f_7$
41	42.8435(7)	0.109(4)	346.6(2.0)	15.4	$\sim f_1$	91	25.7102(15)	0.055(4)	338.3(3.9)	7.8	$f_{17} - f_{52}$
42	36.8443(8)	0.105(4)	112.6(2.1)	14.8	$f_{15} + f_6$	92	20.8218(10)	0.055(4)	155.3(2.8)	7.8	$\sim f_{68}$
43	2.4055(8)	0.101(4)	136.5(2.1)	14.3	$\sim f_{40} (\sim 5f_{\text{orb}})$	93	3.9291(15)	0.055(4)	285.6(3.9)	7.8	$\sim f_4 (\sim 8f_{\text{orb}})$
44	36.2434(8)	0.100(4)	237.7(2.1)	14.2	$f_{25} + f_6$	94	25.4293(15)	0.055(4)	265.8(3.9)	7.8	$f_{17} - f_{21}$
45	44.8672(8)	0.100(4)	264.7(2.2)	14.2	$f_7 - f_{15}$	95	1.4383(15)	0.055(4)	104.2(3.9)	7.8	$\sim f_{19}$
46	48.3698(8)	0.100(4)	207.5(2.2)	14.2	$f_{43} + f_7$	96	2.6032(15)	0.054(4)	118.0(4.0)	7.7	$2f_{62}$
47	1.1960(8)	0.099(4)	186.5(2.2)	14.0	$f_6 - f_{14}$	97	30.0329(15)	0.054(4)	73.3(4.0)	7.7	$f_{13} + f_{25}$
48	51.2482(8)	0.099(4)	153.2(2.2)	14.0	$f_5 - f_{15}$	98	22.2310(15)	0.054(4)	75.7(4.0)	7.6	$f_{67} - f_{23}$
49	51.4208(9)	0.093(4)	257.2(2.3)	13.1	$f_5 - f_{21}$	99	20.4400(15)	0.053(4)	137.0(4.1)	7.5	$f_9 - f_{60}$
50	31.3374(9)	0.088(4)	174.8(2.5)	12.4	$f_2 - f_{28}$	100	26.7978(15)	0.053(4)	88.3(4.1)	7.5	$f_{17} + f_{54}$
51	39.2382(9)	0.085(4)	123.1(2.5)	12.1	$f_{20} + f_{28}$	101	32.1186(15)	0.052(4)	261.7(4.1)	7.4	$\sim f_2$
52	0.7211(10)	0.084(4)	177.8(2.6)	12.0	$f_2 - f_{50}$	102	1.0506(16)	0.051(4)	170.3(4.3)	7.2	$\sim f_{15}$
53	2.8416(9)	0.085(4)	89.9(2.5)	12.0	$f_9 - f_1$	103	32.8280(16)	0.050(4)	330.6(4.3)	7.1	$f_2 + f_{28}$
54	0.3935(10)	0.084(4)	76.9(2.6)	11.9	$f_1 - f_{16}$	104	2.6963(16)	0.050(4)	187.1(4.3)	7.1	$f_{20} - f_6$
55	1.5332(10)	0.080(4)	180.7(2.7)	11.3	$\sim f_{19}$	105	20.6377(16)	0.050(4)	317.0(4.3)	7.1	$f_{98} - f_{22}$
106	38.3485(16)	0.049(4)	348.9(4.4)	7.0	$f_{31} + f_8$	158	46.9567(22)	0.036(4)	355.8(5.9)	5.2	$f_{21} + f_7$
107	22.1147(17)	0.049(4)	184.3(4.4)	6.9	$f_1 - f_{105}$	159	17.2165(22)	0.036(4)	100.6(6.0)	5.1	$f_5 - f_{30}$
108	19.0463(17)	0.048(4)	157.4(4.5)	6.8	$f_{92} - f_8$	160	6.6583(23)	0.035(4)	68.6(6.1)	5.0	$\sim f_{155}$
109	37.2262(17)	0.047(4)	288.9(4.6)	6.6	$f_{19} + f_6$	161	48.8020(23)	0.035(4)	346.3(6.1)	5.0	$f_4 + f_{45}$
