College of Natural and Applied Sciences

2012

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Seismic evidence for non-synchronization in two close sdb+dM binaries from *Kepler* photometry

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ABSTRACT

We report on extended photometry of two pulsating subdwarf B (sdB) stars in close binaries. For both cases, we use rotational splitting of the pulsation frequencies to show that the sdB component rotates much too slowly to be in synchronous rotation. We use a theory of tidal interaction in binary stars to place limits on the mass ratios that are independent of estimates based on the radial velocity curves. The companions have masses below $0.26\,M_\odot$. The pulsation spectra show the signature of high-overtone g-mode pulsation. One star, KIC 11179657, has a clear sequence of g modes with equal period spacings as well as several periodicities that depart from that trend. KIC 02991403 shows a similar sequence, but has many more modes that do not fit the simple pattern.

Key words: binaries: close – stars: horizontal branch – stars: oscillations – stars: rotation – subdwarfs.

1 INTRODUCTION

Close binary systems are typically those in which the semimajor axis of the orbit is of comparable size to the radii of the stars themselves. In such systems, circularization of the orbit and synchronization of the components through tidal interactions is often assumed. The precise mechanisms of tidal coupling, and the resulting time-scales, have been under debate for a number of years. Observational tests have been difficult to implement. While orbital period determination is usually straightforward (through radial ve-

locity curves and/or photometry), measuring the rotation of the component stars is challenging. Determinations of rotation periods using starspots becomes difficult in binary systems and impossible when those systems are evolved. It is possible to measure rotational broadening of spectral lines, but that requires metal lines which are inherently weak and need high signal-to-noise ratio (S/N); in binaries with compact components other broadening mechanisms swamp the rotational broadening signal for rotation rates of interest. When there are pulsations in one of the stars, asteroseismology can provide an alternative method for measuring rotation. The spinning of the star breaks degeneracy in the pulsation modes of non-radial pulsators causing single peaks to split into multiplets. This splitting can, through a simple relation, yield the rotation rate of the star (Ledoux 1951).

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One class of non-radially pulsating stars that can be ideal for this type of analysis is the pulsating subdwarf B (sdB) stars. These stars, remnants of low mass stars that have undergone helium core ignition, lie along the extreme horizontal branch with temperatures 22 000–40 000 K and masses of $\approx 0.47\,M_\odot$ (Heber et al. 1984; Saffer et al. 1994). Their surface gravities (log g ranging from $\sim$5.0–6.0) are typically higher than main sequence stars with corresponding temperatures. The formation process for a star with these characteristics is difficult to identify; one proposed formation channel is through common envelope ejection (Han et al. 2002, 2003). This implies that a significant number of these objects are members of binary systems.

In addition, a selection of these stars pulsate non-radially. These pulsations fall into two distinct classes. The p-mode pulsators, also called V361 Hya stars, have periods that are generally in the 2–4 min range, with pulsation amplitudes ≈ 1 per cent of their mean brightness (Kilkenny 2007; Reed et al. 2007). The g-mode pulsators, also known as V1093 Her stars, have pulsation periods between 45 min and 4 h and typical amplitudes less than 0.1 per cent of their mean brightness (Green et al. 2003; Østensen 2010; Reed et al. 2011).

Given their small pulsation amplitudes and multiperiodic nature, resolving the oscillation spectra of these g-mode pulsators is extremely challenging using ground-based facilities. In particular, the periods of the g-mode pulsators result in only a few cycles for a single night's observing. To use the pulsations to measure rotational effects requires identification of the azimuthal order of the modes, meaning that small frequency spacings between individual periodicities in the Fourier transform need to be measured unambiguously. Even with multisite campaigns it is challenging to obtain a sufficient baseline for detailed study.

Recently, data on sdB pulsators provided by the *Kepler* mission have spurred rapid progress in our understanding of these stars. The broader science goals, mission design and overall performance of *Kepler* are reviewed by Borucki et al. (2010) and Koch et al. (2010); Gilliland et al. (2010b) review the asteroseismology component. The *Kepler* Asteroseismic Science Consortium (KASC) working group on compact pulsators has made significant strides towards our understanding of the non-radial g-mode pulsators as a group (Gilliland et al. 2010b; Kawaler et al. 2010b; Reed et al. 2010, 2011), and have provided detailed seismic fits to two g-mode pulsators (Van Grootel et al. 2010; Charpinet et al. 2011). Many of these multiperiodic pulsators show distinct sequences of modes that are equally spaced in period, as is expected for high-overtone g modes (Reed et al. 2011).

Two of the KASC targets are g-mode pulsators in close reflection-effect binary systems with periods of approximately 0.4 d: KIC 02991403 and KIC 11179657. 30 days of *Kepler* data from the survey phase, hinted that neither system was in synchronous rotation, though the data durations were too short to fully resolve the pulsations (Kawaler et al. 2010b). In a separate examination of an sdB star in the old open cluster NGC 6791 (KIC 02438324, identified as 'B4' by Kaluzny & Udalski 1992), Pablo, Kawaler & Green (2011) used 6 months of *Kepler* data to show that it too is in a close reflection-effect binary. B4 rotates with a period that is significantly longer than the orbital period of the system. The similarity between these three systems suggests that the binary properties are closely related to their origin.

