



College of Natural and Applied Sciences

12-1-2012

The discovery of two pulsating subdwarf B stars in NGC 6791 using Kepler data

Michael D. Reed
Missouri State University

Andrzej S. Baran
Missouri State University

R. H. Østensen

J. Telting

S. J. O'Toole

Follow this and additional works at: <https://bearworks.missouristate.edu/articles-cnas>

Recommended Citation

Reed, M. D., A. Baran, R. H. Østensen, J. Telting, and S. J. O'Toole. "The discovery of two pulsating subdwarf B stars in NGC 6791 using Kepler data." *Monthly Notices of the Royal Astronomical Society* 427, no. 2 (2012): 1245-1251.

This article or document was made available through BearWorks, the institutional repository of Missouri State University. The work contained in it may be protected by copyright and require permission of the copyright holder for reuse or redistribution.

For more information, please contact [BearWorks@library.missouristate.edu](mailto: BearWorks@library.missouristate.edu).

The discovery of two pulsating subdwarf B stars in NGC 6791 using *Kepler* data

M. D. Reed,^{1*} A. Baran,^{1,2} R. H. Østensen,³ J. Telting⁴ and S. J. O’Toole⁵

¹*Department of Physics, Astronomy and Materials Science, Missouri State University, 901 S. National, Springfield, MO 65897, USA*

²*Suhora Observatory and Krakow Pedagogical University, ul. Podchorążych 2,30-084 Kraków, Poland*

³*Instituut voor Sterrenkunde, KU Leuven, Celestijnenlaan 200 D, 3001 Leuven, Belgium*

⁴*Nordic Optical Telescope, Apartado 474, 38700 Santa Cruz de La Palma, Spain*

⁵*Australian Astronomical Observatory, PO Box 296, Epping, NSW 1710, Australia*

Accepted 2012 September 4. Received 2012 September 4; in original form 2012 June 19

ABSTRACT

We report the discovery of two new pulsating subdwarf B (sdB) stars in the open cluster NGC 6791 using data from the *Kepler* spacecraft. Three sdB stars were observed for one month in short-cadence (1 min) mode and three months in long-cadence (30 min) mode during Quarter 11 (fall 2011). The stars have *Kepler* Input Catalogue numbers of 2437937, 2569576 and 2569583 with previous designations of B5, B3 and B6, respectively. Another sdB star exists in the cluster and it is also known to be a pulsator. We also obtained Nordic Optical Telescope spectra to update effective temperatures, surface gravities and helium abundances and compare the spectroscopic properties of all four stars on a uniform model grid.

We detect four periodicities between 0.9 and 2.4 h in B3 above a detection limit of 0.53 parts per thousand (ppt) and nine periodicities between 1.1 and 2.2 h in B5 above a detection limit of 0.37 ppt. No pulsations were detected in B6 to the detection threshold of 0.29 ppt. The long-cadence data were less useful as few observations are obtained per pulsation period, yet they do indicate that the pulsations are variable from month to month. The spacings between the pulsation periods are similar to other g-mode pulsating sdB stars observed by *Kepler*, indicating that the periodicities can be associated with $\ell = 1$ modes. A fit to the periods give spacings of 234.6 ± 0.6 and 242.6 ± 1.5 s for B3 and B5, respectively.

Key words: stars: oscillations – subdwarfs..

1 INTRODUCTION

Subdwarf B (sdB) stars are extreme horizontal branch stars with masses $\approx 0.5 M_{\odot}$ and thin ($< 10^{-2} M_{\odot}$) hydrogen shells (Heber 1984; Saffer et al. 1994). Spectroscopically, they have temperatures from 22 000 to 40 000 K with $\log g$ from 5.2 to 6.0. SdB variables were first discovered in 1996 and now consist of two well-established classes. These are the short-period, pressure (p)-mode pulsators which are designated V361 Hya stars (Kilkenny et al. 1997) and the longer period, gravity (g)-mode pulsators designated V1093 Her stars (Green et al. 2003). The p-mode pulsations have periods of a few minutes, while the g-mode ones have periods of 45 min to a few hours. There are also hybrid pulsators, which show both types of variations. For reviews of sdB stars and pulsators, see Heber (2009) and Østensen (2010).

16 pulsating sdB stars were discovered by the *Kepler* spacecraft during its first 2 years with results reported in Østensen et al.

(2010a,b, 2011), Kawaler et al. (2010a,b), Reed et al. (2010) and Baran et al. (2011), including a pulsator in NGC 6791 (Pablo, Kawaler & Green 2011). All but one of these are dominated by g-mode pulsations and 10 are hybrid pulsators. Analysis of those *Kepler* data established that the g-mode pulsations are dominated by $\ell = 1$ and 2 modes and the periods follow the asymptotic relations with $\ell = 1$ period spacings near 250 s (Reed et al. 2011). The aim of these studies is the seismic interpretation of the pulsations to discern their interior structure (van Grootel et al. 2010; Charpinet et al. 2011).