110	44.9835(17)	0.047(4)	224.2(4.6)	6.6	$\sim f_{61}$	162	40.1608(23)	0.035(4)	49.4(6.1)	5.0	$f_{16} - f_{12}$
111	24.4311(17)	0.047(4)	211.9(4.6)	6.6	$f_{17} - f_{27}$	163	0.6455(23)	0.035(4)	73.7(6.2)	4.9	$\sim f_{122}$
112	8.4919(17)	0.046(4)	172.3(4.7)	6.5	$f_{48} - f_1$	164	5.2801(23)	0.035(4)	12.8(6.2)	5.0	$f_{20} - f_{11}$
113	41.9693(18)	0.046(4)	11.6(4.7)	6.5	$f_1 - f_{28}$	165	19.9050(23)	0.035(4)	238.0(6.2)	4.9	$\sim f_{79}$
114	4.3361(18)	0.045(4)	120.2(4.8)	6.4	$2f_{18}$	166	32.1574(23)	0.035(4)	82.3(6.3)	4.9	$\sim f_{101}$
115	4.8420(18)	0.045(4)	135.0(4.8)	6.4	$f_{36} (\sim 10f_{\text{orb}})$	167	30.4923(23)	0.035(4)	297.0(6.2)	4.9	$\sim f_{57}$
116	0.9479(18)	0.045(4)	333.3(4.8)	6.3	$f_{21} (\sim 2f_{\text{orb}})$	168	1.9616(23)	0.034(4)	131.4(6.3)	4.9	$\sim f_{27}$
117	36.5458(18)	0.045(4)	61.8(4.8)	6.4	$\sim f_{31}$	169	41.3975(23)	0.034(4)	105.5(6.3)	4.9	$2f_{126}$
118	20.9556(18)	0.045(4)	310.5(4.8)	6.3	$f_{58} - f_{19}$	170	2.7815(24)	0.034(4)	82.2(6.4)	4.8	$f_4 - f_{15}$
119	19.5619(18)	0.045(4)	73.5(4.8)	6.3	$f_7 - f_{17}$	171	29.9767(24)	0.033(4)	297.8(6.4)	4.7	$\sim f_{97}$
120	4.4001(18)	0.045(4)	205.5(4.8)	6.3	$2f_{18} (\sim 9f_{\text{orb}})$	172	19.3448(24)	0.033(4)	133.4(6.5)	4.7	$f_{49} - f_2$
121	4.2295(17)	0.046(4)	156.0(4.7)	6.5	$2f_{33}$	173	33.5976(24)	0.033(4)	203.8(6.5)	4.7	$f_{19} + f_2$
122	0.5931(18)	0.045(4)	30.9(4.8)	6.3	f_{25}	174	32.6167(20)	0.033(4)	46.2(5.5)	4.7	$f_2 + f_{25}$
123	35.5960(18)	0.044(4)	150.7(4.9)	6.2	$f_{14} + f_{21}$	175	30.1725(24)	0.033(4)	223.6(6.6)	4.7	$f_2 - f_{27}$
124	55.6929(18)	0.044(4)	197.0(4.9)	6.2	$f_{11} + f_{58}$	176	38.6373(25)	0.033(4)	278.8(6.6)	4.6	$2f_{172}$
125	44.7450(19)	0.043(4)	292.9(5.0)	6.2	$f_1 + f_{27}$	177	18.0151(25)	0.033(4)	226.0(6.6)	4.6	$f_1 - f_{80}$
126	20.7269(19)	0.043(4)	282.6(5.0)	6.1	$f_1 - f_{107}$	178	42.3919(25)	0.033(4)	107.4(6.6)	4.6	$f_1 - f_{54}$
127	3.0471(19)	0.042(4)	114.2(5.2)	5.9	$2f_{55}$	179	4.7722(25)	0.032(4)	103.8(6.6)	4.6	$2f_{43}$
128	48.9086(19)	0.042(4)	0.7(5.2)	5.9	$2f_{111}$	180	3.6402(25)	0.033(4)	194.4(6.6)	4.6	$2f_8$