In this paper, we report on results from longer duration observations of KIC 02991403 and KIC 11179657 with *Kepler*. We identify several rotational triplets, demonstrating that the stars are not in synchronous rotation. These results are consistent with the results of

B4 shown in (Pablo et al. 2011), and suggests that sdB stars in ≈ 0.5-d binary systems with low-mass M dwarf companions do not appear to be in synchronous rotation. KIC 11179657 shows a clear sequence of equally spaced periods as seen in many other g-mode sdB pulsators, including B4 (Pablo et al. 2011). KIC 02991403 also shows a sequence of modes that share a constant spacing in period, but shows many more modes that do not follow this pattern.

2 OBSERVATIONS

All observations were obtained by the *Kepler* spacecraft between 2010 March and 2011 March. *Kepler* data are made available in 3-month spans and identified by quarter number. The observations we are analysing are from quarters Q5 to Q8. The data were obtained in short cadence (SC) mode (Gilliland et al. 2010a) which has a cadence of 58.85 s. Data were processed through the standard pipeline (Jenkins et al. 2010). All data products received through KASC have undergone pre-search data conditioning. However, since this conditioning is optimized for exoplanet science, we used the simple aperture photometry flux. These fluxes are converted to fractional variations from the mean (i.e. differential intensity $\delta I/I$). The data show (mostly) subtle baseline changes from month to month, and so we treated each month of data individually, resulting in a light curve that is continuous across each quarter. We further edited the data by removing outliers; we clipped individual data points that departed from the (local) mean by 4σ. This resulted in a reduction of 1847 points (out of 486 336) in KIC 02991403 and 947 points (out of 392 532) in KIC 11179657.

Under normal operating circumstances, data received from *Kepler* is continuous with the exception of small gaps, the largest of which is due to the quarterly roll of the spacecraft. For this reason *Kepler* has a duty cycle of over 90 per cent. There are a small number of instrumental artefacts in the data commensurate with the long cadence (LC) readout rate ($1/30 \times SC$) producing peaks at multiples of 566.44 µHz, with the highest amplitude peaks generally lying in the 4000–7000 µHz region (Gilliland et al. 2010a). These artefacts are at a significantly higher frequency than the physical periodicities in these stars, and so do not impact our analysis.

We obtained 12 months of data (Q5–Q8) on KIC 02991403, resulting in a (formal) frequency resolution ($1/T$) of 0.032 µHz. The actual frequency precision achieved through least-squares fitting of sinusoids to the data (Montgomery & O'Donoghue 1999) is significantly higher, but the higher precision is only realized if the individual periodicities are isolated from any other signal. Kawaler et al. (2010b) identified 16 independent oscillation frequencies using 1 month of data from Q1. This star is a reflection effect binary with an orbital period of 10.633 762 $\pm$ 0.000 015 h. No significant signal is seen at the subharmonic of this periodicity, and the first harmonic is present at the 13 per cent level. The phase of this harmonic peak is such that the maxima of the harmonic are at the extrema of the main peak, as is expected for a reflection-effect binary. Preliminary radial velocity measurements on the sdB star have an of amplitude 36 $\pm$ 2 km s^{-1} (Telting et al. 2011). This velocity implies that the (unseen, except for the reflection effect) companion is lower in mass than the primary ($M < 0.47\,M_\odot$) if the inclination angle of the system is greater than 15°. The absence of an eclipse places an upper limit on the inclination of approximately 80°, and places a lower limit on the companion mass of $\approx 0.089\,M_\odot$. The sdB star has $T_{\rm eff} = 27\,300 \pm 200$ K and log $g = 5.43 \pm 0.03$ (Østensen et al. 2010).

For the second target, KIC 11179657, we obtained 9 months of data (Q5–Q7); in Q8, KIC 11179657 fell on the beleaguered

Module 3 in the *Kepler* focal plane which is no longer functional. The resulting formal frequency resolution is 0.042 μHz, though as noted above, isolated frequencies can be determined to much higher precision. This star is also a reflection effect binary with an orbital period of 9.466 936 ± 0.000 024 h. It shows eight oscillation frequencies in the 30-d survey data from Q2. The binarity in this reflection-effect system has also been confirmed via a measured velocity amplitude for the sdB star of 21 ± 2 km s^{-1} (Telting et al. 2011). Assuming a non-zero inclination angle the companion in this system is again of low mass, with a minimum mass ≈0.047 M$_\odot$ if seen nearly edge-on; the companion exceeds the mass of the sdB if the inclination is less than approximately 8°.5. The sdB star is slightly cooler and lower-gravity than its counterpart, with $T_{\rm eff} = 26\,000 \pm 800$ K, and $\log g = 5.14 \pm 0.13$ (Østensen et al. 2010).

3 ANALYSIS

We determined the frequencies of pulsation (and the orbital modulation period from the reflection effect) through Fourier analysis combined with non-linear least-squares fitting and pre-whitening, as described in Kawaler et al. (2010a,b) and Reed et al. (2010). This process identifies peaks in the Fourier transform and fits the amplitude, frequency and phase using a non-linear least-squares procedure. A sine curve with the fit parameters is then subtracted from the light curve to remove the periodicity. This process is then iterated until all significant peaks have been identified, fitted and removed. A peak is defined as significant if it is more than 4σ above the mean noise level. This was calculated by finding the mean value of the Fourier transform, outside of obvious peaks, in the g-mode region of each star.