Other interesting *Kepler*-produced results include the discovery of a pulsating blue horizontal branch (but not sdB) star with period spacings similar to the sdB stars (Østensen et al. 2012) and the discovery of similar g-mode period spacings in the cores of horizontal branch red clump stars (Beck et al. 2012). These results indicate that sdB stars really do represent the cores of most horizontal branch stars from the red to extremely blue, giving extra importance to discerning sdB structure.

Four extreme horizontal branch stars were spectroscopically detected in NGC 6791 by Liebert, Saffer & Green (1994) and

*E-mail: mreed@sdbv.missouristate.edu

Table 1. Properties of the stars in this paper. Star B4 is included for comparison. Columns 1 and 2 supply the designations from Kaluzny & Udalski (1992) and the KIC, column 3 the *Kepler* bandpass magnitudes and columns 4–6 the effective temperature, surface gravity and helium abundance, including formal fitting errors.

Name	KIC #	K_p	T_{eff}	$\log g$	$\log N_{\text{He}}/N_{\text{H}}$
B3	2569576	17.801	24 250 (459)	5.17 (0.05)	−2.81 (0.12)
B5	2437937	17.978	23 844 (676)	5.31 (0.09)	−2.71 (0.22)
B6	2569583	17.660	37 008 (539)	5.72 (0.06)	−2.69 (0.24)
B4	2438324	17.924	24 786 (665)	5.30 (0.09)	−2.86 (0.20)

designated as B3 through B6.¹ To determine spectroscopic properties consistent with Østensen et al. (2010b, 2011, 2012), we obtained spectra with ALFOSC at the Nordic Optical Telescope (NOT) in 2012 May and fit them to the same local thermodynamic equilibrium grid of model atmospheres (see Heber, Reid & Werner 2000; Ramspeck, Heber & Edelmann 2001, for details). The spectra span the wavelength range of 3530–5090 Å, with a dispersion of 0.76 Å pixel^{−1} and a resolution just under ≈4 Å. Targets B3 and B6 were observed simultaneously; two exposures were co-added with total observing time of 110 min star^{−1}, leading to signal-to-noise ratio (S/N) ≈ 50 pixel^{−1}. For B4 and B5 a single simultaneous exposure of 60 min leads to S/N ≈ 35. Table 1 lists resultant effective temperatures (T_{eff}), surface gravities ($\log g$) and helium abundances ($\log N_{\text{He}}/N_{\text{H}}$) along with *Kepler* Input Catalogue (KIC) numbers and *Kepler* magnitudes. Fig. 1 shows the temperatures and gravities of B3 through B6 along with a selection of sdB pulsators.

High-speed ground-based observations were obtained during 2001, ideally to search for p-mode pulsations in B3, B4, B5 and B6 (Reed, Kilkenny & Terndrup 2006). The observations spanned about 2 h star^{−1} and failed to detect any variations at the detection limits, which were around 5 parts per thousand (ppt). Those observations were too short to be sensitive to typical g-mode pulsations. *Kepler* Guest Observer programme observations of B4 detected 16 low-amplitude periodicities associated with g-mode pulsations (Pablo et al. 2011). Many of the periods fit the asymptotic spacing observed in other sdB stars (Reed et al. 2011), allowing the modes to be identified. B4 is in a short-period binary with a period of 0.3985 d, and it was determined that B4 rotates subsynchronously with a period near 9.63 d. Another subsynchronously rotating sdB binary was discovered by Telting et al. (2012) and a 25.6-d rotation period was discovered in the non-binary sdB pulsator KIC 10139564 (Baran et al. 2012).

Considering the high fraction of g-mode sdB pulsators discovered by *Kepler* and the exciting discoveries these data have produced, we requested, and were granted, Director’s Discretionary Time (DDT)² during Quarter (Q)11 (fall 2011) to observe B3, B5 and B6.

