KIC 4544587: an eccentric, short-period binary system with δ Scuti pulsations and tidally excited modes

K. M. Hambleton, D. W. Kurtz, A. Prša, J. A. Guzik, K. Pavlovski, S. Bloemen, J. Southworth, K. Conroy, S. P. Littlefair and J. Fuller

1Jeremiah Horrocks Institute, University of Central Lancashire, Preston PR1 2HE, UK
2Instituut voor Sterrenkunde, KU Leuven, Celestijnenlaan 200D, B-3001 Leuven, Belgium
3Department of Astronomy and Astrophysics, Villanova University, 800 East Lancaster Avenue, Villanova, PA 19085, USA
4Los Alamos National Laboratory, XTD-2 MS T-086, Los Alamos, NM 87545-2345, USA
5Department of Physics, Faculty of Science, University of Zagreb, Croatia
6Astrophysics Group, Keele University, Staffordshire ST5 5BG, UK
7Department of Physics and Astronomy, Vanderbilt University, Nashville, TN 37235, USA
8Department of Physics and Astronomy, University of Sheffield, Sheffield S3 7RH, UK
9Center for Space Research, Department of Astronomy, Cornell University, Ithaca, NY 14853, USA

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ABSTRACT

We present Kepler photometry and ground-based spectroscopy of KIC 4544587, a short-period eccentric eclipsing binary system with self-excited pressure and gravity modes, tidally excited modes, tidally influenced p modes and rapid apsidal motion of 182 yr per cycle. The primary and secondary components of KIC 4544587 reside within the δ Scuti and γ Dor instability region of the Hertzsprung–Russell diagram, respectively. By applying the binary modelling software PHOEBE to prewhitened Kepler photometric data and radial velocity data obtained using the William Herschel Telescope and 4-m Mayall telescope at Kitt Peak Northern Observatory (KPNO), the fundamental parameters of this important system have been determined, including the stellar masses, 1.98 ± 0.07 and 1.60 ± 0.06 M⊙, and radii, 1.76 ± 0.03 and 1.42 ± 0.02 R⊙, for the primary and secondary components, respectively. Frequency analysis of the residual data revealed 31 modes, 14 in the gravity mode region and 17 in the pressure mode region. Of the 14 gravity modes, 8 are orbital harmonics: a signature of tidal resonance. While the measured amplitude of these modes may be partially attributed to residual signal from binary model subtraction, we demonstrate through consideration of the folded light curve that these frequencies do in fact correspond to tidally excited pulsations. Furthermore, we present an echelle diagram of the pressure mode frequency region (modulo the orbital frequency) and demonstrate that the tides are also influencing the p modes. A first look at asteroseismology hints that the secondary component is responsible for the p modes, which is contrary to our expectation that the hotter star should pulsate in higher radial overtone, higher frequency p modes.

Key words: binaries: eclipsing – stars: individual: KIC 4544587 – stars: oscillations – stars: variables: δ Scuti.

1 INTRODUCTION

The δ Scuti stars form an integral part of the instability strip, spanning a 2-mag range of evolutionary stages, from pre-main sequence to the terminal-age main sequence (Rodríguez & Breger 2001). Their luminosities are in the range 0.6 ≤ log (L/L⊙) ≤ 2.0 and their effective temperatures in the range 6300 ≤ T_eff ≤ 9000 K (Buzasi et al. 2005). They oscillate in radial and non-radial pressure modes (p modes) and low-order gravity modes (g modes) with observed periods ranging from approximately 18 min to 8 h (Pamyatnykh 2000; Amado et al. 2004; Grigahcène et al. 2010a).

The κ-mechanism is the primary driving mechanism of δ Scuti pulsations, although Antoci et al. (2011) suggested that one δ Scuti star may pulsate with stochastically excited modes similar to those seen in the Sun and solar-like pulsators. δ Scuti stars have a mass range between 1.5 and 2.5 M⊙ (Lefèvre et al. 2009). At approximately 2 M⊙ there is a transitional phase where the size of the convective outer envelope becomes negligible for higher mass stars and their outer envelopes become dominated by radiative energy transport; at approximately 1.5 M⊙, stars of higher mass develop

*E-mail: kmhambleton@uclan.ac.uk

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a convective core (Aerts, Christensen-Dalsgaard & Kurtz 2010). As this critical transition in the convective envelope occurs within the range of masses encompassed by δ Scuti stars, the asteroseismic investigation of δ Scuti stars may eventually unveil fundamental information pertaining to the physical processes that govern this transition.

γ Dor stars are main-sequence stars in the temperature range $6800 \leq T_{\text{eff}} \leq 7600$ K that pulsate in high-order gravity modes driven by convective blocking (Guzik et al. 2000) with pulsation periods typically of the order of 1 d (Grigahcène et al. 2010b). As γ Dor stars are a relatively new class of stars (Balona, Krickiscuñas & Cousins 1994), until recently their recorded numbers were low and consequently δ Scuti stars were believed to dominate the classical pulsators on the main sequence (Breger 2000). However, with the implementation of advanced instruments such as Kepler (Borucki et al. 2010; Batalha et al. 2010; Gilliland et al. 2010), MOST (Walker et al. 2003) and CoRoT (Baglin et al. 2006), many stars demonstrating both δ Scuti and γ Dor characteristics have been observed; thus, new classification criteria, containing γ Dor–δ Scuti and δ Sct–γ Dor hybrid stars, have been introduced (Grigahcène et al. 2010a).

Following this revision, through the characterization of 750 A–F type main-sequence stars, the percentage of δ Scuti stars on the main sequence is now estimated to be 27 per cent, γ Dor stars accounting for 13 per cent, hybrids accounting for 23 per cent and the remaining stars being classified as other types of variables, e.g. spotted stars showing rotational variations (Uytterhoeven et al. 2011).

In a study of 119 A0–A9 stars, 35 ± 5 per cent were found to be in multiple systems (Abt 2009). However, only 22 per cent of the δ Scuti stars catalogued are known to be multiple stars (Rodríguez & Breger 2001). In binary systems the rotational velocity of each stellar component tends towards a velocity that is synchronous with the orbital period as the orbit evolves. As synchronous velocity depends linearly on radius and scales with orbital period (to the power of 2/3), it generally implies an equatorial velocity less than of 120 km s$^{-1}$ (Abt 2009), while most δ Scuti stars are found to have velocities greater than 120 km s$^{-1}$. Below this value the turbulence in the outer stellar envelope only enables a negligible amount of meridional mixing to occur. This allows for diffusion to take place, which prevents pulsation through the settling of helium out of the Ne ii ionization zone (Breger 1970). Thus, it has previously been assumed that multiplicity indirectly inhibits pulsation. However, there are many cases, including HD 174884 (Maceroni et al. 2009), HD 177863 (Willems & Aerts 2002) and the newly identified class of eccentric ellipsoidal variables known as heartbeat stars (Thompson et al. 2012) – including the iconic KOI-54 (Welsh et al. 2011; Burkart et al. 2012; Fuller & Lai 2012) – that demonstrate how, in some circumstances, multiplicity can not only alter but also increase pulsation amplitudes through the tidal excitation of eigen-modes. It is worthy of note, however, that the existence of tidally driven modes in binary star systems does not invalidate the theory that binarity also indirectly suppresses self-excited modes.

Through the use of binary modelling techniques, direct measurements of stellar masses, radii and distances are possible. Asteroseismic modelling of the identified modes can provide information pertaining to the internal stellar structure and rotation of the pulsating component, making multiple systems with δ Scuti components extremely valuable. Currently, the thorough asteroseismic analysis of δ Scuti stars is rarely achieved due to our current inability to model a large number of oscillatory modes excited via the $\kappa$-mechanism. However, with the advent of cutting-edge observations from instruments such as Kepler and CoRoT and new methodologies such as those used by García Hernández et al. (2009) on HD 174936, it is expected that an increasing number of these intriguing objects will be solved in the foreseeable future.