Normal modes of oscillation in stars are characterized by the set of indices n, l and m. The radial order n provides a measure of the number of nodes in the radial direction for the given oscillation mode. The angular indices l and m correspond to the spherical harmonic $Y_l^m(\theta, \phi)$. For non-radial oscillations, in the absence of processes that break azimuthal symmetry, the oscillation frequencies depend only on n and l; modes with different m values are degenerate in frequency. If the star is rotating (or has a sufficiently

strong magnetic field), this can lift the m degeneracy, revealing an equally spaced multiplet of $2l + 1$ peaks if all m components are present and if the rotation is sufficiently slow (or the magnetic field sufficiently weak). For solid-body rotation with a period of $P_{\rm rot}$, the frequency spacing is proportional to the rotation rate

$$f_{n,l,m} = f_{n,l,0} + \frac{m}{P_{\rm rot}}(1 - C_{n,l}) \tag{1}$$

(Ledoux 1951) where $C_{n,l}$ is the Ledoux constant. $C_{n,l}$ is determined by the oscillation eigenfunctions. For models appropriate to KIC 02991403 and KIC 11179657 the range of $C_{n,l}$ is discussed in Kawaler et al. (2010b), with $C_{n,1}$ between 0.465 and 0.496 while $C_{n,2}$ is between 0.158 and 0.165. For these two targets, if the sdB components are in synchronous rotation, the rotational splitting should be approximately 13–15 μHz for $l = 1$ modes.

3.1 KIC 02991403

With a full year of data, the number of detected oscillation modes has increased significantly compared to what was found by Østensen et al. (2010). All 16 modes previously identified are still present, and 18 additional periodicities lie above our significance threshold of 0.141 ppt (parts per thousand). The amplitude spectrum of the data is shown in Fig. 1, and the significant periodicities are listed in Table 1. In this table, frequencies identified in Kawaler et al. (2010b) are f1 through f16; the new periodicities, ordered by increasing frequency, are f18 through f34. The phase is given as an offset from T_0 of the first time of maximum (for that periodicity).

As noted in Kawaler et al. (2010b), there is little evidence for frequency spacings between modes that match the expectations from synchronous rotation. The few splittings that are near the orbital frequency can be explained by the common period spacing in $l = 1$ g modes (see below). In the range of frequencies typical for g modes, the period spacing coincides with the system's orbital frequency.

With the improved frequency resolution and sensitivity available with 1 year of data, several equally spaced triplets are now seen in the data, with spacing that is substantially smaller than the orbital frequency. One true triplet (f13, f14, f15) was identified by
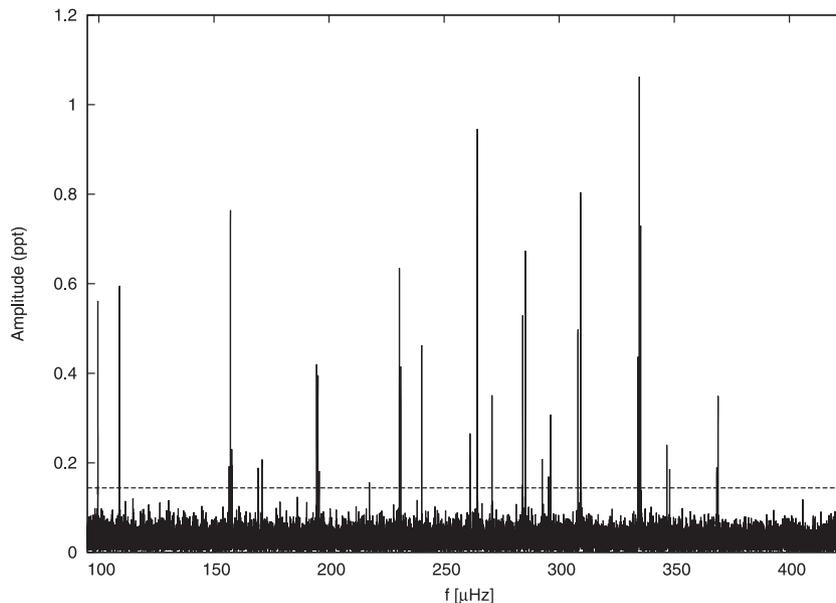

Figure 1. The g-mode region of KIC 02991403. The 4σ significance threshold is represented by the dotted line.

Table 1. Periodicities of KIC 02991403. Quoted errors are formal least-squares errors. Periodicities marked with an asterisk are slightly below the 4σ cut-off but included in the fit.