129	39.4243(19)	0.042(4)	249.3(5.2)	5.9	$f_1 - f_{39}$	181	22.1419(25)	0.032(4)	151.6(6.7)	4.6	$\sim f_{107}$
130	20.3935(20)	0.041(4)	140.7(5.2)	5.8	$\sim f_{99}$	182	46.0709(25)	0.032(4)	329.3(6.8)	4.5	$\sim f_{86}$
131	40.5931(20)	0.041(4)	181.9(5.3)	5.8	$f_1 - f_{18}$	183	5.3576(25)	0.032(4)	67.7(6.8)	4.5	$2f_{104} (\sim 11f_{\text{orb}})$
132	0.2442(20)	0.041(4)	25.7(5.3)	5.8	$2f_{76}$	184	61.0292(25)	0.032(4)	105.4(6.8)	4.5	$2f_{167}$
133	40.6784(20)	0.041(4)	358.4(5.3)	5.8	$\sim f_{59}$	185	27.2649(25)	0.032(4)	211.7(6.8)	4.5	$f_3 - f_4$
134	45.8460(20)	0.040(4)	49.6(5.4)	5.7	$f_1 + f_{127}$	186	44.6598(26)	0.031(4)	2.6(6.9)	4.4	$f_1 + f_{73}$
135	26.3035(20)	0.040(4)	333.7(5.4)	5.7	$f_3 - f_{36}$	187	37.8561(26)	0.031(4)	155.1(7.0)	4.4	$f_1 - f_{36}$
136	22.7176(20)	0.040(4)	357.9(5.4)	5.6	$f_{68} + f_8$	188	20.0717(26)	0.031(4)	190.3(7.0)	4.4	$f_{48} - f_3$
137	34.5357(20)	0.040(4)	275.4(5.4)	5.6	$f_2 + f_{38}$	189	31.8666(26)	0.031(4)	311.0(7.0)	4.3	$f_6 - f_4$
138	3.5239(20)	0.040(4)	259.1(5.4)	5.6	$2f_{35}$	190	1.8647(26)	0.031(4)	102.7(7.1)	4.3	$\sim f_{73}$
139	47.0788(20)	0.039(4)	347.8(5.5)	5.6	$f_{15} + f_7$	191	31.4266(26)	0.031(4)	351.0(7.1)	4.3	$f_{11} - f_8$
140	49.0482(18)	0.039(4)	203.8(4.9)	5.5	$f_{39} + f_9$	192	46.1387(27)	0.030(4)	304.1(7.1)	4.3	$2f_{82}$
141	36.1581(20)	0.039(4)	96.9(5.5)	5.6	$\sim f_{29}$	193	55.3013(27)	0.030(4)	260.3(7.2)	4.3	$f_{10} + f_5$
142	24.2120(21)	0.039(4)	145.6(5.5)	5.6	$f_{17} - f_{18}$	194	40.9614(27)	0.030(4)	262.9(7.2)	4.2	$f_1 - f_8$
143	37.7069(21)	0.039(4)	155.8(5.5)	5.5	$f_{27} + f_6$	195	22.3105(27)	0.030(4)	61.1(7.2)	4.2	$f_1 - f_{99}$
144	39.7305(21)	0.039(4)	19.5(5.5)	5.5	$2f_{79}$	196	5.7976(27)	0.030(4)	318.7(7.3)	4.2	$2f_{75} (\sim 12f_{\text{orb}})$
145	21.5332(21)	0.039(4)	303.5(5.6)	5.5	$f_{17} - f_{36}$	197	14.6695(27)	0.029(4)	15.4(7.3)	4.2	$f_7 - f_{50}$
146	8.8001(21)	0.039(4)	67.6(5.6)	5.5	$2f_{120}$	198	12.7117(25)	0.032(4)	111.6(6.7)	4.5	$f_1 - f_{97}$
147	3.2603(21)	0.038(4)	323.0(5.6)	5.4	$2f_{37}$	199	20.4710(27)	0.030(4)	193.4(7.3)	4.2	$\sim f_{99}$