The Kepler satellite, with its highly precise photometry, is generating observations unparalleled in precision and subsequently giving greater insight into the study of stellar structure through the use of asteroseismology. The primary objective of the Kepler mission is the identification and classification of planets through the transit method. However, the instrumentation required for such observations is highly applicable to the field of asteroseismology (Gilliland et al. 2010). Attributes, such as a stable platform, that enable extended observations, and a precision as good as a few parts per million, make the Kepler observations quintessential for the advancement of asteroseismology. A dynamic range of over 10 mag, in addition to a 105 deg$^2$ field of view, gives Kepler an unprecedented advantage for obtaining high-quality asteroseismic data. Moreover, the ability to generate short-cadence data of ~1 min time resolution allows for detailed photometric analyses of pulsating stars across the Hertzsprung–Russell (H-R) diagram.

KIC 4544587 (where KIC is an acronym for ‘Kepler Input Catalogue’) is an eccentric ($e = 0.28$), short-period ($P = 2.1891$ d) binary system that contains at least one pulsating component (cf. Table 1 for a list of observable information and identifiers). It was initially identified as a binary by Prša et al. (2011) as part of the first release of the Kepler Eclipsing Binary Catalog (http://keplerbios.villanova.edu). The temperature of the primary component is equivalent to a late A-type star that is within the δ Scuti instability strip and the secondary component’s temperature is indicative of an early F star, which is likely to be a γ Dor variable.

Primarily this object was selected as a likely candidate for tidally induced pulsations due to the close proximity of the components at periastron, ~ 4 R$_\odot$ surface to surface. KIC 4544587 also has interesting orbital characteristics including a brightening at periastron in the Kepler photometric light curve due to the combination of tidal distortion and substellar heating. Such a feature is indicative of an eccentric binary with its components in close proximity (Maceroni et al. 2009; Thompson et al. 2012).

In this paper, information obtained from modelling the binary features of the photometric and radial velocity (RV) curves of KIC 4544587, and the results of the pulsational frequency analysis are presented. In Section 2, the observations are discussed, including adjustments to the original data set. Sections 3 and 4 describe the spectral disentangling and the atmospheric parameters determined from the disentangled spectra. In Section 5, the determination of the orbital period is detailed. In Section 6, the binary light-curve modelling method is discussed, which focuses on the use of the binary modelling software, PHOEBE (Prša & Zwitter 2005). Section 7

**Table 1.** Other identifiers and basic data for KIC 4544587. The Kp passband specified is derived from the Kepler broad-band filter.

| Identifiers | TYC         | 3124-1348-1 |
|            | GSC         | 03124-01348 |
|            | 2MASS       | J19033272+3940103 |
| Position and brightness | RA (J2000) | 19:03:32.7274 |
|            | Dec. (J2000)| +39:41:00.314 |
|            | $V$         | 10.8 |
|            | $B$         | 10.9 |
|            | $Kp$        | 10.8 |
contains the frequency analysis and includes discussion of the evidence for resonance effects. A summary of this paper, with concluding remarks, is given in Section 8.

2 OBSERVATIONS

2.1 Kepler photometry

The Kepler photometric observations of KIC 4544587 consist of both long-cadence (hereafter LC) data, during Quarters 0–11, and short-cadence (hereafter SC) data during Quarters 3.2, 7, 8, 9 and 10. For our purposes we used a subset of these data up to and including Quarter 8 (see Table 2 and Fig. 1), which were available at the time of analysis. A quarter is defined as a quarter of a complete, 372.5-d, Kepler orbit around the Sun (Kjeldsen et al. 2010). LC data correspond to a sampling rate of 29.4244 min and SC data to a sampling rate of 58.8488 s. For both formats 6.02-s exposures are co-added on board; this occurs 270 times to form an LC and 9 times to form an SC data point (Caldwell et al. 2010), with any remaining time attributed to readout time. The data are time-stamped with truncated Barycentric Julian Date (Gilliland et al. 2010), which is Barycentric Julian Date minus 2400000. The total Kepler photometric observations that have been analysed span from 2009 May to 2011 March and comprise 277 514 data points.

The photometric observations were made using the Kepler broad-band filter, which is similar to Cousins Rc. It is advised in the data release notes that accompany the Kepler data that the corrections made in the pipeline can have adverse effects on the binary signal in the data. For this reason the simple aperture photometry light curves were used instead of those created by the photometer performance assessment portion of the pipeline (Li et al. 2010).

From the total data set, 9471 points were removed as outliers, of which 661 data points were removed from Quarter 3.2, 2448 from Quarter 7 and 5597 from Quarter 8. These outliers were selected by eye as the intrinsic variations in the data significantly reduce the effectiveness of automated sigma clipping. Cosmic rays and other noise sources are the dominant causes of outliers, and small gaps in the data are also present due to safe-mode events, spacecraft rolls and brightening events known as Argabrightening, named after the discoverer, V. Argabright (Van Cleve 2009). These gaps, however, are minimal, which can be seen by the high duty cycle that was obtained for each quarter independently, with the exception of the safe-mode event at the beginning of Quarter 8.

The SC data have the advantage of increased time resolution, which enables the identification of the p-mode pulsations present in this object (see Fig. 2). Consequently, Quarters 7 and 8 were used for the binary modelling and mode identification of KIC 4544587 (with the exception of modelling the rate of apsidal advance where all LC data were used). A customized target mask was constructed for Quarters 7 and 8 so that the average flux level was consistent over the two quarters. This is important for asteroseismic analysis as quarter-to-quarter flux variations can cause instrumental amplitude modulation in the data. Pyke software (provided by the Kepler Guest Observer office: http://keplergo.arc.nasa.gov/) was used to define the mask, generate the new data files and convert the data from FITS to ASCII format. We detrended and normalized each month of data individually by fitting a first- or second-order Legendre

Table 2. The number of data points and duty cycle acquired for each individual Kepler quarter. The LC data correspond to a sampling rate of 29.4244 min and SC data to a sampling rate of 58.8488 s.

| Quarter | Cadence | Number of data points | Duty cycle (per cent) |
|---------|---------|-----------------------|----------------------|
| 0       | LC      | 476                   | 99.5                 |
| 1       | LC      | 1639                  | 98.1                 |
| 3.2     | SC      | 44 000                | 98.5                 |
| 6       | LC      | 4397                  | 97.2                 |
| 7       | SC      | 128 830               | 98.1                 |
| 8       | SC      | 98 190                | 94.3                 |

Figure 1. The observed Kepler SC light curve of KIC 4544587 for Quarters 7 (upper panel) and 8 (lower panel). Data are missing from the beginning of Quarter 8 due to a safe-mode event. The time is in BJD.
The initial RV curves were determined using the 2D cross-correlation technique as implemented in TODCOR (Two-dimensional Correlation Technique, Zucker & Mazeh 1994) on the red and blue spectra together. The templates for the primary and secondary components were taken from Castelli & Kurucz (2004) model atmospheres, using $T_1 = 8250$ K, $\log g_1 = 4.0$, [M/H]$_1 = 0.0$ and $T_2 = 8000$ K, $\log g_2 = 4.0$, [M/H]$_2 = 0.0$, respectively. Of the 38 spectra taken, cross-correlation failed to produce a good RV fit for one spectrum. Subsequent improvement to the RV curves was done by revising the templates according to the best-fitting photometric model and applying them to both blue and red ends: $T_1 = 8600$ K, $\log g_1 = 4.24$ and $T_2 = 7750$ K, $\log g_2 = 4.33$, respectively. A systematic offset slightly larger than 1σ was found between the RVs of the red arm and the blue arm. As there is no obvious cause for this discrepancy, each simultaneous exposure was averaged over the two arms and the discrepancy included in the uncertainty of the RV measurements. The final RV data have a typical 1σ uncertainty of $\sim 7.3 \text{ km s}^{-1}$ and are listed in Table 3 and depicted in Fig. 3 with the best-fitting RV model folded on the period and zero-point obtained from the light curve.