ID	Frequency (µHz)	Period (s)	Amplitude (ppt)	T_{max}[a] (s)	Orbital splitting	Fine structure
	Binary period and first harmonic					
$1f_{orb}$	26.122 249(36)	38 281.542(51)	17.657(35)	15 971.0(24)		
$2f_{orb}$	52.244 51(28)	19 140.8(10)	2.279(35)	16 062.0(93)		
f17	99.5625(11)	10 043.94(0.11)	0.562(35)	7122.0(200)		
f18	108.994(11)	9174.816(88)	0.601(35)	3352.0(170)		
f19*	114.8141(48)	8709.73(0.37)	0.131(35)	5486.0(740)		
f20	156.6102(41)	6385.28(0.17)	0.153(35)	1678.0(460)		
f1	157.171 97(82)	6362.458(34)	0.763(35)	2306.0(92)		f20+0.562
f21	157.6653(35)	6342.55(0.14)	0.195(36)	1549.0(380)		
f22	157.7319(25)	6339.87(0.11)	0.255(36)	5551.0(290)		f1+0.560
f23	169.2203(32)	5909.46(0.11)	0.200(35)	5618.0(330)		
f24	170.8781(29)	5852.124(99)	0.219(35)	3699.0(300)	f22+13.146	
f25*	186.2481(48)	5369.18(0.14)	0.128(35)	4935.0(460)		
f2	194.6251(15)	5138.083(39)	0.434(35)	2350.0(130)		
f3	195.1789(15)	5123.50(4)	0.417(35)	5055.0(140)		f2+0.554
f26	195.7147(37)	5109.477(97)	0.171(35)	1161.0(330)	f24+24.837	f3+0.536
f27	217.5162(41)	4597.358(87)	0.154(35)	3131.0(330)		
f4	230.554(10)	4337.386(19)	0.626(35)	1671.0(77)	f27+13.038	
f5	231.1063(15)	4327.014(29)	0.409(35)	2463.0(120)		f4+0.552
f28	240.2369(14)	4162.558(23)	0.466(35)	2530.0(99)		
f29	261.2529(23)	3827.709(34)	0.273(35)	479.0(150)		
f6	264.439 48(66)	3781.5836(95)	0.956(35)	376.0(44)		
f7	270.7766(18)	3693.081(25)	0.345(35)	868.0(120)		
f8	284.1718(12)	3518.998(14)	0.541(35)	481.0(72)		
f9	285.2697(93)	3505.455(1)	0.684(35)	1768.0(57)		f8+1.098
f30	292.5943(29)	3417.702(34)	0.218(35)	3399.0(170)		
f31	295.409(36)	3385.137(42)	0.174(35)	2719.0(210)		
f10	296.316(2)	3374.78(23)	0.311(35)	3061.0(120)		
f11	308.1784(12)	3244.874(14)	0.484(35)	1164.0(74)		
f12	309.279 64(79)	3233.3199(83)	0.800(35)	1470.0(45)		f11+1.101
f13	334.2474(16)	2991.796(14)	0.402(35)	2987.0(82)		
f14	334.819 55(59)	2986.6835(51)	1.078(35)	728.0(31)		f13+0.572
f15	335.372 12(87)	2981.7625(77)	0.729(35)	1943.0(45)		f14+0.553
f32	346.7506(25)	2883.917(21)	0.241(35)	71.0(130)		
f33	347.995(33)	2873.605(26)	0.194(35)	227.0(160)	f14+13.145	f32+1.244
f34	368.4757(36)	2713.883(25)	0.178(35)	1188.0(170)		
f16	369.0067(18)	2709.978(12)	0.350(35)	1881.0(86)		

[a] T_0 is BJD 245 5276.479 3502.

Kawaler et al. (2010b), but its spacing was near the run resolution. We now see several doublets and triplets with very similar spacings of ≈ 0.56 µHz; these are shown in Fig. 2. Of the 34 periodicities in Table 1, 16 are components of multiplets that show this spacing. The rotational period calculated using this frequency splitting assuming $l = 1$ is approximately 11 days. This is an order of magnitude longer than the orbital period, confirming that this system is not in synchronous rotation. This ratio is very similar to that seen in B4 (Pablo et al. 2011). The possibility exists that the modes that are part of these multiplets with a 0.56 µHz spacing are $l = 2$ rather than $l = 1$, even though no quintuplets are present. If that were the case, the rotation period would be longer. A rotation period of 11 days corresponds to a rotation velocity of approximately 1 km s^{-1}. This rotation is slower than what is generally seen in more ordinary (cooler) horizontal branch stars both in clusters and in the field (Behr 2003a,b). It is also consistent with spectroscopic measurements of many individual sdB pulsators (Heber 2000). Since this is significantly longer than the orbital period, it is clear that not much spin up has occurred in these systems.