2 OBSERVATIONS AND ANALYSIS

Stars B3, B5 and B6 were observed for one month each using short-cadence (SC) mode which stacks images into a 58.85-s integration. *Kepler* has a limited number of SC slots as they use more spacecraft memory and so our stars were observed one per month over the

three-month quarter in the order B5, B6 and then B3. The stars were also observed in long-cadence (LC) mode, which accumulates 30 SC integrations into an ≈30 min integration for the entirety of Q11, roughly three months. We retrieved the pixel files (shown in Fig. 2) from the Mikulski Archive for Space Telescopes³ (MAST) as well as the processed light curves. Fourier transforms (FTs) of the *Kepler* pipeline-processed light curves (Jenkins et al. 2010) showed pulsation peaks where we would expect for g-mode pulsations in B3 and B5, but B6 did not show any indications of p- or g-mode variations. Because of the crowded fields, we elected to extract the fluxes from the pixel files ourselves. We were concerned about contamination of our objects and a possibility that the periodicities originate in neighbouring stars rather than our targets. Fig. 2 shows a colour image (from Sloan⁴) and a portion of the full-frame image for the corresponding month, with the pixel area extracted by *Kepler* indicated. We tested all available pixels separately to determine if the fluxes were detected from the expected pixels for our objects. The pixels where signal occurred, which we used to generate our light curves, are marked in Fig. 2. We did not find any pulsations in either combined or individual pixels for B6, with our best extraction yielding a detection threshold of 0.29 ppt. We only extracted fluxes from those pixels with pulsations, limiting potential contamination, which is particularly severe for B5. We used PYKE⁵ to extract fluxes and to remove time series trends systematic to the spacecraft and its environment rather than our targets. Additional long-term trends (>6 d) were removed by fitting and subtracting a cubic spline curve. Finally, we normalized the fluxes so variations are recorded as ppt.

Once the light curves were processed, we analysed them using FTs. We calculated the detection threshold in the usual way as four times the average value (4σ) of the residual FT (Breger et al. 1994). Sometimes, spurious peaks, which are not considered intrinsic to the star, can be detected above this limit (see Østensen et al. 2012) and so we also calculated a false alarm probability (FAP) in the following way. We kept the integration times fixed, randomly shuffled the processed fluxes and then recorded the highest amplitude peak in the FT. We did this 1000 times so the second highest amplitude has an FAP = 99.9 per cent. We label pulsations with amplitudes above 4σ but below FAP = 99.9 per cent as tentative, requiring further observations to confirm them.

B3. After processing the images, we used 46 651 SC data points in our FT analysis. Peaks indicated in the FTs were then simultaneously fitted to the light curves using a non-linear least-squares program and subsequently pre-whitened (removed as a sinusoidal variation). Fig. 3 shows the original (top) and pre-whitened FTs (bottom), converted to period for asymptotic analysis. In total, nine periodicities were detected above the 4σ threshold of 0.53 ppt, seven of which surpass the FAP = 99.9 per cent limit of 0.64 ppt. All these periods are between 4000 and 8000 s, indicating they are g-mode pulsations, as we expected given B3’s temperature and gravity. The periods/frequencies and amplitudes, with the fitting errors, are provided in Table 2.

We also examined the 4 499 LC data points spanning nearly 97 d. The LC Nyquist frequency is at 283.21 μHz (3531 s), which means that six periodicities (f1 through f6) are sampled less than three times per pulsation cycle. The 30-m integration time also reduces

³ <http://archive.stsci.edu/kepler/>

⁴ Sloan Digital Sky Survey (SDSS) images retrieved using the SDSS Data Release 7 (DR7) Finding Chart Tool at <http://cas.sdss.org/dr7/en/tools/chart/chart.asp>

⁵ <http://keplergo.arc.nasa.gov/PyKE.shtml>

¹ Star B1 is a background main-sequence B star and star B2 is an sdO star.