Subsequently, five high-resolution spectra were taken using the echelle spectrograph on the 4-m Mayall telescope at KPNO with $R \sim 20 000$ and a wavelength range of 4500–9000 Å. The data were wavelength-calibrated and flux-normalized as depicted in Fig. 4, where Doppler splitting is clearly visible. As the per-wavelength S/N ratio of the KPNO spectra is notably lower than the WHT spectra, the 2D cross-correlation technique, TODCOR, gave significantly larger uncertainties. We consequently used the broadening function technique (Rucinski 1992) to determine the RVs for KPNO spectra. The broadening functions are rotational broadening kernels, where the centroid of the peak yields the Doppler shift and where the width of the peak is a measure of the rotational broadening. For the template we used the RV standard HD 182488, with $v_{\text{rot}} = -21.508 \text{ km s}^{-1}$.

### 3 SPECTRAL DISENTANGLING: ORBIT

We applied the technique of spectral disentangling (hereafter SPD) to isolate spectra for the two binary components individually (Simon & Sturm 1994). Through this technique we determined the effective polynomial to segments of data separated by gaps (i.e. caused by spacecraft rolls and safe-mode events). As the eclipses affect the detrending process, we elected to fit the polynomials to the out-of-eclipse envelope only. The out-of-eclipse envelope was identified by sigma clipping the data. Using this method we (temporarily) removed all data points 5σ above and 0.05σ below the light curve. The long-term trends in the out-of-eclipse envelope were then fitted and the trends removed from the original data. Finally, we applied a Fourier transform to the polynomials and found that all significant peaks were $\nu < 0.03$ d$^{-1}$, showing that we did not remove any information intrinsic to the system through this method.

As each Kepler pixel is 4 x 4 arcsec, it is expected that some contamination may occur within the photometric mask. The contamination value for KIC 4544587, specified by the Kepler Asteroseismic Science Operations Center, is estimated to be 0.019, where 0 implies no contamination and 1 implies complete contamination of the CCD pixels. This contamination value suggests that KIC 4544587 suffers minimally from third light, if at all. We applied the PAMELA software to the target pixel files to assess the flux incident on each individual pixel. Light curves for each pixel were generated and the flux distribution over the newly defined masks was examined. From this we determined that the contamination level for KIC 4544587 is negligible.

#### 2.2 Ground-based spectroscopy

38 spectra were obtained using the Intermediate dispersion Spectrograph and Imaging System (ISIS) on the William Herschel Telescope (WHT). The spectra were taken on 2011 June 18–21 and 2012 June 7–14 with resolving powers of $R \sim 17 000$ and $\sim 22 000$, respectively. Calibration exposures using CuAr and CuNe lamps were taken prior to each 300-s exposure of KIC 4544587. Blue and red spectra were obtained using wavelength coverages of 4200–4550 and 6100–6730 Å, respectively. The gratings H2400B (blue arm) and R1200R (red arm) were used. A 0.5-arcsec slit was used to give Nyquist sampling on the CCD and to limit RV errors due to the positioning of the star within the slit. The signal-to-noise (S/N) obtained was $\sim 100$ per resolution element. The data were reduced using optimal extraction techniques as implemented in the PAMELA package (Marsh 1989).
temperatures of the two components using the Balmer lines. The medium-resolution ISIS/WHT spectra, described in Section 2.2, contain Hγ and Hδ lines, and the medium-resolution echelle KPNO spectra contain Hβ and Hγ lines. The fdbinary1 code (Ilijić et al. 2004), which is based on a Fourier variant of SPD (Hadrava 1995), was first applied to the time series of ISIS/WHT spectra since they are more numerous than the KPNO spectra. Since some of the eclipse spectra are affected by the Rossiter–McLaughlin effect, and the line profiles are disturbed, only out-of-eclipse spectra were used. This substantially reduced the number of spectra available for SPD, but the phase coverage was still adequate to suppress the undulations in the disentangled spectra of the components (Hensberge, Ilijić & Torres 2008). The absence of in-eclipse spectra resulted in an ambiguity in the placement of the continuum of the disentangled spectra. Therefore, we performed SPD in separation mode, and then corrected the separated spectra for line blocking and light dilution using the procedure described in Pavlovski & Hensberge (2005).

In SPD individual component spectra are calculated simultaneously and are self-consistently optimized with the orbital parameters, whereby the determination of RVs is bypassed (Simon & Sturm 1994; Hadrava 1995). In this sense, each individual RV exposure is not optimized and as such no comparison can be made with measured RVs (Pavlovski & Hensberge 2010). The orbital parameters calculated by SPD are given in Table 4 and represent the mean values calculated through disentangling five short spectral regions from the ISIS/WHT blue spectra, which cover the spectral interval from 4200 to 4600 Å. Telluric lines affect the ISIS/WHT red spectra, which are centred on the Hγ line; thus, we removed them manually before the application of SPD. Since only five spectra were available in the region of the Hγ line, when using SPD, we fixed all the orbital parameters with the exception of the time of periastron.

An important outcome of SPD is an enhancement of the S/N ratio in the disentangled spectra, as the spectra are co-added during the SPD process. Due to the significant number of WHT/ISIS blue and red spectra, the S/N has vastly improved. However, for the KPNO spectra the gain is small due to the limited number of spectra available for analysis. The effect of disentangling on the S/N ratio, for different numbers of input spectra (as well as their original S/N), is clearly depicted in Fig. 5.

### 4 ATMOSPHERIC PARAMETERS

Once separated, the spectra remain in the common continuum of the binary system, diluted by their companion’s contribution to the total light of the system. The light ratio between the components is derived from the light-curve solution and makes renormalization of the individual component spectra straightforward. We further computed the light ratio for the Johnson $U$ (0.685), $B$ (0.697) and $V$ (0.667) passbands, whilst keeping all other parameters fixed, to determine the deviation of the light ratio as a function of wavelength. We note that the value derived from the light curve using the Kepler passband (0.670) is approximately equal to that of the Johnson $V$ band, so we expected that the $Hγ$ line is most affected by our selection as its wavelength is furthest from the Johnson $V$ band. Consequently, with the surface gravities of the components known from the complementary light and RV curve solutions, the degeneracy between the effective temperature and the surface gravity can be broken. We determined the components’ effective temperatures by fitting the renormalized individual spectra with the synthetic theoretical spectra (Tamajo, Pavlovski & Southworth 2011).

The genetic algorithm, as implemented in PIKAIA (Charbonneau 1990), was used in the global optimization of the code STARFIT (Pavlovski et al., in preparation). A grid of local thermodynamic

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1. http://sail.zpf.fer.hr/fdbinary