In many g-mode sdB pulsators, the periods of the modes display period spacings that are integer multiples of a common period spacing (Reed et al. 2011), as expected from asymptotic theory for models without internal compositional discontinuities. To examine the possibility that KIC 02991403 shows this signature, we attempted to find a common period spacing. For $l = 1$ modes in sdB stars, this spacing has been observationally determined to be remarkably uniform; most stars show a spacing near 250 s, which is consistent with the asymptotic $l = 1$ spacing from theoretical models (Reed et al. 2011). Kawaler et al. (2010b) explored this question with 1 month of data and concluded that there might be a mix of $l = 1$ and 2 modes in KIC 02991403. With these new data, most of the periods corresponding to the centres of the triplets in Fig. 2 seem consistent with a spacing of 269.6 s. Folding all identified periodicities at that spacing leads to the échelle diagram shown in Fig. 3. A likely $l = 1$ sequence seems to be present near 60 s in this figure; however, many peaks are not associated with this group. Theoretical models of high-overtone g modes (see, for example Van Grootel et al. 2010; Charpinet et al. 2011) show periods that
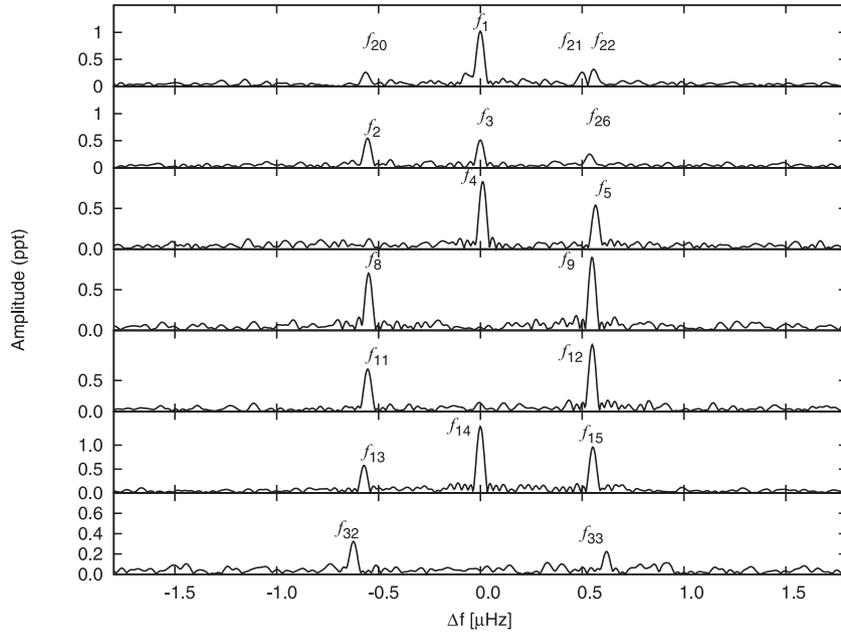
Figure 2. Amplitude spectra of several multiplets in the g-mode region of KIC 02991403. The frequencies of each peak can be found with corresponding labels in Table 1. There are three triplets with an average spacing of 0.56 μHz. Several doublets show twice this splitting. There is some ambiguity in placement of f4 and f5 in the third panel from the top; they could be shifted to lower frequencies by 0.56 μHz since we cannot uniquely assign m values.
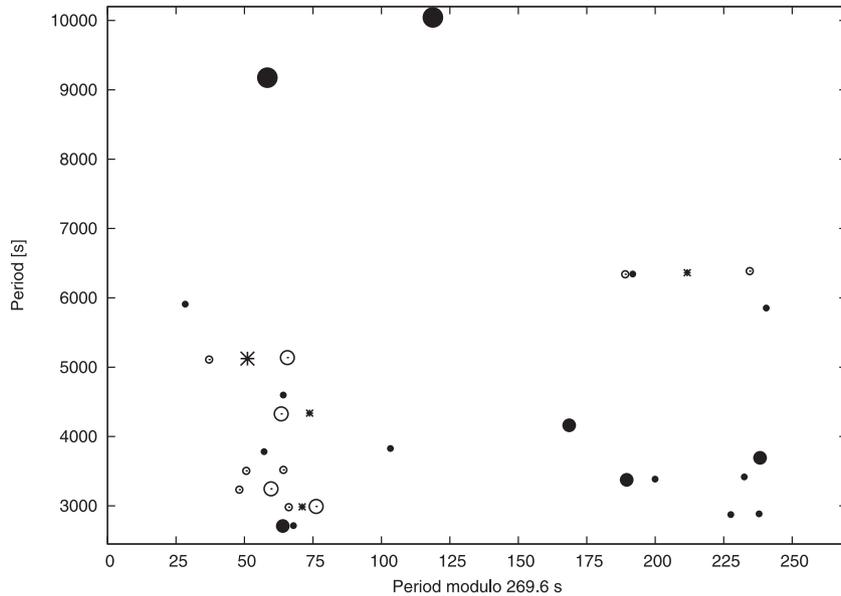

Figure 3. This échelle diagram contains symbols for all periodicities identified in KIC 02991403. The points are plotted modulo a fixed period spacing; those that have periods that are integer multiples of this period spacing will be aligned vertically. Stars denote $m = 0$ modes (those at the centre of triplets), and open circles are suspected $m = \pm 1$ modes. Filled circles are isolated periods. Larger symbols indicate higher amplitude peaks. A vertical column centred near 50–75 s contains most of the identified triplets. There are also several points that lie far away from this grouping, and may be indicative of higher l modes, or modes that are strongly affected by internal composition gradients. There is an artificial offset of 50 s imposed in the figure so the points do not fold across 0 s.

approximate this behaviour, though large departures (up to 100 s) are common. These departures from uniform period spacing are the consequence of internal composition transition zones, which lead to mode trapping and departure from the asymptotic relationship. In KIC 02991403, the spread of points in the échelle diagram (Fig. 3) may be because some of the periodicities are $l = 2$ modes, or that the internal structure of this star contains features that cause mode trapping. Thus the problem remains as far as clearly identifying l for many of the modes of KIC 02991403.

3.2 KIC 11179657

Nine months of data *Kepler* photometry on KIC 11179657 brings the 4σ noise threshold down to an amplitude of 0.146 ppt. At this level, combined with the frequency resolution gain, we can identify 18 periodicities in the light curve in addition to the eight periodicities found by Kawaler et al. (2010b); two that were close to the detection threshold in Kawaler et al. (2010b) are confirmed. Fig. 4 shows the amplitude spectrum of the new data over the range
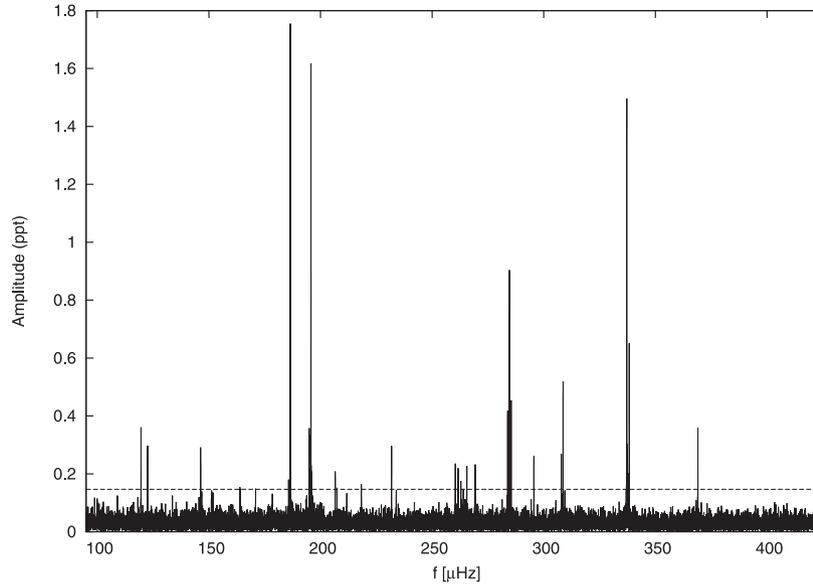
Figure 4. The g-mode region of KIC 11179657. The 4σ level above the noise is represented by the dotted line.