Table A.3. continued.

i	f_i (cycle d ⁻¹)	A (mmag)	Φ (°)	S/N	Combination	i	f_i (cycle d ⁻¹)	A (mmag)	Φ (°)	S/N	Combination
148	42.5082(21)	0.038(4)	107.0(5.6)	5.4	$\sim f_{16}$	200	30.3682(27)	0.029(4)	323.0(7.3)	4.2	$f_2 - f_{24}$
149	52.1283(21)	0.038(4)	234.1(5.6)	5.4	$f_5 - f_{63}$	201	25.7937(27)	0.029(4)	307.8(7.3)	4.2	$f_9 - f_{79}$
150	32.0740(21)	0.038(4)	155.6(5.6)	5.4	$\sim f_2$	202	41.3180(28)	0.029(4)	269.4(7.4)	4.1	$2f_{105}$
151	35.0707(21)	0.038(4)	321.2(5.7)	5.4	$f_{10} + f_2$	203	23.1963(28)	0.029(4)	320.4(7.4)	4.1	$f_1 - f_{119}$
152	57.5595(21)	0.038(4)	132.2(5.7)	5.4	$f_{17} + f_3$	204	33.5568(28)	0.029(4)	121.2(7.5)	4.1	$\sim f_{173}$
153	7.2727(21)	0.038(4)	73.8(5.7)	5.4	$f_{20} - f_3$	205	5.7395(28)	0.029(4)	232.6(7.6)	4.0	$2f_{53}$
154	52.2290(22)	0.037(4)	298.6(5.8)	5.3	$f_4 + f_{46}$	206	27.3890(28)	0.029(4)	45.5(7.6)	4.0	$f_{17} + f_{21}$
155	6.6020(22)	0.037(4)	52.6(5.8)	5.3	$f_1 - f_{29}$	207	24.3535(28)	0.028(4)	100.3(7.6)	4.0	$f_{17} - f_{26}$
156	25.8713(22)	0.037(4)	60.0(5.8)	5.3	$f_{17} - f_{25}$	208	34.1713(28)	0.028(4)	356.5(7.6)	4.0	$f_2 + f_{33}$
157	32.9928(22)	0.037(4)	136.8(5.9)	5.2	$f_2 + f_{34}$						

Table A.4. Combined frequencies of KIC 11175495.