² <http://keplergo.arc.nasa.gov/index.shtml>

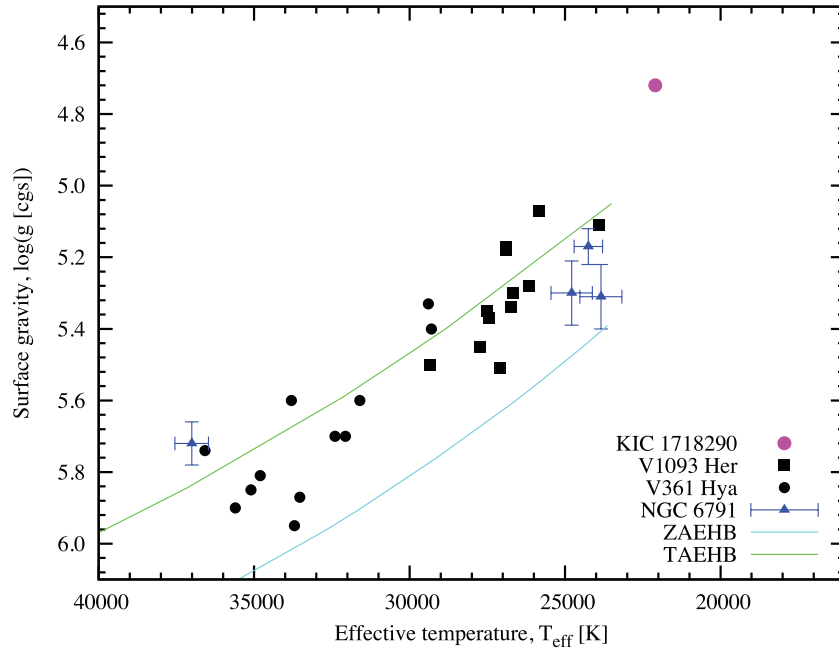


Figure 1. $T_{\text{eff}}-\log g$ diagram of sdB stars. The blue triangles are B3, B4, B5 and B6 from our NOT spectra, the black circles (squares) are a selection of p-mode (g-mode) sdB pulsators (Østensen et al. 2012) and the magenta circle is the newly discovered pulsating blue horizontal branch star KIC 1718290 (Østensen et al. 2012). The blue (green) line is the zero-(terminal)-age extended horizontal branch from Kawaler & Hostler (2005).

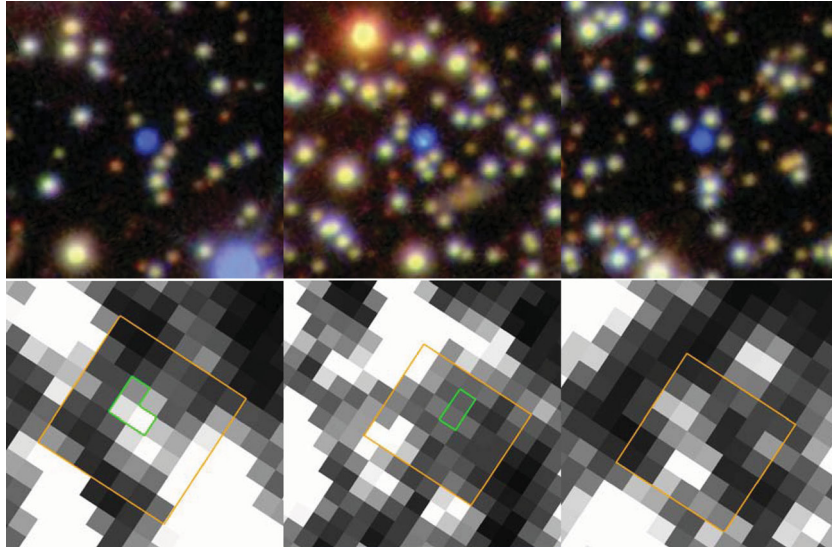


Figure 2. Images for B3 (left), B5 (middle) and B6 (right). On top are $50 \times 50 \text{ arcsec}^2$ SDSS DR 7 images and on the bottom the corresponding portion of the *Kepler* Full Frame Integration image showing the same region as the Sloan image with the DDT pixel mask (orange outline) and the pixels used in our analysis (green outline).

the amplitudes since the star is varying during the integration, which can only capture an average of the flux. With these limitations, we did not fit and pre-whiten the LC data, but rather just compared it with the SC results. All of the SC periodicities appear in the LC FT though the amplitudes of f4, f7 and f9 are clearly not significant. Surprisingly the amplitude of f5 is higher in the LC data than the SC data and the LC data show new peaks at 236.7 and 304.5 μHz (4225.3 and 3284.1 s, labelled as f1 and f3, respectively, in Table 2). Fig. 4 shows FTs of the LC data, including monthly FTs, along with the SC FT (bottom panel). From the figure, it is clear that B3's

amplitudes are variable. Both of the new periods observed in the LC data have their highest amplitudes during the first month and their lowest during the last month, which coincides with the SC data. For f1, we have chosen a period shorter than the Nyquist since there is a small ‘bump’ in the SC FT at that location. In truth, we cannot really discern if the intrinsic periods for f1 or f3 are above or below the LC Nyquist frequency. Only further SC data will clarify this point.

B5. We analysed 45 436 SC data points after processing the pixel data in the same way as B3. We detected four periodicities above the