Table 2. Periodicites of KIC 11179657. Quoted errors are formal least-squares errors. Periodicities marked with an asterisk are slightly below the 4σ cut-off but included in the fit.

ID	Frequency (µHz)	Period (s)	Amplitude (ppt)	T_{max} [a] (s)	Orbital splitting	Fine structure
	Binary period and first harmonic					
$1f_{orb}$	29.341 887(74)	34 080.971(87)	9.36(3)	19 462.0(35.0)		
$2f_{orb}$	58.6836(11)	17 040.53(0.31)	0.66(3)	2582.0(250.0)		
f9	119.6149(19)	8360.16(0.13)	0.36(0.03)	1152.0(220)		
f10	122.5558(24)	8159.55(0.16)	0.29(0.03)	838.0(270)		
f11	146.2958(24)	6835.47(0.11)	0.29(0.03)	560.0(220)		
f12	185.7243(35)	5384.3(0.10)	0.20(0.03)	5382.0(260)		
f1	186.4778(39)	5362.569(1)	1.77(0.03)	5157.0(29)		f12+0.753
f13	194.925(2)	5130.169(51)	0.35(0.03)	5002.0(140)		
f2	195.722 84(43)	5109.266(1)	1.63(0.03)	3465.0(30)		f13+0.798
f14	206.5921(33)	4840.455(78)	0.21(0.03)	139.0(220)		
f15	218.2891(41)	4581.081(87)	0.17(0.03)	2368.0(260)		
f16	231.8228(23)	4313.64(0.43)	0.30(0.03)	1005.0(140)		
f17	260.39(3)	3840.391(45)	0.23(0.03)	2825.0(160)		
f18	261.6353(32)	3822.114(47)	0.22(0.03)	185.0(170)	f16+29.8125	f17+1.245
f19	262.873(4)	3804.117(58)	0.17(0.03)	2051.0(210)		f18+1.238
f20	265.5517(33)	3765.746(46)	0.21(0.03)	861.0(170)		f19+2.679
f21	269.278(3)	3713.634(42)	0.23(0.03)	2098.0(160)		
f22	283.83(17)	3523.235(21)	0.42(0.03)	2681.0(81)		
f3	284.628 43(78)	3513.3525(96)	0.90(0.03)	3283.0(37)		f22+0.798
f4	285.4093(16)	3503.74(0.02)	0.44(0.03)	591.0(77)		f3+0.781
f5	295.5828(25)	3383.15(0.03)	0.27(0.03)	890.0(120)		
f23	307.8559(25)	3248.273(28)	0.27(0.03)	1018.0(120)		
f6	308.6558(14)	3239.855(14)	0.52(0.03)	1356.0(60)		f23+0.800
f24*	309.4427(48)	3231.62(0.05)	0.14(0.03)	71.0(210)		f6+0.787
f7	337.173 68(46)	2965.8306(41)	1.48(0.03)	1963.0(19)	f23+29.3178	
f25	337.9506(38)	2959.013(33)	0.19(0.03)	470.0(150)	f6+29.2948	f7+0.777
f8	338.2984(12)	2955.97(0.10)	0.60(0.03)	698.0(47)	f6+29.6426	f7+1.125
f26	369.0297(19)	2709.809(14)	0.36(0.03)	2115.0(73)		

[a] T_0 is BJD 245 5276.480 1154.

of frequencies where significant periodicities are found. Table 2 presents the frequency list; we use the same naming convention as used for KIC 02991403.

Kawaler et al. (2010b) failed to identify any equally spaced triplets using the one-month survey data. With the extended data from Q5 to Q7, we find that all but one of the previously detected frequencies (f5) is a member of a triplet or pairs with another frequency at twice the triplet splitting. These common frequency spacings are much smaller than the orbital frequency. The most common spacing is approximately 0.78 µHz; 12 periodicities are
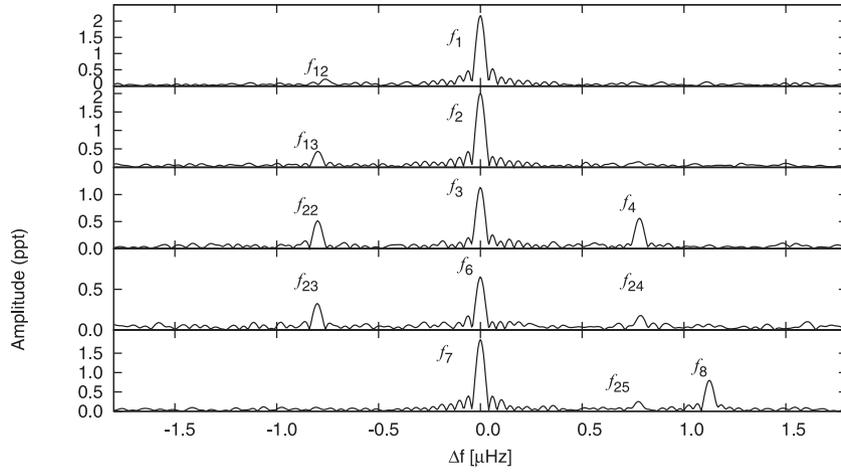
Figure 5. Rotationally split multiplets in KIC 11179657 associated with the suspected $l = 1$ spacing ≈ 0.784 μHz. The frequencies of each peak can be found with corresponding labels in Table 2. There are two triplets (middle and second to bottom) with an average spacing of 0.793 μHz, though we note that f24 is slightly below our formal detection threshold. There are several doublets which show this splitting. In the bottom panel centred on f7, f25 is spaced at the $l = 1$ rotational splitting distance. The f8 peak is separated by 1.12 μHz from f7, which is smaller than the expected $l = 2$ splitting.