i	f_i (cycle d ⁻¹)	A (mmag)	Φ (°)	S/N	Combination	i	f_i (cycle d ⁻¹)	A (mmag)	Φ (°)	S/N	Combination
2	64.40521(7)	1.304(5)	304.8(2)	139.1	$\sim f_1$	19	3.38379(41)	0.212(5)	92.2(1.4)	22.6	$f_1 + f_{15} - f_2$
3	1.36722(8)	1.063(5)	217.8(3)	113.4	$\sim 3f_{\text{orb}}$	20	0.52127(43)	0.203(5)	111.0(1.5)	21.7	$\sim f_{10}$
6	0.86680(15)	0.590(5)	49.5(5)	63.0	$\sim 2f_{\text{orb}}$	21	3.25720(39)	0.222(5)	349.4(1.4)	23.7	$f_1 + f_{14} - f_2$
7	1.82891(18)	0.492(5)	243.2(6)	52.4	$2f_3 - f_6$ ($\sim 4f_{\text{orb}}$)	22	3.12018(43)	0.202(5)	190.7(1.5)	21.6	$f_{18} + f_6$
8	0.40957(20)	0.443(5)	241.3(7)	47.3	$2f_6 - f_3$	23	59.96398(43)	0.202(5)	0.2(1.5)	21.6	$f_{15} + f_5$
9	63.35075(26)	0.338(5)	158.8(9)	36.0	$f_1 + f_5 - f_4$	24	3.65783(46)	0.191(5)	79.0(1.6)	20.4	$2f_7$ ($\sim 8f_{\text{orb}}$)
10	0.48404(29)	0.307(5)	309.2(1.0)	32.7	$f_3 - f_6$	25	0.95169(47)	0.185(5)	31.7(1.6)	19.7	$2f_{10}$
11	1.34190(27)	0.327(5)	263.7(9)	34.9	$\sim f_3$	26	58.55804(51)	0.170(5)	80.0(1.8)	18.1	$f_4 + f_6$
12	0.88765(34)	0.258(5)	40.4(1.2)	27.5	$\sim f_6$	27	64.45435(52)	0.169(5)	53.7(1.8)	18.1	$\sim f_1$
13	0.44978(37)	0.238(5)	104.5(1.3)	25.4	$\sim f_8$ ($\sim f_{\text{orb}}$)	28	0.24723(52)	0.169(5)	177.7(1.8)	18.0	$f_{17} - f_{19}$
14	3.18422(37)	0.235(5)	325.8(1.3)	25.0	$f_3 + f_7$ ($\sim 7f_{\text{orb}}$)	29	0.99190(52)	0.168(5)	207.6(1.8)	18.0	$\sim f_{25}$
15	3.30932(37)	0.234(5)	123.2(1.3)	25.0	$f_{10} + 2f_7 - f_6$	30	3.74719(52)	0.167(5)	230.5(1.8)	17.8	$f_{15} + f_8$
16	63.49224(37)	0.234(5)	296.5(1.3)	24.9	$f_2 - f_{12}$	31	59.68547(53)	0.164(5)	136.8(1.9)	17.5	$f_9 - f_{24}$
17	3.60719(37)	0.233(5)	58.2(1.3)	24.9	$f_{14} + f_8$	32	56.81998(55)	0.158(5)	59.0(1.9)	16.9	$f_4 - f_{12}$
18	2.28168(41)	0.213(5)	157.3(1.4)	22.7	$f_{12} + f_3$ ($\sim 5f_{\text{orb}}$)	33	1.20786(57)	0.155(5)	271.9(2.0)	16.5	$f_{25} + f_{28}$
34	0.68659(61)	0.143(5)	92.9(2.1)	15.3	$f_{28} + f_8$	96	4.31165(141)	0.062(5)	321.5(4.9)	6.6	$\sim 2f_{65}$
35	1.25552(63)	0.139(5)	10.7(2.2)	14.9	$f_6 + f_8$	97	1.52062(144)	0.061(5)	289.8(5.0)	6.5	$\sim f_{83}$
36	2.95933(65)	0.135(5)	31.7(2.3)	14.4	$f_{31} - f_5$	98	0.32617(139)	0.063(5)	144.2(4.8)	6.7	$\sim 2f_{69}$
37	3.35549(65)	0.134(5)	347.1(2.3)	14.3	$\sim f_{19}$	99	3.53124(147)	0.060(5)	193.1(5.1)	6.4	$\sim f_{38}$
38	3.49251(65)	0.135(5)	325.7(2.3)	14.4	$f_{22} + f_8$	100	63.86457(147)	0.060(5)	241.0(5.1)	6.4	$f_1 - f_{39}$
39	0.61957(69)	0.127(5)	59.6(2.4)	13.6	$f_6 - f_{28}$	101	59.46952(147)	0.060(5)	265.9(5.1)	6.4	$f_4 + f_{48}$
40	1.03807(69)	0.127(5)	282.8(2.4)	13.5	$2f_{20}$	102	2.40976(146)	0.060(5)	284.4(5.1)	6.4	$\sim f_{67}$
41	61.01844(70)	0.124(5)	340.9(2.5)	13.3	$f_1 - f_{19}$	103	1.74104(148)	0.059(5)	329.0(5.2)	6.3	$\sim f_{48}$
42	60.10398(70)	0.124(5)	154.5(2.5)	13.2	$f_{19} + f_5$	104	6.43695(153)	0.057(5)	108.1(5.3)	6.1	$2f_{44}$
43	55.23233(74)	0.118(5)	53.2(2.6)	12.6	$f_{26} - f_{15}$	105	60.65355(157)	0.056(5)	37.3(5.5)	6.0	$f_1 - f_{30}$
44	3.21401(76)	0.115(5)	180.9(2.6)	12.3	$\sim f_{14}$	106	3.17826(161)	0.054(5)	20.1(5.6)	5.8	$\sim f_{14}$ ($\sim 7f_{\text{orb}}$)