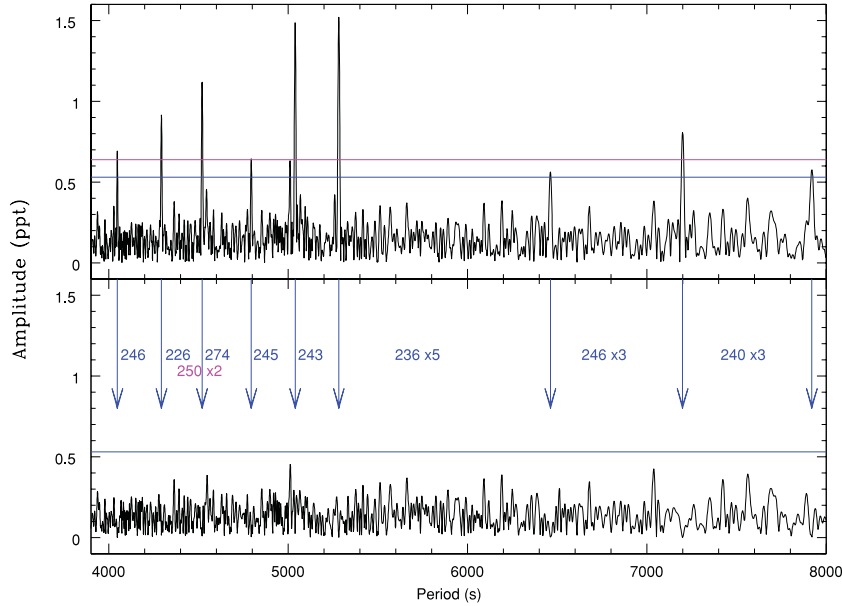


Figure 3. Temporal spectra of B3. Top panel shows the original FT with the 4σ detection threshold and the FAP = 99.9 limit. The bottom panel shows the pre-whitened FT, with the fitted periods indicated by arrows and the period spacing between them indicated.

Table 2. Periodicities detected in B3. Column 1 provides the ID, columns 2–4 the fitted periods, frequencies and amplitudes, and columns 5–7 mode identifications and deviations from an even period spacing as discussed in Section 3. Note that the zero-point of the radial index is arbitrarily chosen such that there are no negative values.

ID	Period (s)	Frequency (μHz)	Amplitude (ppt)	ℓ	n'	ΔP (s)
f1 ^a	3284.1	304.5	0.92	–	–	–
f2	4047.14 (0.47)	247.087 (0.028)	0.69 (0.11)	1	0	-13.9
f3 ^a	4224.8	236.7	0.62 (0.11)	–	–	–
f4	4293.13 (0.40)	232.929 (0.021)	0.91 (0.11)	1	1	-9.2
f5	4519.55 (0.36)	221.260 (0.017)	1.13 (0.11)	1 ^b	2	-24.0
f6	4793.87 (0.68)	208.599 (0.029)	0.67 (0.11)	1	3	9.0
f7	5038.63 (0.33)	198.466 (0.013)	1.50 (0.11)	1	4	12.5
f8	5282.00 (0.36)	189.322 (0.013)	1.51 (0.11)	1	5	14.6
f9 ^c	6461.64 (1.46)	154.759 (0.034)	0.56 (0.11)	1	10	-12.1
f10	7198.70 (1.28)	138.913 (0.024)	0.80 (0.11)	1	13	1.1
f11 ^c	7919.19 (2.17)	126.275 (0.034)	0.57 (0.11)	1	16	-2.2

^aPeriodicities observed only in LC data. Those frequencies were estimated ‘by eye’ and not fitted.

^bTentative mode identification.

^cTentative frequencies with amplitudes above 4σ and below FAP = 99.9 per cent.

4σ detection threshold of 0.37 ppt, with two above the FAP = 99.9 per cent limit of 0.42 ppt. Fig. 5 shows the raw and pre-whitened FTs for B3, again converted to period. The periods, frequencies and amplitudes are listed in Table 3 and indicated by arrows in the figure.

There appear to be more peaks below the 4σ threshold and so we also examined the 4498 LC data points. Fig. 6 shows FTs of the LC data, combined and by months along with the SC FT next to the corresponding LC month. The peaks in the SC FT cross the LC Nyquist, making aliasing across the Nyquist more of a problem. It appears that the SC data were obtained during an opportune time as f4 is *only* seen in the LC FT during that month. There is also a peak during Q11M2 near 170 μHz , which is just below 4σ .

A cursory look at Q11M3 shows another peak near to but not at 170 μHz , indicating that the Q11M2 periodicity did not persist into the next month. Again, only further SC observations will clarify the periodicities in B5, and we expect further observations to reveal many more pulsations.

B6. Based on B6’s spectroscopic properties, we were searching for p-mode pulsations, rather than g-mode ones. Since fewer sdB stars pulsate in p modes, we were hopeful but not optimistic about discovering pulsations in B6. Unfortunately, this was the case. We examined 44 130 SC data points obtained during Q11M2 and found no periodicities above the 4σ detection threshold of 0.29 ppt in either the p- or g-mode regions.