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| Table 3. RV data of the primary (RV1) and secondary (RV2) components and their respective uncertainties (standard deviation) for 38 spectra obtained with the WHT and 5 spectra from the 4-m Mayall telescope. The ISIS was used in conjunction with the WHT to obtain simulations red-band (6100–6730 Å) and the blue-band (4200–4550 Å) spectra. The average RV for each given time is specified. The echelle spectrograph was used on the 4-m Mayall telescope. |
|---|---|---|
| Time (BJD) | RV1 (km s$^{-1}$) | RV2 (km s$^{-1}$) |
|---|---|---|
| WHT | | |
| 245 5730.621 52 | 71.9 ± 5.2 | -133.8 ± 6.5 |
| 245 5730.657 50 | 91.2 ± 4.7 | -154.5 ± 5.8 |
| 245 5730.699 32 | 102.2 ± 4.1 | -177.3 ± 5.3 |
| 245 5731.556 25 | -52.2 ± 5.3 | 30.9 ± 5.7 |
| 245 5731.601 21 | -62.3 ± 5.3 | 37.8 ± 5.7 |
| 245 5731.646 68 | -69.4 ± 5.9 | 43.8 ± 5.5 |
| 245 5731.701 16 | -77.3 ± 4.8 | 50.4 ± 5.9 |
| 245 5732.439 58 | -79.5 ± 4.9 | 54.9 ± 5.8 |
| 245 5732.485 00 | -67.9 ± 4.7 | 46.0 ± 5.3 |
| 245 5732.525 38 | -54.9 ± 4.7 | 36.8 ± 5.9 |
| 245 5732.577 57 | -38.0 ± 5.0 | 16.1 ± 8.7 |
| 245 5732.622 38 | -25.4 ± 3.8 | 5.3 ± 9.3 |
| 245 5732.637 57 | -12.2 ± 4.3 | 19 ± 12 |
| 245 5732.692 00 | 13.9 ± 9.6 | -52 ± 39 |
| 245 5732.726 88 | 29.2 ± 3.5 | -103.1 ± 9.2 |
| 245 5733.411 85 | 46.1 ± 7.3 | -74.6 ± 5.0 |
| 245 5733.459 56 | -2 ± 22 | -55.3 ± 5.5 |
| 245 5733.504 35 | -23.6 ± 9.7 | -42.6 ± 5.2 |
| 245 5733.540 24 | -31.4 ± 5.3 | -22.6 ± 5.9 |
| 245 5733.576 12 | -32.5 ± 9.7 | -4.6 ± 9.5 |
| 245 5733.667 81 | -41 ± 17 | 14 ± 14 |
| 245 5734.031 71 | 170 ± 4.8 | 81 ± 20 |
| 245 5734.434 76 | -108.0 ± 7.2 | 79.0 ± 7.4 |
| 245 5734.515 79 | -100.0 ± 6.8 | 72.8 ± 8.0 |
| 245 5734.559 67 | -99.2 ± 9.0 | 66.5 ± 8.7 |
| 245 5734.602 65 | -94.6 ± 9.0 | 53.4 ± 8.9 |
| 245 6068.653 88 | -108.1 ± 4.2 | 82.3 ± 5.1 |
| 245 6087.475 73 | 82.3 ± 4.5 | -146.8 ± 5.5 |
| 245 6087.579 88 | 119.9 ± 4.2 | -193.3 ± 5.3 |
| 245 6087.671 36 | 123.6 ± 4.2 | -198.0 ± 5.1 |
| 245 6087.734 10 | 113.4 ± 4.0 | -184.5 ± 5.0 |
| 245 6088.612 05 | -91.0 ± 4.2 | 59.7 ± 4.9 |
| 245 6089.573 01 | 37.8 ± 3.8 | -105.8 ± 6.5 |
| 245 6089.678 23 | 88.0 ± 4.1 | -155.9 ± 4.9 |
| 245 6089.732 87 | 109.0 ± 4.7 | -181.1 ± 5.6 |
| 245 6090.717 62 | -79.3 ± 4.4 | 49.7 ± 5.1 |
| 245 6091.496 76 | -71.9 ± 5.4 | 39.4 ± 6.3 |
| 245 6092.449 32 | 37 ± 15 | -64.9 ± 7.1 |

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1. http://sail.zpf.fer.hr/fdbinary
Figure 3. Top panel: RV curve generated from 38 spectra obtained using ISIS on the WHT and 5 spectra obtained using the echelle spectrograph on the 4-m Mayall telescope at KPNO, folded over the orbital period. The blue solid circles and light blue open circles represent the primary component from the WHT and KPNO data, respectively, the green solid triangles and the pink open triangles represent the secondary component from the WHT and KPNO data, respectively, and the solid and dashed lines represent the primary and secondary components. The errors bars show the uncertainties in the RV measurements. Bottom panel: the residuals from the best fit to the RV data.

Figure 4. The Hα region of the five echelle spectra acquired by the 4-m Mayall telescope at Kitt Peak with $R \sim 20,000$ and the wavelength span 4500–9000 Å. The components are clearly resolved in the five spectra.

Table 4. The orbital elements of the binary system KIC 4544587 derived by SPD of time series ISIS/WHT blue spectra.

| Parameter                  | SPD          |
|----------------------------|--------------|
| Orbital period $P$ (d)     | 2.189 094 (fixed) |
| Time of periastron passage, $T_0$ (BJD) | 245 5461.450(1) |
| Eccentricity, $e$          | 0.288(26)    |
| Longitude of periastron, $\omega$ | 328.5(22)    |
| Velocity semi-amplitude $K_A$ (km s$^{-1}$) | 117.8(9)     |
| Velocity semi-amplitude $K_B$ (km s$^{-1}$) | 145.8(10)    |
| Mass ratio $q$             | 0.808(8)     |

Figure 5. Comparison between disentangled spectra in the common continuum of the binary system (red lines, differentiable also by the noise) and best-fitting theoretical spectra (blue lines) for the secondary component (upper three spectra) and primary component (lower three spectra). The Hα, Hβ and Hγ lines are depicted in ascending order and have been offset by 0.1 for clarity.
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(Prša et al. 2011), an interactive package with a graphical user interface (GUI) that incorporates three methods: Lomb–Scargle (Lomb 1976; Scargle 1982), analysis of variance (Schwarzenberg-Czerny 1989) and box-fitting least squares (Kovács, Zucker & Mazeh 2002), as implemented in the VARTOOLS package (Hartmann 1998). Using KEPHEM, the period and time of primary minimum were found interactively. The period was determined by dragging the mouse over a periodogram in the lower panel of the GUI to see how it affected the alignment of the phased data presented in the upper panel of the GUI. To determine an accurate period, the zoom tool was utilized on both the periodogram and phased data. The zero-point was then selected by dragging the primary eclipse in the top panel containing the phased data and align it with zero phase. The ephemeris was found to be Min I = BJD 245 5462.006 137(9)+2.189 094(5) × E, where the values in the parentheses give the uncertainty in the previous digits. The uncertainties were obtained by identifying the range of values that would yield a visibly indistinguishable result; beyond this uncertainty range the discrepancy is notably increased. Due to apsidal motion, the relative separation of the eclipses changes as a function of the rotation of the orbit. Consequently, the period specified is the anomalous period, which is the period measured by phasing the data on one eclipse (primary eclipse), leaving the other eclipse (secondary eclipse) smeared. Although this is a small effect, the smearing could be seen over the duration of the data used in this analysis. See Section 6.2 for further discussion on the apsidal motion of KIC 4544587.

6 BINARY MODELLING

6.1 PHOEBE

PHOEBE (Prša & Zwitter 2005) is a binary modelling package based on the Wilson–Devlinney (hereafter WD) code (Wilson & Devinney 1971; Wilson 1979; Wilson & Van Hamme 2004). PHOEBE incorporates all the functionality of the WD code but also provides an intuitive GUI alongside many other improvements that make PHOEBE highly applicable to the precise Kepler data. These include: uncertainty calculations through heuristic scanning algorithms (which scan parameter space by generating results from multiple starting points to determine the mean and standard deviation); the facility to phase bin the data; updated filters for the various recent space missions including Kepler; the correct treatment of reddening and the ability to work with a large number of data points.

When modelling the data, the initial inputs were a combination of the effective temperatures and log g values identified through fitting the disentangled spectra with the light factors as a free parameter, 8600 ± 100 K, 7750 ± 180 K, 4.12 and 4.31, for the primary and secondary, respectively. We elected to use the results from this mode as a single light factor does not account for the change in each component’s relative light contribution for the different spectral ranges. For the initial investigation, a model light curve was generated from the observationally constrained and estimated input parameters. First, the passband luminosity of the model was computed so that the out-of-eclipse flux levels were correctly positioned with respect to the observed light-curve data. Following this the eccentricity (e) and argument of periastron (ω) were adjusted until the separation between the primary and secondary eclipses, which is proportional to e cos ω, was equal to that of the observed data. This also involved adjusting the phase shift to retain the position of the model’s eclipses. Once the separation was tightly constrained, the phase shift, e and ω were further adjusted, whilst maintaining the value for e cos ω, to obtain the relative widths of the primary

Table 5. Atmospheric parameters for the components of KIC 4544587, derived from a constrained optimal fit of the disentangled spectra with the light factor as a fixed (upper section) and free (middle section) parameter. For both the fixed and free case, the projected rotational velocities (lower section) are fixed to the values derived by the optimal fitting of the metallic lines in the disentangled ISIS/WHT blue spectra.

| Parameter         | Primary          | Secondary         |
|-------------------|------------------|-------------------|
| T eff (K)         | 8900(90)         | 7620(135)         |
| log g (cgs)       | 4.22 (fixed)     | 4.23 (fixed)      |
| Light factor      | 0.670 (fixed)    | 0.330 (fixed)     |
| T eff (K)         | 8600(100)        | 7750(180)         |
| log g (cgs)       | 4.12(2)          | 4.31(2)           |
| Light factor      | 0.634(0.646)     | 0.3660(0.354)     |
| v sin i (km s⁻¹)  | 86.5(13)         | 75.8(15)          |

equilibrium synthetic spectra was calculated using the UCLSYN² code (Smalley, Smith & Dowretskey 2001) and ATLAS9 model atmospheres for solar metallicity [M/H] = 0 (Castelli, Gratton & Kurucz 1997). The grid covers T eff from 6000 to 10 000 K in steps of 250 K, and log g from 3.50 to 4.50 in steps of 0.5 dex.