45	4.36825(77)	0.113(5)	346.7(2.7)	12.1	$f_1 - f_{42}$	107	5.45249(162)	0.054(5)	38.7(5.6)	5.8	$\sim f_{86}$ ($\sim 12f_{\text{orb}}$)
46	0.09085(78)	0.112(5)	37.9(2.7)	12.0	$f_{27} - f_2$	108	0.58531(163)	0.054(5)	163.8(5.7)	5.7	$\sim f_{39}$
47	0.05064(78)	0.112(5)	224.9(2.7)	12.0	$\sim f_{46}$	109	8.37012(166)	0.053(5)	241.0(5.8)	5.6	$2f_{58}$
48	1.70977(75)	0.116(5)	15.1(2.6)	12.4	$2f_6$	110	8.56671(162)	0.054(5)	314.4(5.7)	5.7	$f_{45} + f_{58}$
49	2.90720(79)	0.111(5)	149.4(2.7)	11.8	$f_{15} - f_8$	111	5.71908(165)	0.053(5)	197.4(5.7)	5.7	$f_{16} - f_4$
50	1.65466(80)	0.110(5)	324.4(2.8)	11.7	$f_{28} + f_3$	112	59.19399(171)	0.051(5)	133.2(6.0)	5.4	$f_{42} - f_6$
51	1.40892(81)	0.108(5)	124.9(2.8)	11.6	$\sim f_3$	113	3.45528(173)	0.051(5)	305.1(6.0)	5.4	$\sim f_{38}$
52	63.12586(81)	0.108(5)	41.9(2.8)	11.5	$f_1 - f_{11}$	114	7.25311(173)	0.051(5)	206.7(6.0)	5.4	$2f_{17}$
53	1.15871(82)	0.106(5)	68.6(2.9)	11.3	$f_3 - f_{28}$	115	1.68147(177)	0.049(5)	115.5(6.2)	5.3	$\sim f_{48}$
54	61.43248(83)	0.105(5)	290.1(2.9)	11.3	$f_{24} + f_4$	116	7.70438(177)	0.049(5)	216.6(6.2)	5.3	$f_2 - f_5$
55	57.59890(83)	0.105(5)	299.6(2.9)	11.2	$f_5 + f_6$	117	9.03287(179)	0.049(5)	221.0(6.3)	5.2	$f_{116} + f_3$
56	0.91893(86)	0.101(5)	288.1(3.0)	10.8	$\sim f_{12}$ ($\sim 2f_{\text{orb}}$)	118	5.27079(180)	0.049(5)	289.3(6.3)	5.2	$f_1 - f_{112}$
57	60.36164(87)	0.101(5)	339.6(3.0)	10.7	$f_{24} + f_5$	119	1.01573(180)	0.049(5)	16.1(6.3)	5.2	$\sim f_{29}$
58	4.19846(88)	0.100(5)	182.8(3.1)	10.6	$f_{15} + f_6$	120	0.11468(178)	0.049(5)	122.5(6.2)	5.2	$\sim f_{46}$
59	3.80825(89)	0.099(5)	97.5(3.1)	10.5	$f_{19} + f_8$	121	5.58206(177)	0.049(5)	263.8(6.2)	5.3	$2f_{92}$
60	3.98995(89)	0.098(5)	198.1(3.1)	10.5	$f_{22} + f_6$	122	5.68781(175)	0.050(5)	342.0(6.1)	5.3	$\sim f_{111}$
61	2.32040(89)	0.098(5)	36.4(3.1)	10.5	$\sim f_{18}$ ($\sim 5f_{\text{orb}}$)	123	4.25506(182)	0.048(5)	47.7(6.4)	5.1	$f_{19} + f_6$
62	59.73760(93)	0.094(5)	24.2(3.3)	10.0	$f_9 - f_{17}$	124	0.29489(178)	0.049(5)	69.1(6.2)	5.2	$\sim f_{98}$
63	2.70018(94)	0.093(5)	65.6(3.3)	9.9	$2f_3$	125	0.26510(183)	0.048(5)	155.3(6.4)	5.1	$\sim f_{28}$
64	1.61743(97)	0.090(5)	87.9(3.4)	9.6	$\sim f_{50}$	126	1.36573(181)	0.048(5)	275.1(6.3)	5.2	$\sim f_3$ ($\sim 3f_{\text{orb}}$)
65	2.15359(97)	0.090(5)	22.3(3.4)	9.6	$f_{38} - f_3$	127	5.96780(188)	0.046(5)	184.4(6.6)	5.0	$f_3 + f_{85}$
66	57.88188(100)	0.087(5)	349.2(3.5)	9.3	$f_{33} + f_5$	128	2.88337(188)	0.047(5)	40.6(6.5)	5.0	$\sim f_{49}$
67	2.43657(101)	0.086(5)	246.4(3.5)	9.2	$2f_{33}$	129	2.73741(192)	0.045(5)	32.2(6.7)	4.9	$\sim f_{63}$ ($\sim 6f_{\text{orb}}$)
68	3.42549(101)	0.087(5)	244.5(3.5)	9.2	$\sim f_{19}$	130	4.85377(193)	0.045(5)	206.5(6.7)	4.8	$2f_{67}$
69	0.18319(105)	0.083(5)	72.6(3.7)	8.8	$2f_{46}$	131	7.91884(194)	0.045(5)	269.4(6.8)	4.8	$f_{109} - f_8$
70	0.54808(104)	0.084(5)	39.1(3.6)	8.9	$\sim f_{20}$	132	68.61260(196)	0.045(5)	162.0(6.8)	4.7	$f_1 + f_{58}$
71	1.08424(108)	0.081(5)	258.7(3.8)	8.6	$2f_{20}$	133	10.66222(199)	0.044(5)	348.9(6.9)	4.7	$f_{109} + f_{18}$