3 DISCUSSION

We have detected nine g-mode periodicities in B3 and four in B5 shown in Figs 3 and 5. Since asymptotic period spacings were discovered in *all* of the other *Kepler*-observed g-mode sdB stars (Reed et al. 2011), our figures are shown in period rather than frequency to reveal that the peaks are nearly equally spaced in period. The Reed et al. (2011) spacings were used to identify the modes, with $\ell = 1$ spacings near 250 s and those of $\ell = 2$ near 145 s. Spacings for B3 and B5 near these values are given in the bottom panels of Figs 3 and 4. The spacings for B3 easily reveal a sequence of spacings near 245 s, while those in B5, which has fewer periods to work with, are all multiples of ≈ 235 s. Fitting linear regressions to the marked periods results in period spacings of 241.3 ± 0.8 and 234.6 ± 0.6 s for B3 and B5, respectively, indicating that they are $\ell = 1$ modes. These fits are of course preliminary, which will be tested with further *Kepler* observations. Since the period spacings are different for $\ell = 1$ and 2 modes, the sequences cross, which allows the possibility for misidentification.

We also fit a linear regression to B4 using the 16 pulsation periods determined by Pablo et al. (2011) and find an $\ell = 1$ mode spacing of 239.7 ± 1.1 . In increasing order of temperature (or gravity), the $\ell = 1$ period spacings are 241.3, 234.6 and 239.7. As these stars are within the same cluster, it is assumed that they formed coevally

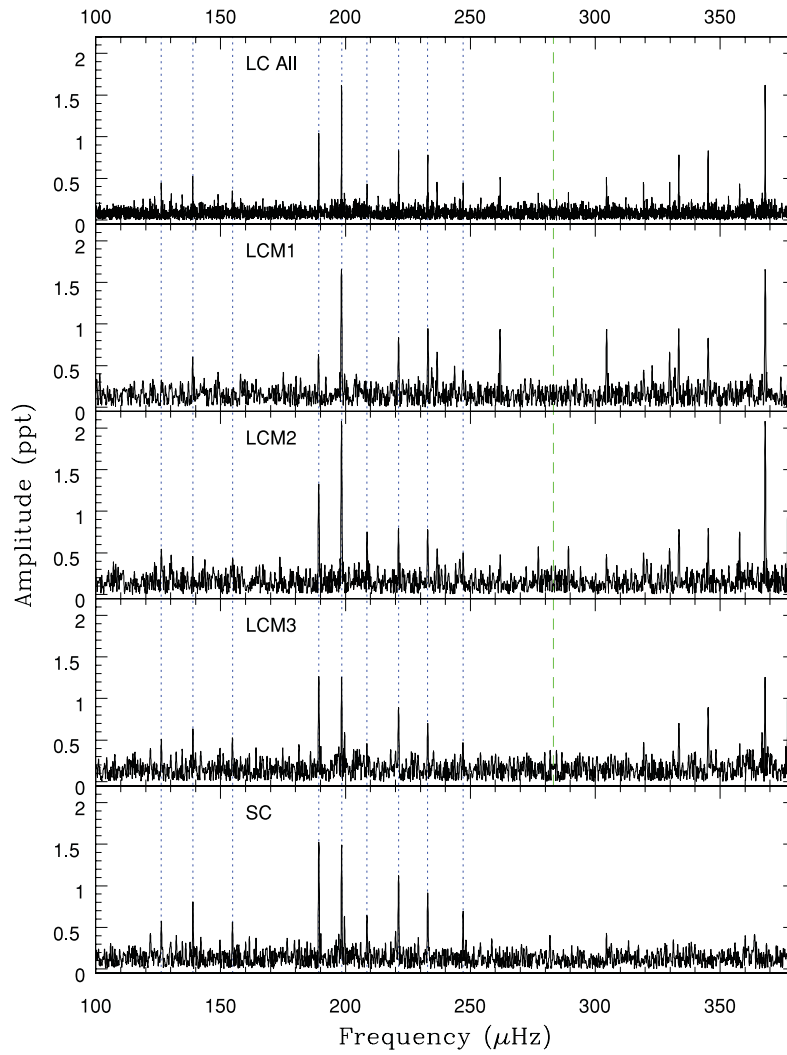


Figure 4. Temporal spectrum of LC data for B3. Top panel shows all of Q11 combined, while subsequent panels show one month's data, with the bottom LC panel corresponding to the SC observations, the FT of which is also shown in the bottom panel. Vertical dotted lines indicate periods detected in SC data and the dashed line indicates the LC Nyquist frequency.