The Projected rotational velocities of the components were also optimized. However, as convolution with the rotational kernel has little influence on the broad Balmer lines, we avoided simultaneous determination of the T eff and v sin i. Instead, we determined the v sin i of the components by fitting the least blended metal lines. The results are given in Table 5. As v sin i = 86 ± 13 km s⁻¹, KIC 4544587 has an equatorial velocity of v eq < 120 km s⁻¹, below which diffusion can occur. Thus, it is likely that the primary component is a metallic-lined Am star (Abt 2009).

Alongside the optimal fitting of the renormalized disentangled spectra of Hγ, Hβ and Hα lines separately (with the surface gravities and projected rotational velocities held fixed), we have also derived optimal atmospheric parameters in the constrained mode (Tamajo et al. 2011). In constrained mode, the light ratio between the components is a free parameter when fitting for the effective temperatures. Also, the surface gravities were left to be free parameters. In the search for the optimal set of parameters, we also adjusted for the velocity shift between disentangled and theoretical spectra, to enable a slight adjustment of the continua of the disentangled spectra. Disentangling the Balmer lines is a difficult task due to their broadening, which is much larger than their Doppler shift. Moreover, when determining the effective temperature, the correct continuum placement is difficult because the Balmer lines of the primary extend over a considerable number of echelle orders, making the correction of the blaze and order merging somewhat uncertain. The optimal set of the parameters obtained when performing constrained fitting, with the light factor as both a free and fixed parameter, is given in Table 5.

5 PERIOD DETERMINATION

Period analysis was performed to identify the orbital period of the binary system. An initial estimate was obtained by applying PERIOD04 (Lenz & Breger 2004) to the SC data from Quarter 3.2 only. PERIOD04 applies a Fourier transform to the data and uses a least-squares fit to optimize the amplitudes and phases. Further analysis was then performed on all the SC data (Quarters 3.2, 7 and 8) using KEPHEM.

² http://www.astro.keele.ac.uk/~bs/pubs/uclsyn.pdf

Downloaded from https://academic.oup.com/mnras/article-abstract/434/2/925/1076715 by California Institute of Technology user on 25 April 2019
Table 6. Adjusted parameters and coefficients of the best-fitting model to the *Kepler* light curve for Quarters 7 and 8. The limb darkening coefficients correspond to the logarithmic limb darkening law. The uncertainties were determined through modelling and Monte Carlo methods, and concurred with those obtained through fitting the disentangled spectra. The limb darkening coefficients were taken from the PHOEBE limb darkening tables (Prša et al. 2011).

| Parameter                          | Values          |
|-----------------------------------|-----------------|
| Mass ratio                        | 0.810(12)       |
| Primary mass ($M_1$), $M_1$       | 1.98(7)         |
| Secondary mass ($M_2$), $M_2$     | 1.61(6)         |
| Primary radius ($R_1$), $R_1$     | 1.82(3)         |
| Secondary radius ($R_2$), $R_2$   | 1.58(3)         |
| Phase shift                       | 0.0831(3)       |
| Semimajor axis ($R_1$), $a$       | 10.855(46)      |
| Orbital eccentricity, $e$         | 0.275(4)        |
| Argument of periastron (rad), $\omega$ | 5.74(3)    |
| Orbital inclination (degrees), $i$ | 87.9(3)        |
| Primary $T_{\text{ret}}$ ($K$), $T_1$ | 86000(100)    |
| Secondary $T_{\text{ret}}$ ($K$), $T_2$ | 7750(180)     |
| Primary potential, $\Omega_1$     | 7.09(10)        |
| Secondary potential, $\Omega_2$   | 7.12(10)        |
| Gamma velocity (km s$^{-1}$)      | $-20.13(7)$     |
| Apsidal advance (yr per cycle)    | 182(5)          |
| Sidereal period (d)               | 2.189 0951(7)   |
| Primary relative luminosity        | 0.668(2)        |
| Secondary relative luminosity      | 0.332(1)        |
| Primary log $g$ (cgs), log $g_1$  | 4.241(9)        |
| Secondary log $g$ (cgs), log $g_2$| 4.33(1)         |
| Primary linear limb darkening coeff. | 0.634       |
| Secondary linear limb darkening coeff. | 0.664       |
| Primary logarithmic limb darkening coeff. | 0.282       |
| Secondary logarithmic limb darkening coeff. | 0.268       |

Table 7. Fixed parameters and coefficients for the *Kepler* best-fitting model to the *Kepler* light curve for Quarter 7. The rotation is specified as a ratio of stellar to orbital rotation, and the fine grid raster is the number of surface elements per quarter of the star at the equator and coarse grid raster is used to determine whether the stars are eclipsing at a given phase.

| Parameter                          | Values          |
|-----------------------------------|-----------------|
| Third light                       | 0.0             |
| Orbital period (d)                | 2.189 094(5)    |
| Time of primary minimum (BJD)     | 245 5462.006 137(9) |
| Primary rotation                  | 1.83            |
| Secondary rotation                | 1.83            |
| Primary bolometric albedo         | 1.0             |
| Secondary bolometric albedo       | 1.0             |
| Primary gravity brightening       | 1.0             |
| Secondary gravity brightening     | 1.0             |
| Primary fine grid raster          | 90              |
| Secondary fine grid raster        | 90              |
| Primary coarse grid raster        | 60              |
| Secondary coarse grid raster      | 60              |

and secondary eclipses, which are proportional to $e \sin \omega$. The combined depths and widths of the eclipses were then adjusted by altering the inclination and stellar potentials, respectively.

Once an initial model had been generated, the differential corrections algorithm was applied in an iterative process to obtain an accurate fit to the light-curve data. Once the model was tightly constrained, the RV curves were incorporated to fit the mass ratio, gamma velocity and the projected semimajor axis. As the photometric light curve contains essentially no information about these parameters for a detached system, the fit was performed on the RV curves independently. This avoids improper weighting due to the vastly different number of data points between the different types of curves. Once the best-fitting solution had been achieved for these parameters, the differential corrections algorithm was applied to the light curve for all other parameters specified in Table 6.

When generating the model we assumed pseudo-synchronous stellar rotation after Hut (1981), which was determined to be 1.87 times the orbital period. Pseudo-synchronous rotation is indicative of the rotational velocity of the stellar components at periastron. We also fixed the orbital period since KEPHEM is more appropriate for period determination than the differential corrections algorithm. Due to the low contamination and following the analysis of the pixel level data, we assumed no third light in the system.

When modelling a binary system with one or more pulsating components (where the pulsations occur on the time-scale of the orbit), multiple iterations are required so that the data are thoroughly prewhitened, leaving only the binary signature. This enables the orbital characteristics to be modelled correctly without interference from the stellar pulsations. The method used involved subtracting the computed orbital model from the original observed data, subsequent frequency analysis on the residual data, and finally, the removal of the identified pulsations from the original data. This method is only viable when the pulsations can be considered as perturbations, which is the case for KIC 4544587. What remains is a light curve predominantly free of pulsations for subsequent binary modelling. Three iterations were required when modelling KIC 4544587, with subsequent iterations having negligible effect. The fitted and fixed parameters, and their corresponding values for our best-fitting model, can be found in Tables 6 and 7, respectively.