Notes. The errors are given in parentheses alongside values and correspond to the last digit(s).

Table A.4. continued.

i	f_i (cycle d ⁻¹)	A (mmag)	Φ (°)	S/N	Combination	i	f_i (cycle d ⁻¹)	A (mmag)	Φ (°)	S/N	Combination
72	3.87676(107)	0.081(5)	229.1(3.7)	8.7	$f_{10} + f_{19}$	134	2.11934(199)	0.044(5)	73.0(6.9)	4.7	$\sim f_{65}$
73	1.97785(109)	0.080(5)	264.7(3.8)	8.5	$2f_{29}$	135	60.59249(201)	0.044(5)	11.2(7.0)	4.7	$f_1 - f_{59}$
74	0.77595(104)	0.084(5)	7.5(3.6)	9.0	$2f_8$	136	0.38425(201)	0.043(5)	167.8(7.0)	4.6	$\sim f_8$
75	0.84148(107)	0.081(5)	93.6(3.7)	8.7	$\sim f_6$	137	4.91633(202)	0.043(5)	6.6(7.0)	4.6	$2f_{67}$
76	4.68101(112)	0.078(5)	54.0(3.9)	8.3	$2f_{61}$	138	6.80779(202)	0.043(5)	271.7(7.1)	4.6	$2f_{19}$
77	4.45612(119)	0.074(5)	78.9(4.1)	7.9	$f_1 - f_{23}$	139	8.20629(202)	0.043(5)	117.7(7.1)	4.6	$f_{138} + f_3$
78	61.16886(119)	0.074(5)	166.6(4.1)	7.8	$f_1 - f_{15}$	140	8.59947(205)	0.043(5)	210.6(7.2)	4.5	$\sim f_{110}$
79	3.14996(120)	0.073(5)	105.5(4.2)	7.8	$\sim f_{14}$	141	6.76162(198)	0.044(5)	232.7(6.9)	4.7	$2f_{19}$
80	4.04953(116)	0.075(5)	43.5(4.1)	8.0	$f_1 - f_{57}$	142	5.34972(204)	0.043(5)	40.2(7.1)	4.6	$f_3 + f_{60}$
81	3.90357(124)	0.071(5)	333.6(4.3)	7.5	$\sim f_{72}$	143	4.47995(210)	0.042(5)	76.9(7.3)	4.4	$\sim f_{77}$
82	2.58997(127)	0.069(5)	56.5(4.4)	7.4	$f_3 + f_{33}$	144	4.56633(210)	0.042(5)	69.8(7.3)	4.4	$\sim f_{85}$
83	1.48190(128)	0.068(5)	111.5(4.5)	7.3	$f_3 + f_{46}$	145	64.38585(213)	0.041(5)	140.7(7.4)	4.4	$\sim f_2$
84	6.88673(131)	0.067(5)	76.7(4.6)	7.1	$2f_{68}$	146	2.82380(214)	0.041(5)	330.2(7.5)	4.3	$\sim f_{92} (\sim 5f_{\text{orb}})$
85	4.59910(133)	0.066(5)	279.6(4.6)	7.0	$2f_{18} (\sim 10f_{\text{orb}})$	147	5.10994(214)	0.041(5)	135.7(7.5)	4.4	$f_3 + f_{30}$
86	5.49568(131)	0.067(5)	227.5(4.6)	7.1	$f_{24} + f_7$	148	5.90376(220)	0.040(5)	357.2(7.7)	4.2	$2f_{36}$
87	3.07847(135)	0.065(5)	121.1(4.7)	6.9	$\sim f_{22}$	149	5.61781(218)	0.040(5)	24.3(7.6)	4.3	$\sim f_{121}$
88	1.32254(135)	0.065(5)	188.5(4.7)	6.9	$\sim f_3 (\sim 3f_{\text{orb}})$	150	1.18403(224)	0.039(5)	339.5(7.8)	4.2	$\sim f_{33}$
89	4.16421(136)	0.064(5)	275.9(4.7)	6.9	$\sim f_{58}$	151	11.12242(226)	0.039(5)	294.3(7.9)	4.1	$2f_{121}$
90	64.26968(138)	0.063(5)	310.0(4.8)	6.8	$f_1 - f_{69}$	152	7.98735(226)	0.039(5)	95.6(7.9)	4.1	$2f_{60}$
91	1.88998(139)	0.063(5)	207.3(4.8)	6.7	$2f_{25}$	153	3.70102(228)	0.038(5)	190.4(7.9)	4.1	$\sim f_{24}$
92	2.79699(122)	0.072(5)	29.2(4.3)	7.7	$2f_{51}$	154	1.29126(228)	0.038(5)	300.5(8.0)	4.1	$\sim f_{35}$
93	62.21289(141)	0.062(5)	17.6(4.9)	6.6	$f_2 - f_{65}$	155	4.21931(227)	0.038(5)	187.5(7.9)	4.1	$\sim f_{58}$
94	6.34907(141)	0.062(5)	348.4(4.9)	6.6	$2f_{14}$	156	20.99231(230)	0.038(5)	104.9(8.0)	4.1	$f_{117} + f_{132} - f_5$
95	1.37020(141)	0.062(5)	197.7(4.9)	6.6	$\sim f_3 (\sim 3f_{\text{orb}})$						