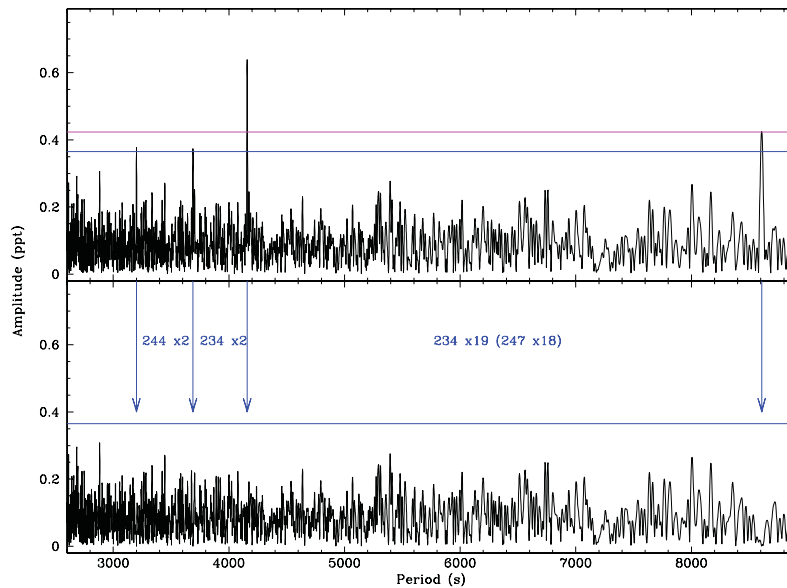


Figure 5. Same as Fig. 3, but for B5.

Table 3. Same as Table 2, but for B5.

ID	Period (s)	Frequency (μHz)	Amplitude (ppt)	ℓ	n'	ΔP (s)
f1 ^a	3200.81 (0.41)	312.421 (0.040)	0.38 (0.07)	1	0	-12.2
f2 ^a	3689.63 (0.55)	271.030 (0.041)	0.37 (0.07)	1	2	7.4
f3	4158.06 (0.41)	240.497 (0.024)	0.64 (0.07)	1	4	6.6
f4	8607.42 (2.62)	116.179 (0.035)	0.43 (0.07)	1	23	-1.8

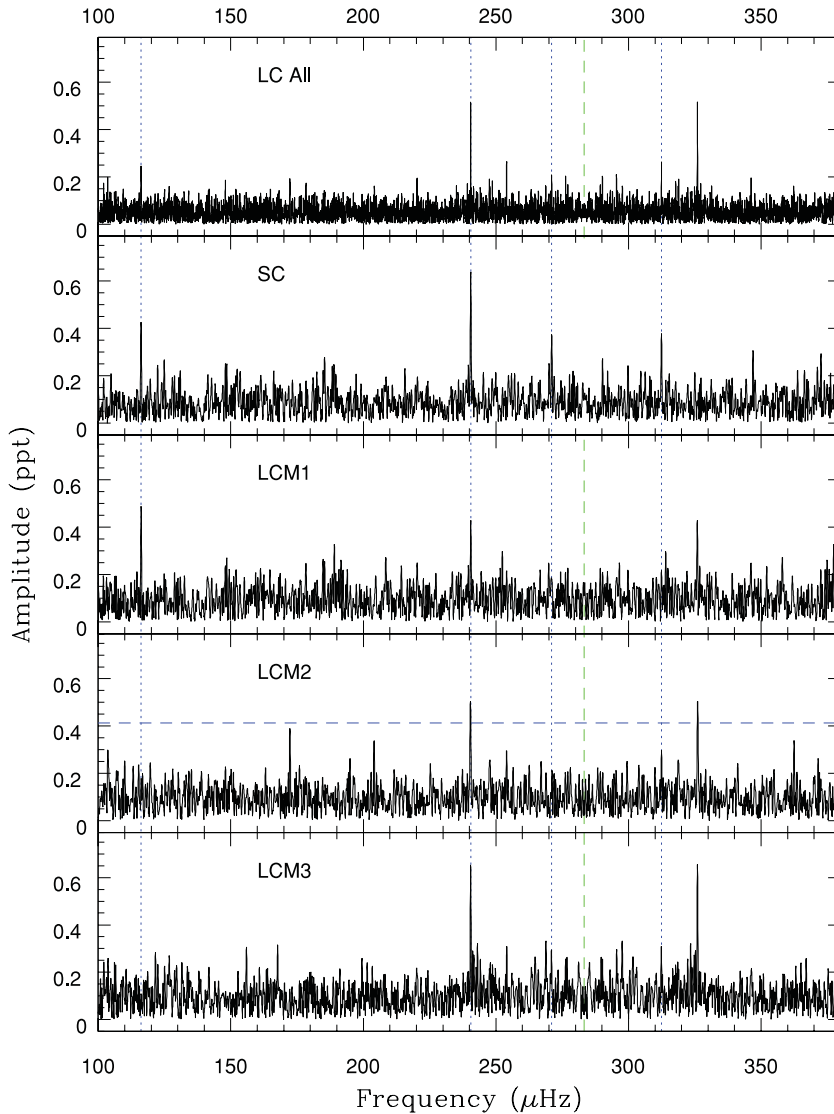
^aTentative frequencies with amplitudes above 4σ and below FAP = 99.9 per cent.