The model obtained for KIC 4544587, as seen in Fig. 6, still shows some systematic discrepancies in the residuals during primary and secondary eclipses. These discrepancies arise from a combination of (1) the existence of pulsations that are commensurate with the orbital period and (2) the precise nature of the *Kepler* data. As some of the pulsations are commensurate with the orbital period, they occur at precisely the same time each orbit. During eclipse phase, however, the relative flux from the pulsating component either increases or decreases, dependent on which star is being eclipsed. This introduces a change in the amplitude of the pulsation during eclipse phase that manifests itself in the residuals of the model. Additionally, the highly precise *Kepler* data have highlighted the inadequate treatment of parameters such as limb darkening, stellar albedo and the incomplete treatment of surface discretization (Prša & Zwitter 2005), which have previously been considered satisfactory. Currently efforts are being made towards improving the models to account for the physics that has previously been omitted (Prša et al., in preparation). However, until this major task, which is outside the scope of this paper, is completed, these systematics are unavoidable when generating a binary model of the *Kepler* data and thus are accounted for in the uncertainties attributed to the fitted parameters.

Uncertainty estimates were obtained using a combination of formal errors, generated by fitting all the parameters simultaneously using PHOEBE, and those determined through Monte Carlo heuristic scanning. A scan of the parameter space was undertaken for the most correlated parameters using Monte Carlo methods. The results of the Monte Carlo simulations can be found in Figs 7 and 8. The Monte Carlo simulations perturbed the solutions of the best-fitting model by a predefined amount (5 percent) in order to identify the
The eccentric δ Sct binary: KIC 4544587

Figure 6. Middle panel: theoretical PHOEBE model (red line) and observed light curve, prewhitened with the pulsation frequencies displayed in Section 7 (black points) for the SC data of Quarters 7 and 8. Lower panel: the residuals (black points) of the best-fitting model. Upper panel: a magnified image of the out-of-eclipse data and PHOEBE model fit.

Figure 7. Density maps showing the distribution of results from the Monte Carlo simulations for the most correlated parameters: potential of the primary versus inclination (top left), primary versus secondary potential (top right), argument of periastron versus eccentricity (bottom left) and the luminosity of the primary versus the luminosity of the secondary (bottom right). The contours represent the uncertainty in terms of standard deviation, with the innermost contour representing the 1σ uncertainty and subsequent contours representing increments of 1σ.

6.2 Orbital evolution

Apsidal motion is the rotation of the elliptical orbit about the centre of mass (Claret & Gimenez 1993), which can be caused by the presence of a tertiary component or through the gravitational interactions occurring between the binary components. Using PHOEBE we determined the rate of apsidal advance for KIC 4544587 to...
occurs due to the radiative damping of tidally excited oscillations in the stellar outer envelope. For this reason, the eccentric short-period nature of KIC 4544587 is either the result of tidal capture, recent formation of the system, the presence of a tertiary component or a consequence of its resonant pulsations. As the Kepler field does not contain any prominent star-forming regions, it is not expected that KIC 4544587 is a newly formed binary system. Furthermore, as the system is formed from two intermediate-mass main-sequence stars, it is also unlikely that the system has undergone tidal capture. Thus, the eccentric nature of KIC 4544587 is likely a consequence of either a third body or the system’s extreme tidal interactions (see Section 7.1 for a discussion of tidal resonance).

7 PULSATION CHARACTERISTICS

The light curve of KIC 4544587 demonstrates clear pulsations in two regions of the frequency spectrum: with periods of the order of days and periods of the order of 30 min, both of which can be seen in the light curve. We used PERIOD04 and our own codes to generate a frequency spectrum of the residual data (the detrended data with the orbital fit subtracted), which can be seen in Fig. 10. We also performed eclipse masking by removing the data points occurring during eclipse phases to remove any residual binary information from the light curve. In the Fourier transform, the gaps created in the data manifest themselves in the window pattern, with peaks separated from the real peak by the orbital frequency. Although this is not ideal, masking is highly important for the identification of resonantly excited modes, which is a crucial aspect of the analysis of KIC 4544587. Without removing the aforementioned points, the systematics would have presented themselves as frequencies at multiples of the orbital frequency, identical to the signature of tidally excited modes; thus, masking was required to differentiate between these two possibilities.

PERIOD04 incorporates a least-squares fitting technique to simultaneously generate amplitudes and phases for all the identified frequencies. For an assumed background level of 40 μmag, we report the frequencies with amplitudes of 3σ or more. The prominent frequency peaks were identified in two regions, 0–5 and 30–50 d⁻¹, which correspond to g modes and p modes, respectively, although the lowest frequency peak [f₂₄ = 0.040 89(6) d⁻¹] is possibly due to remaining instrumental effects.

The high-frequency, high-overtone p-mode frequencies are typical for a δ Scuti star of temperature similar to that of the primary star, which is towards the hotter, blue edge of the instability strip. An estimate of the radial overtones of the modes can be made from the pulsation constant, Q, defined by the period–density relation:

$$P \sqrt{\frac{\rho}{\rho_\odot}} = Q,$$

which can be rewritten in the form

$$\log Q = -6.454 + \log P + 0.5 \log g + 0.1 M_{\text{bol}} + \log T_{\text{eff}}.$$  (2)

From the latter relation and the fundamental parameters given in Table 6, we find for the frequency range 30–50 d⁻¹ for the primary star 0.017 > Q > 0.012, and for the secondary star 0.021 > Q > 0.015. These are indicative of radial overtones in the range 3 ≤ n ≤ 5 (Stellingwerf 1979). Pulsation in higher radial overtone p modes such as these (as opposed to pulsation in the fundamental and first overtone modes) is more typical of hotter δ Scuti stars, and hence suggests that the p modes arise in the primary star.

We applied a Fourier transform up to the SC Nyquist frequency but did not find any peaks beyond 48.044 49(19) d⁻¹. Once the
frequencies specified in Table 8 had been prewhitened, an amplitude excess still remained in both the p-mode and g-mode regions. However, as we could not be certain that further detections were real, we did not continue to extract modes beyond this point.

We identified 31 frequencies, 14 in the lower frequency g-mode region and 17 p-mode region, in the frequency spectrum between 0.1 and 49 d^{-1} (see Table 8). Of the 14 g-mode frequencies, we identified 8 that are multiples of the orbital frequency (see Section 7.1).

The remaining g modes are either γ Dor pulsations, most likely from the secondary component, which is in the γ Dor instability strip, or non-resonant tidally driven modes, as predicted by Weinberg et al. (2012). Currently we are unable to differentiate as both outcomes have identical signatures, although as the secondary is in the γ Dor instability strip we would expect it to pulsate with intrinsically excited g modes.

7.1 Tidal interactions and combination frequencies

Tidally excited modes are stellar pulsations that have been excited by the tidal forces of the companion star. A prime example of this is KOI-54 (Welsh et al. 2011). In a binary system with an eccentric orbit, when a stellar eigenfrequency is close to a multiple of the orbital frequency, a near-resonance occurs that causes an increase in oscillation amplitude (relative to non-resonant modes). The signature of a tidally excited mode is an oscillation frequency at a multiple of the orbital frequency. We identified eight frequencies in the g-mode region that are multiples of the orbital frequency. We expect that these are tidally excited l = 2 modes; however, as the eclipses are only partial, we are unable to use the in-eclipse data to determine mode angular degrees or which modes belong to which star.