Appendix B: Spot migration

This appendix includes information about the migration of spots in time for all systems. Details can be found in Sect. 3.

Fig. B.1. Upper panel: spot migration diagram for KIC 06669809. Lower panels: the location of the spot (crosses) on the surface of the secondary component during the first day (left) and the last day (right), when the system is at orbital phase 0.34.

Fig. B.2. Same as Fig. B.1, but for the first spot of KIC 10581918, when the system is at orbital phase 0.32.

Fig. B.3. Same as Fig. B.1, but for the second spot of KIC 10581918, when the system is at orbital phase 0.76.

Table B.1. Spot parameters for all systems.

Time (days)	Co-lat. (°)	Long. (°)	Radius (°)	$Tf(\frac{T_{\text{spot}}}{T_{\text{eff}}})$	Time (days)	Co-lat. (°)	Long. (°)	Radius (°)	$Tf(\frac{T_{\text{spot}}}{T_{\text{eff}}})$
KIC 06669809					21.645	26.5	42.8	25.4	0.67
0.367	59.6	27.1	20.5	0.80	22.379	25.7	44.8	25.7	0.64
1.101	58.7	26.0	20.4	0.80	23.113	25.4	45.5	25.3	0.63
1.834	59.2	25.9	19.6	0.78	23.846	25.3	46.5	25.2	0.62
2.568	57.7	27.4	19.6	0.77	24.580	24.6	47.4	25.3	0.61
3.302	56.3	27.5	19.9	0.77	25.314	23.7	48.3	25.7	0.63
4.036	55.7	27.7	20.3	0.76	26.048	24.1	46.9	25.7	0.63
4.769	54.5	28.5	19.9	0.76	26.781	26.6	46.4	24.9	0.67
5.503	51.4	31.7	20.2	0.78	27.515	27.2	46.8	25.1	0.68
6.237	49.5	30.7	20.4	0.77	28.249	26.6	48.2	25.6	0.68
6.971	48.4	30.0	20.1	0.76	28.983	28.8	47.3	25.1	0.72
7.704	46.5	28.9	20.2	0.73	29.716	28.5	47.6	24.6	0.67
8.438	45.2	32.2	20.7	0.73	30.450	27.4	47.0	25.3	0.67
9.172	45.0	33.8	21.2	0.74	KIC 11175495				
9.905	40.9	35.4	21.4	0.72	1.096	46.0	263.1	24.0	0.91
10.639	40.3	34.6	21.6	0.68	3.287	44.8	262.9	24.3	0.91
11.373	39.2	33.0	22.3	0.67	5.478	37.3	253.0	31.3	0.92
12.107	38.2	34.2	22.6	0.69	7.669	34.6	242.8	32.6	0.93
12.840	36.8	33.5	23.0	0.71	9.860	42.9	226.7	25.8	0.92
13.574	37.1	34.5	22.7	0.70	12.051	73.1	217.0	27.7	0.94
14.308	36.0	33.9	22.9	0.71	14.242	75.6	200.3	31.9	0.94
15.042	34.7	36.9	23.4	0.68	16.433	71.1	194.9	28.8	0.95
15.775	32.4	36.0	23.5	0.71	18.624	77.1	188.5	22.6	0.92
16.509	32.5	35.4	22.3	0.68	20.815	79.7	185.3	22.3	0.94
17.243	32.3	39.1	23.2	0.64	23.007	86.1	188.3	18.0	0.92
17.977	32.1	37.8	23.2	0.62	25.198	86.8	200.6	17.3	0.95
18.710	30.4	39.4	22.8	0.62	27.389	86.5	198.5	17.3	0.94
19.444	30.9	38.5	23.7	0.66	29.580	84.8	208.9	19.0	0.95
20.178	27.5	39.2	25.2	0.66	31.771	90.5	205.2	26.3	0.94
20.912	27.1	41.3	25.5	0.66	KIC 10581918				
Spot 1					Spot 2				
0.901	87.9	56.2	19.9	0.86	0.901	146.2	288.6	50.0	0.80
2.703	89.9	56.0	18.1	0.81	2.703	123.3	283.5	54.5	0.91
4.505	90.7	63.0	17.3	0.81	4.505	131.3	281.8	54.3	0.89
6.307	95.2	59.6	13.9	0.66	6.307	134.1	283.3	52.0	0.88
8.108	84.9	52.0	14.3	0.75	8.108	138.0	284.5	53.6	0.88
9.910	92.6	53.5	14.3	0.73	9.910	133.4	280.2	51.8	0.88
11.712	92.5	52.0	14.1	0.70	11.712	134.0	281.0	52.1	0.87
13.514	92.3	57.4	13.6	0.66	13.514	128.8	280.7	49.9	0.87
15.316	87.8	52.2	12.3	0.69	15.316	131.5	282.4	49.1	0.86
17.118	86.5	63.4	12.9	0.76	17.118	132.5	278.6	48.2	0.86
18.920	89.5	57.3	13.6	0.82	18.920	130.6	280.0	49.5	0.87
20.721	89.9	62.1	13.2	0.85	20.721	134.0	279.5	50.4	0.86
22.523	89.9	56.0	13.2	0.87	22.523	127.6	274.6	52.6	0.88
24.325	113.9	63.4	13.1	0.84	24.325	133.6	277.4	53.8	0.87
26.127	123.8	76.7	12.2	0.78	26.127	128.6	276.6	51.2	0.87
27.929	120.3	80.6	11.4	0.81	27.929	130.1	273.4	49.3	0.86
KIC 10619109					Spot 2				
Spot 1					Spot 2				
1.023	97.5	11.1	13.8	1.10	1.023	92.2	251.1	16.6	1.21
3.068	94.0	52.3	12.2	1.09	3.068	92.9	256.5	17.0	1.21
5.113	86.3	62.3	17.9	1.06	5.113	95.1	258.2	16.2	1.19
7.158	107.5	12.5	10.5	1.14	7.158	96.6	237.5	16.5	1.22
9.203	108.1	15.5	10.0	1.13	9.203	97.3	244.9	15.6	1.27
11.249	98.5	0.6	9.0	1.19	11.249	95.2	256.8	17.7	1.26
13.294	98.5	0.0	9.0	1.09	13.294	95.8	259.7	17.9	1.26
15.339	106.4	5.6	11.8	1.16	15.339	96.7	262.6	17.8	1.29
17.384	107.2	17.9	10.9	1.15	17.384	90.4	275.1	15.6	1.29
19.429	94.6	6.4	9.3	1.13	19.429	91.6	259.3	14.4	1.27
21.474	96.2	51.8	15.5	1.11	21.474	90.2	257.0	15.3	1.28
23.520	87.0	42.3	11.6	1.14	23.520	89.2	246.9	15.6	1.26
25.565	87.0	27.5	9.1	1.10	25.565	87.4	252.9	11.2	1.27

Fig. B.4. Same as Fig. B.1, but for the first spot of KIC 10619109, when the system is at orbital phase 0.40.

Fig. B.6. Same as Fig. B.1, but for KIC 11175495, when the system is at orbital phase 0.84.

Fig. B.5. Same as Fig. B.1, but for the second spot of KIC 10619109, when the system is at orbital phase 0.80.