and since horizontal branch evolution is much faster than main-sequence evolution, these sdB stars must have evolved from similar-massed main-sequence stars. As such, comparison of their period spacings, combined with other studies of NGC 6791, which have constrained cluster parameters such as Y , $[\text{Fe}/\text{H}]$, age, turn-off mass and red giant mass, among others (Brogaard et al. 2012; Buzzoni et al. 2012; Corsaro et al. 2012), allows the possibility to reveal their internal structure and illuminate interesting processes including diffusion and radiative levitation.

We anticipate that once longer duration *Kepler* data are available, many more pulsation periods will be detected. The temporal spectra from just one month of SC and three months of LC data hint that both of these pulsators may be quite complex, with pulsations coming and going even on the time-scale of a month. As such, even six or nine months of *Kepler* data could provide many pulsation periods, which could be used to constrain models. Since these three stars should have evolved with the same metallicity and nearly the same mass, the pulsation differences may be able to teach us a lot about the internal structure of sdB stars. And thanks to *Kepler*, we are learning that sdB stars do represent the cores of many horizontal branch stars (Beck et al. 2012; Østensen et al. 2012).

ACKNOWLEDGMENTS

Funding for this Discovery mission is provided by NASA's Science Mission Directorate. The authors gratefully acknowledge the entire *Kepler* Guest Observer team, whose efforts have made these results possible. MDR was partially funded by a Missouri State University Faculty Research Grant. MDR and AB were funded by the National Science Foundation grant #1009436. Any opinions, findings

**Figure 6.** Same as Fig. 4, but for B5.

and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation. The spectroscopic observations used in this work were made with the Nordic Optical Telescope located at the Roque de los Muchachos and operated jointly by Denmark, Finland, Iceland, Norway and Sweden. Some/all of the data presented in this paper were obtained from the Mikulski Archive for Space Telescopes (MAST). STScI is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555. Support for MAST for non-HST data is provided by the NASA Office of Space Science via grant NNX09AF08G and by other grants and contracts.

REFERENCES

- Baran A. et al., 2011, MNRAS, 414, 2871
 Baran A. et al., 2012, MNRAS, 424, 2686
 Beck Paul et al., 2012, Nat, 481, 55
 Breger M. et al., 1994, A&A, 289, 162
 Brogaard K., 2012, A&A, 543, 106
 Buzonni A., Bertone E., Carraro G., Buson L., 2012, ApJ, 749, 35
 Charpinet S. et al., 2011, A&A, 530, 3
 Corsaro E. et al., 2012, ApJ, 757, 190
 Green E. M. et al., 2003, ApJ, 583, L31
 Heber U., 1984, A&A, 130, 119
 Heber U., 2009, ARA&A, 47, 211
 Heber U., Reid I. N., Werner K., 2000, A&A, 363, 198
 Jenkins J. et al., 2010, ApJ, 713, L87
 Kaluzny J., Udalski A., 1992, Acta Astron., 42, 29
 Kawaler S. D., Hostler S. R., 2005, ApJ, 621, 432
 Kawaler S. D. et al., 2010a, MNRAS, 409, 1487
 Kawaler S. D. et al., 2010b, MNRAS, 409, 1509
 Kilkeny D., Koen C., O'Donoghue D., Stobie R. S., 1997, MNRAS, 285, 640
 Liebert J., Saffer R. A., Green E. M., 1994, AJ, 107, 1408
 Østensen R. H., 2010, Astron. Nachr., 331, 1029
 Østensen R. et al., 2010a, MNRAS, 408, L510
 Østensen R. et al., 2010b, MNRAS, 409, 1470
 Østensen R. et al., 2011, MNRAS, 414, 2860
 Østensen R. H. et al., 2012, ApJ, 753, L17
 Pablo H., Kawaler S. D., Green E. M., 2011, ApJ, 47, L1
 Ramspeck M., Heber U., Edelman H., 2011, A&A, 379, 235
 Reed M. D., Kilkeny D., Terndrup D. M., 2006, Baltic Astron., 15, 65
 Reed M. D. et al., 2010, MNRAS, 409, 1469
 Reed M. D. et al., 2011, MNRAS, 414, 2885
 Saffer R. A., Bergeron P., Koester D., Liebert J., 1994, ApJ, 432, 351
 Telting J. H. et al., 2012, A&A, 544, A1
 van Grootel V. et al., 2010, ApJ, 718, L97

This paper has been typeset from a $\text{\TeX}/\text{\LaTeX}$ file prepared by the author.