parts of multiplets with this splitting. The uniformity of this splitting is shown in Fig. 5 where we expand the Fourier transform around each multiplet. In two instances, the central peak has the largest amplitude, and we align the incomplete multiplets assuming the large amplitude component is the central one. The labelled peaks are all above or near our significance threshold as indicated by the number corresponding to the entry in Table 2. These modes are split by the same spacing of 0.78 μHz.

Four other periodicities (f17, f18, f19, and f20) show a spacing of ≈ 1.29 μHz. The ratio between the 0.78 and 1.29 μHz splitting is 1.65, consistent with that expected for $l = 1$ modes (0.78 μHz) and $l = 2$ modes (1.29 μHz). Thus the four frequencies appear to be part of an $l = 2$ quintuplet which is missing one peak. The calculation of

the rotational period from these spacings is consistent with ≈ 7.4 d which, as in KIC 02991403 and B4, is much longer than the orbital period. We note that the frequency spacing between f7 and f8 is close to, but significantly smaller than, the $l = 2$ spacing.

Unlike KIC 02991403, most of the periodicities of KIC 11179657 have a consistent period spacing. The period spacing found in this star is 265.3 s and appears to be fairly uniform. In Fig. 6, we see a well-defined column of periodicities that are all consistent with being $l = 1$ modes. A few of the periodicities are offset from the ridge by about 140 s, which may indicate modes that are affected by mode trapping by internal composition transition zones (see above). Note that in Fig. 6 the suspected $l = 2$ multiplet is also offset from the $l = 1$ ridge.
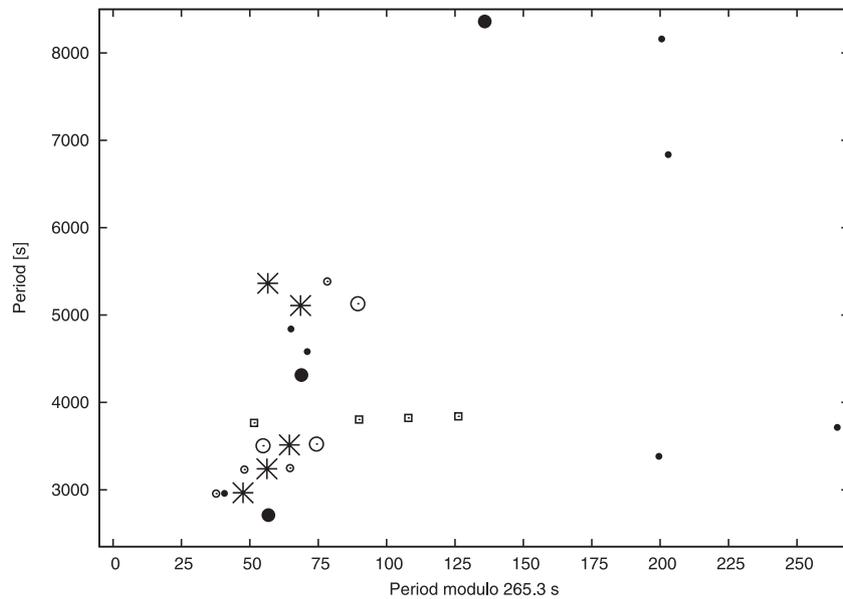

Figure 6. Échelle diagram of the periodicities f1–f 26 of KIC 11179657 with a folding period is 265.3 s. Filled circles are undetermined peaks, stars are $l = 1$, $m = 0$ modes, open circles $l = 1$ $m = \pm 1$ modes, and open squares are suspected members of an $l = 2$ multiplet. The symbol size is proportional to peak amplitude. There is a clear grouping around 70 s which is most likely associated with $l = 1$. The members of the $l = 2$ multiplet are offset from the $l = 1$ ridge, though the highest frequency member (and the missing adjacent mode) do overlap with the $l = 1$ ridge. This overlap is not unexpected as they can have different values of n.

4 SYNCHRONIZATION

Synchronization has not been reached in either KIC 02991403 or KIC 11179657, meaning that the synchronization time-scale must be significantly longer than the time that these systems have been in their current configuration. The time-scale for life as a helium core burning sdB star is 10^8 years. Without more precise models of these stars (constrained by seismology) it is difficult to know their ages, but we can estimate the synchronization times using two prescriptions. KIC 02991403 and KIC 11179657 have very similar system parameters in terms of masses, rotation rates, and orbital periods. Therefore, the analysis below applies to both systems.