Previously believed to be short-lived, Witte & Savonije (1999) demonstrated that the duration of tidal resonance can be prolonged through resonant locking. Resonant locking is a result of the change in stellar spin, due to the exchange of angular momentum in the system as the orbit evolves, causing variations in the eigenfrequencies of the stellar components. This, combined with the change in the orbital period of the system, causes a coupling between the newly

| Designation | Frequency (d^{-1}) | Amplitude (flux × 10^{-3}) | Phase (rad) |
|-------------|-------------------|----------------------------|-------------|
| f_1 = ν_{orb} | 0.456 81(1) | 1.001 0.746(3) |           |
| f_2 = 4ν_{orb} | 1.827 10(1) | 0.593 0.382(4) |           |
| f_3 | 2.011 24(1) | 0.561 0.0758(5) |           |
| f_4 = 3ν_{orb} | 1.370 41(1) | 0.520 0.3514(5) |           |
| f_5 | 3.468 22(1) | 0.373 0.9864(7) |           |
| f_6 | 48.022 31(4) | 0.329 0.5472(2) |           |
| f_7 = 7ν_{orb} | 3.197 60(2) | 0.244 0.301(1) |           |
| f_8 | 41.370 20(5) | 0.236 0.8923(3) |           |
| f_9 | 4.484 95(6) | 0.181 0.7803(3) |           |
| f_10 | 0.125 46(3) | 0.164 0.9962(3) |           |
| f_11 | 46.196 62(8) | 0.152 0.9904(3) |           |
| f_12 | 0.127 21(4) | 0.140 0.9962(2) |           |
| f_13 = 97ν_{orb} | 44.309 82(9) | 0.134 0.7764(3) |           |
| f_14 = 2ν_{orb} | 0.913 88(4) | 0.133 0.0262(3) |           |
| f_15 | 48.044 49(19) | 0.122 0.3319(3) |           |
| f_16 = 10ν_{orb} | 4.567 92(4) | 0.116 0.532(2) |           |
| f_17 = 8ν_{orb} | 3.6545(5) | 0.106 0.0552(2) |           |
| f_18 | 39.542 80(11) | 0.106 0.9846(6) |           |
| f_19 | 1.611 86(5) | 0.103 0.8973(3) |           |
| f_20 | 43.447 56(12) | 0.101 0.7336(2) |           |
| f_21 | 42.187 96(12) | 0.099 0.886(3) |           |
| f_22 = 9ν_{orb} | 4.111 22(6) | 0.093 0.813(3) |           |
| f_23 | 46.583 40(13) | 0.092 0.0567(3) |           |
| f_24 | 0.040 89(6) | 0.091 0.829(3) |           |
| f_25 | 1.585 41(7) | 0.078 0.545(3) |           |
| f_26 | 38.226 68(16) | 0.076 0.1098(3) |           |
| f_27 | 44.299 02(21) | 0.054 0.801(3) |           |
| f_28 | 44.361 18(29) | 0.052 0.70(1) |           |
| f_29 | 40.053 72(23) | 0.051 0.30(1) |           |
| f_30 | 46.674 01(23) | 0.051 0.10(1) |           |
| f_31 | 44.756 38(24) | 0.049 0.68(1) |           |
| f_32 | 47.953 73(26) | 0.045 0.69(1) |           |
resonant eigenfrequency and the orbital frequency, which increases the probability of observing this intriguing phenomenon significantly.

During the identification of the frequencies the data were masked so that the Fourier transform was only applied to the out-of-eclipse data. Consequently, it is unlikely that the presence of these frequencies in the Fourier transform can be completely attributed to an inadequate orbital solution. More convincingly, Fig. 11 shows a magnified image of the out-of-eclipse phase-binned data of Quarters 7 and 8 with no frequencies removed (pink, bottom curve), all the identified frequencies except those that are harmonics prewhitened (blue, middle curve) and all the frequencies prewhitened (green, top curve). The blue and pink light curves only demonstrate a minimal difference as all non-commensurate pulsations are cancelled out when the data are phase binned. The only explanation for the remaining variation in the blue and pink light curves is that they are tidally excited pulsations. The light curves have been offset by 0.03 relative flux units for clarity.

The p modes were analysed using the unmasked residual data from Quarters 7 and 8. To look for regular spacings we generated a diagram similar to an echelle diagram (Grec, Fossat & Pomerantz 1983), but modulo the orbital frequency (cf. Fig. 12). We prewhitened all g modes prior to the identification of the p modes to avoid any crosstalk from the window pattern. In Fig. 12 the filled circles represent the frequencies in Table 8 and the open circles represent frequencies with amplitudes in the region 0.02–0.04 relative flux units. The latter are not reported in our table as they are below our predefined confidence limit, although here they highlight the vertical groupings which indicate that many of the p-mode frequencies are multiplets split by the orbital frequency.

Our working hypothesis is that the highest amplitude peak in a vertical group is the self-excited p mode and the remaining p modes in that group are the product of non-linear coupling between the self-excited p modes and tidally induced g modes. To our knowledge this effect has not previously been observed and is considered an important tool for identifying g modes in the Sun (Chapellier et al. 2012). In our case, this deduction suggests that one of the stars is pulsating in both p modes and g modes, information that we could not have determined otherwise. An alternative hypothesis, suggested by Weinberg, Arras & Burkart (2013), states that through non-resonant three wave interactions the dynamical tide can excite daughter p-mode and g-mode waves; however, we refrain from discussing the physical nature of these modes at this time. Three combination modes created from the same type of mode, however, have been observed in numerous stars including the δ Scuti stars FG Virginis (Breger et al. 2005) and KIC 11754974 (Murphy, 2012 submitted), and the white dwarf star GD 358 (Winget et al. 1994). Brickhill (1983) determined that the likely cause of combination frequencies is non-linear interactions related to convective turn-over time-scales. Changes in the convective zone during the pulsation cycle cause a change in the amount of flux attenuation. This distorts the stellar shape and causes the pulsations to deviate from pure sinusoids generating combination frequencies in the Fourier transform.

Wu & Goldreich (2001) demonstrated that non-linear interactions could help with mode identification because non-linear mode coupling will only occur between specific modes and different modes generate different amplitude combinations, e.g. l = 2 modes generate larger amplitude combination frequencies than l = 1 modes. One of the most challenging requirements of modelling δ Sc t stars is mode identification; thus, combination frequencies could be key identifiers to obtaining a true asteroseismic model of the multitude of modes presented by this fascinating object.

7.2 Pulsation frequency modulation: the FM effect

Recently Shibahashi & Kurtz (2012) have shown that pulsating stars in binary orbits have frequency multiplets split by the orbital frequency in their amplitude spectra. This is a simple consequence of the light travel time effect causing the pulsation phases to be

3 After this paper was submitted, we realized that the g modes whose frequencies are not multiples of the orbital frequencies (i.e. $f_3$, $f_5$, $f_{10}$ and $f_{25}$ from Table 8) are also indicative of non-linear tidal processes. Specifically, rather than having frequencies at orbital harmonics, these g modes have frequencies that sum to orbital harmonics. Note that $f_3 + f_5 = 12v_{orb}$ and $f_{10} + f_{25} = 7v_{orb}$. These combination frequencies suggest that these modes are excited by parametric three-mode resonance, as detailed in Weinberg et al. (2012) and by Papaloizou & Pringle (1981). However, the non-linear driving mechanisms may be different for the two pairs of modes listed above. In the language of Weinberg et al. (2012), the excitation of $f_{10}$ and $f_{25}$ may be due to non-linear driving by the dynamical tide. Essentially, this is the standard three-mode coupling in which a parent mode non-linearly drives a pair of daughter modes whose frequencies sum to that of the parent mode, as observed in the KOI-54 system (Burkert et al. 2012; Fuller & Lai 2012). In this case, the parent mode is the dynamical tide at $f_1 = 7v_{orb}$, which is dominated by a nearly resonant g mode. The origin of $f_1$ and $f_3$ likely cannot be explained by this mechanism because there is no visible parent mode at $f_3 + f_5 = 12v_{orb}$. Instead, these modes are likely excited via non-linear driving by the equilibrium tide. In this case, the ‘parent’ mode is the component of the equilibrium tide that oscillates at 12 times the orbital frequency (which is dominated by the f mode rather than a g mode). These findings further substantiate our pulsational models which show that we do not expect to see γ Dor modes in either component.
periodically modulated by the orbital motion as seen by the observer. When the effect is large enough to be measured, RVs can be measured directly from the light curve without the need for spectroscopic RVs. Shibahashi & Kurtz (2012) demonstrate this by deriving the mass function from photometric data alone for the K-K binary and A star in the complex multiple system KIC 4150611 to better precision than has been possible with spectroscopic RVs.

In the case of KIC 4544587 this effect is not measurable, even at the extremely high precision of the Kepler data. Consequently, we are not able to complement our spectrally defined RV points with a photometrically defined RV curve. However, we are able to conclude that the frequency modulation (FM) signature is not present in our frequency spectrum and thus does not interfere with our frequency analysis. Shibahashi & Kurtz (2012) characterize the phase modulation with a parameter, \( \alpha \), given by

\[
\alpha = \frac{2\pi GM_\odot}{c} \left( \frac{m_1}{M_\odot} \right)^{1/3} q(1 + q)^{-2/3} P_{\text{osc}}^{2/3} \frac{P_{\text{orb}}^{2/3}}{P_{\text{osc}}} \sin i,
\]

where \( P_{\text{osc}} \) is the pulsation period, \( P_{\text{orb}} \) is the orbital period, \( m_1 \) is the mass of the primary star and \( q = m_1/m_2 \) is the mass ratio. For KIC 4544587 the exact value of \( \alpha \) depends on which star is considered to be pulsating, which is not yet known, but \( \alpha \sim 0.04 \), in either case, since \( q \sim 1 \). For a value of \( \alpha \) this low, Shibahashi & Kurtz (2012) show that, to first order, a frequency triplet split by the orbital frequency is expected for each pulsation frequency, where the amplitude ratio of the side peaks to the central peak is given by

\[
\frac{A_{+1} + A_{-1}}{A_n} \approx \alpha,
\]

where \( A_{+1}, A_{-1} \) and \( A_n \) represent the amplitudes of the peaks at \( f_n + v_{\text{obs}} \), \( f_n - v_{\text{obs}} \) and \( f_n \), respectively, where \( v_{\text{obs}} = 1/P_{\text{obs}} \) is the orbital frequency. In addition, for this low value of \( \alpha \), the side peaks have essentially the same amplitude.

Table 8 shows that the highest amplitude p mode in KIC 4544587, \( f_6 = 48.0240 \text{ d}^{-1} \), has an amplitude of 329 \( \mu \)mag. Therefore, we expect the orbital sidelobes generated by the light travel time effect to have amplitudes for this best case of about 7 \( \mu \)mag, which is below the limit of detection in our data, but may ultimately be detectable with a more extensive Kepler data set.

7.3 Stellar evolution and pulsation models

To estimate the frequency content expected for stars similar to KIC 4544587, we calculated stellar evolution and pulsation models for single spherically symmetric non-rotating stars using the mass, radius and effective temperature constraints obtained from binary modelling and spectroscopic analysis. The models use the stellar evolution and pulsation codes described in Guzik et al. (2000), including an updated version of the Iben (1963, 1965) stellar evolution code with OPAL (Iglesias & Rogers 1996) opacities, Alexander & Ferguson (1994) low-temperature opacities, the Grevesse & Noels (1993) solar mixture and the Pesnell (1990) linear non-adiabatic stellar pulsation codes. We did not include diffusive helium, element settling or convective overshooting.

We do not know the interior abundances or ages of these stars. However, we attempted to find evolved models of the same initial composition and age that matched the constraints of the two stars in KIC 4544587. The models that were the closest to satisfying these criteria have helium abundance \( Y = 0.27 \), metallicity \( Z = 0.017 \) and mixing length/pressure scaleheight 1.90, very near to the values calibrated for the Sun for these evolution and pulsation codes, and the Grevesse–Noels solar abundance mixture (see, e.g., Guzik & Mussack 2010). The age of the models is approximately 235 Myr. The observational constraints, plus the model parameters for two sets of models, are given in Table 9.
Table 9. Stellar properties derived from observations and stellar evolution models. Y and Z are initial helium and element mass fractions, respectively. The first set of models (column 3) has the same age and composition, while column 4 shows parameters for the best-fitting models that do not have the same age and abundances.

| Parameters | Observations | Coeval models | Single best-fitting models |
|------------|--------------|---------------|----------------------------|
| Primary    |              |               |                            |
| Mass (M⊙)  | 1.98(7)      | 1.95          | 1.98                       |
| Radius (R⊙)| 1.76(3)      | 1.73          | 1.76                       |
| T_eff (K)  | 8600(100)    | 8774          | 8604                       |
| Y          | 0.27         | 0.28          |                            |
| Z          | 0.017        | 0.023         |                            |
| Age (Myr)  | 235          | 171           |                            |
| Secondary  |              |               |                            |
| Mass (M⊙)  | 1.60(6)      | 1.57          | 1.60                       |
| Radius (R⊙)| 1.43(2)      | 1.48          | 1.43                       |
| T_eff (K)  | 7750(180)    | 7543          | 7813                       |
| Y          | 0.27         | 0.27          |                            |
| Z          | 0.017        | 0.016         |                            |
| Age (Myr)  | 235          | 0 (ZAMS)      |                            |

Figure 13. An H-R diagram for the models of Table 9. The boxes outline the parameter space for the observationally derived primary and secondary components. The short-dashed line is zero-age main-sequence position for stellar models with Z = 0.017, Y = 0.27. Also shown are evolutionary tracks for a 1.95-M⊙ (blue) and 1.57-M⊙ (green) model. The two models with the same age and composition (column 3 of Table 9) closest to the observational constraints are connected by the long-dashed line. The red diamonds mark the best-fitting models for each star (column 4 of Table 9) that do not have exactly the same age and composition.

8 SUMMARY AND CONCLUSIONS

We have presented the Kepler photometric and ground-based spectroscopic model of KIC 4544587, a detached eclipsing binary system with p-mode and g-mode pulsations, apsidal motion, tidally excited modes and combination frequencies. The SC data of Quarters 7 and 8 were used in the binary modelling and pulsation analysis.
of KIC 4544587 with the exception of modelling the apsidal motion and eclipse timing variations where all available quarters were used. RV curves have been incorporated into the binary model, which were generated from 38 spectra obtained using ISIS on the WHT and five spectra using the echelle spectrograph on the 4-m Mayall telescope at KPNO.

The binary model was created using PHOEBE in an iterative process where the pulsations were identified in the residuals of the orbital fit and subsequently prewhitened to leave only the binary signature for modelling purposes. We were able to obtain a reasonable, but not completely ideal, binary model fit. Primarily this is due to the resonant pulsations in KIC 4544587, which have periods commensurate with the orbital period and do not diminish when phasing the data. However, it is also because of the inadequate treatment of certain physical parameters (most prominently gravity brightening, limb darkening and albedo) in the binary modelling process, highlighted by the precise nature of the Kepler data. Addressing this deficiency is a work in progress (Degroote et al., in preparation; Prša et al., in preparation).

A best-fitting model was obtained and uncertainty estimates were determined using a combination of formal errors and Monte Carlo simulations, which were used to determine uncertainties for parameters that are highly correlated. The distributions obtained in these simulations demonstrated minimal degeneracy, attesting to the uniqueness of the obtained binary solution. From the binary model fit, we determined the fundamental parameters of the stellar components. These include the mass and radius of the primary \( \delta \) Scuti component, \( 1.98 \pm 0.07 \) \( M_\odot \) and \( 1.82 \pm 0.03 \) \( R_\odot \) and the mass and radius of the secondary component, \( 1.61 \pm 0.06 \) \( M_\odot \) and \( 1.58 \pm 0.03 \) \( R_\odot \). We also determined that the system has rapid apsidal motion, \( 182 \pm 5 \) yr per cycle, which may be partially attributable to the resonant pulsations.

The binary characteristics were subsequently separated from the inherent pulsations and 31 modes were identified, 14 in the g-mode region and 17 in the p-mode region. Of the 14 g-mode pulsations, 8 were found to have frequencies that are multiples of the orbital frequency; therefore, we conclude that the majority of these are tidally excited pulsations. 17 p-mode frequencies were identified in the residuals, many of which demonstrate separations that are multiples of the orbital frequency. Our current hypothesis is that these are combination modes, formed through the non-linear interactions between p modes and g modes. The stellar pulsation models predict many more unstable p modes for the secondary component than the primary, so it is possible that these p modes originate in the secondary component; however, the secondary could also have a few unstable p modes. The pulsation models show that neither star has a convection zone deep enough to produce unstable g modes, at least via the convective blocking mechanism. The g modes, however, could also be tidally driven and originate with either the primary or secondary. Further investigation into the non-linear mode interactions and tidal excitation of the pulsation modes will require modelling of pulsations in tidally distorted rotating stars, and is beyond the scope of this paper.

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