The model of Tassoul & Tassoul (1997) produces a synchronization time that is extremely short for sdb+dM binaries with these periods (as discussed in Pablo et al. 2011). On the other hand, synchronization through coupling via dynamical tides, as proposed by (Zahn 1975), produces an approximate parametrized synchronization time-scale (Claret & Cunha 1997; Pablo et al. 2011).

$$\tau_{\text{syn}} = 3.43 \times 10^6 \, \text{yr} \left(\frac{\beta}{0.13} \right)^2 \left(\frac{1+q}{q} \right)^2 \left(\frac{M}{\text{M}_\odot} \right)^{\frac{7}{3}}$$
$$\times \left(\frac{R}{\text{R}_\odot} \right)^{-7} \left(\frac{P}{\text{day}} \right)^{\frac{17}{3}} \left(\frac{E_2}{10^{-8}} \right)^{-1}, \quad (2)$$

where β is 'the radius of gyration' (the moment of inertia divided by MR^2), q is the mass ratio and E_2 is the tidal constant, which is highly dependent on stellar structure. E_2 is difficult to calculate directly, but is proportional to $(r_c/R)^8$, where (r_c/R) is the fractional radius of the convective core (Zahn 1977). Scaling from main sequence models by Claret (Claret & Cunha 1997) to sdB stars we find that, to within a factor of 3, $E_2 = (r_c/R)^8$. The error introduced is small compared with our other uncertainties. As the sdB star evolves, (r_c/R), R and (to a lesser extent) β can change causing τ_{syn} to vary.

This approach to synchronization can be integrated using the computed τ_{syn} as a function of time via

$$\frac{1}{\tau_{\text{syn}}} = \frac{1}{\Omega - \omega} \frac{d\omega}{dt}, \quad (3)$$

where Ω is the orbital angular velocity and ω is the star's angular rotation velocity. Using the value of τ_{syn} as a function of age allows us to calculate $\omega(t)$. When $\omega \approx \Omega$ this system is synchronized. Conservation of total angular momentum implies that spinning up the sdB star will come at the expense of orbital angular momentum. However, since the rotational inertia of the star is less than 1 per cent of the orbital angular momentum, spin-up of the star will occur on a time-scale that is approximately 100 times shorter than the rate of change of the orbital angular momentum, regardless of the companions mass. We therefore assume that Ω is constant. We also assume that the secondary star is in synchronous rotation so its angular momentum evolution can be ignored. We can also compute the synchronization time as a function of the mass ratio q for comparison with the data – smaller mass ratios imply longer synchronization times. With a typical mass for the sdB star of ≈ 0.47 $\text{M}_\odot$, and values for R and (r_c/R) from representative sequences of evolutionary models (Kawaler & Hostler 2005; Kawaler 2010), the fact that these stars are not yet synchronized (at an upper limit to the age of 10^8 years) we should be able to place limits on the mass of the companion. For values of E_2 greater than $(r_c/R)^8$, if the age of the system is half the mean lifetime (5×10^7 yr) then $M_c < 0.26 \, \text{M}_\odot$. On the other hand, if E_2 is much less than $(r_c/R)^8$ then it is likely that the system will never spin-up. In that case for the system to have spun-*up* to the value observed starting from a

rotation period of 100 d, M_c must be greater than 0.16 $\text{M}_\odot$. The value of M_c is valid for rotation periods longer than about 50 days.

5 DISCUSSION

KIC 02991403 and KIC 11179657 are two very similar sdB g-mode pulsators in binary systems. Both systems have several triplet spacings, which imply rotation periods of 10.3 and 7.4 d, respectively. This assumes solid body rotation, but as the g modes are sensitive to virtually all depths in the star, our conclusions should change little. Since the orbital period in both systems is ≈ 0.4 d both systems are in non-synchronous rotation. These properties are shared with the sdB binary in NGC 6791 investigated by Pablo et al. (2011). These results can place tight constraints on theoretical models for tidal synchronization. For example, the Tassoul & Tassoul (1997) mechanism would synchronize these stars in a very short time.

On the other hand, if the analysis following Zahn (1977) and Pablo et al. (2011) in the previous section is accurate, then we can use the *lack* of synchronization to place limits on the mass ratio and therefore on the mass of the secondary star. This mass limit, along with the radial velocity amplitude, can in turn provide a lower limit on the orbital inclination. If $E_2 > (r_c/R)^8$ this turns out to be $\approx 23°$ for KIC 02991403 and $\approx 13°$ for KIC 11179657. However, if $E_2 < (r_c/R)^8$ then we can set a maximum inclination of $\approx 35°$ for KIC 02991403 and $\approx 19°$ for KIC 11179657. Using the fact that there are no eclipses we can set a independent maximum inclination that is $\approx 80°$ for both stars. While the estimates are rough the synchronization and spectroscopy yield consistent results.

Intriguingly, despite their similar parameters, the period distributions in these stars are quite different. The periods are well behaved, with a clear period spacing, $l = 1$ multiplets and, in the case of KIC 11179657, an $l = 2$ multiplet. While KIC 2991403 does show an $l = 1$ sequence, there is no clear evidence of $l = 2$ multiplets despite having a longer baseline and more pulsation modes than KIC 11179657. Compared to KIC 11179657, KIC 02991403 shows a large number of periodicities that are clearly separated from the $l = 1$ ridge, suggesting that it has several $l = 2$ modes that are not parts of multiplets and/or it has a significant number of modes that are influenced by internal composition transition zones.

We expect to obtain at least 2 years of data on these targets, and perhaps much more, over the course of the *Kepler* mission. With more data, lower-amplitude modes may be revealed that could complete additional multiplets. Given the current observed modes, however, seismic modelling may be able to reveal subsurface composition transitions that would explain the g-mode period distribution.

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