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THE CLASSIFICATION OF *KEPLER* B-STAR VARIABLES

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ABSTRACT

The light curves of 252 B-star candidates in the *Kepler* database are analyzed in a similar fashion to that done by Balona et al. to further characterize B-star variability, increase the sample of variable B stars for future study, and to identify stars whose power spectra include particularly interesting features such as frequency groupings. Stars are classified as either constant light emitters, β Cep stars, slowly pulsating B stars (SPBs), hybrid pulsators, binaries or stars whose light curves are dominated by rotation (Bin/Rot), hot subdwarfs, or white dwarfs. One-hundred stars in our sample were found to be either light constants or to be variable at a level of less than 0.02 mmag. We increase the number of candidate B-star variables found in the *Kepler* database by Balona et al. in the following fashion: β Cep stars from 0 to 10, SPBs from eight to 54, hybrid pulsators from seven to 21, and Bin/Rot stars from 23 to 82. For comparison purposes, approximately 51 SPBs and six hybrids had been known prior to 2007. The number of β Cep stars known prior to 2004 was 93. A secondary result of this study is the identification of an additional 11 pulsating white dwarf candidates, four of which possess frequency groupings.

Key words: stars: early-type – stars: oscillations – stars: variables: general

Online-only material: color figures, machine-readable and VO tables

1. INTRODUCTION

The primary goal of this investigation is to extend the *Kepler* B-star study conducted by Balona et al. (2011) to a substantially larger number of objects. Their paper examined the light curves of 48 B stars in the NASA *Kepler* satellite database and found that their frequency spectra differed from those obtained from ground-based observatories. Much smaller amplitude, high-degree modes are now detectable because of *Kepler*'s high precision and continuous observing cadence. This study further quantifies the nature of B-star variability by uniformly analyzing the power spectra of 252 stars, essentially all B-star candidates with $m_V < 14.5$ in the *Kepler* field-of-view.

Our study was motivated by the puzzling manner in which B stars pulsate. Their interior structures are thought to be nearly identical, so why are their pulsational properties different? The β Cephei (β Cep) stars are typically multi-periodic radial pulsators (Stankov & Handler 2005). However, the β Cep star, β Cru appears to pulsate solely in non-radial modes (de Cat et al. 2004). The spectral range of the β Cep stars also overlaps that of the early-type Be stars. Nearly all (86%) of these latter stars show light and line-profile variations indicative of non-radial pulsation, however, only 40% of mid-type Be stars and 18% of late-type Be stars appear to pulsate in this fashion (Neiner et al. 2009). The Be stars also change their light output on a variety of timescales (Porter & Rivinius 2003). The spectral range of the slowly pulsating B stars (SPBs) also overlaps that of the β Cep (Miglio et al. 2007), but their frequency spectra are different. Their spectral range also overlaps that of the Be stars. These diverse observational behaviors may be due to intrinsic differences such as their rotational velocity distributions, age, metal abundance, magnetic field strengths, or degree of core convective overshooting. They might also be caused by external factors such as the presence of a circumstellar disk, our viewing angle to the star, or a binary companion.

The tools of asteroseismoloy can be used to measure many of the above internal stellar properties (de Cat et al. 2004; Aerts et al. 2008). Ground-based programs have attempted to do this, but they generally detect too small a number of frequencies. The pioneering space-based *WIRE* (*Wide-Field InfraRed Explorer*) and *MOST* (*Microvariability and Oscillations of Stars*) satellites were considerably more successful in this regard and detected dozens of frequencies (Buzasi 2002; Bruntt & Southworth 2007; Matthews et al. 2004; Walker et al. 2005). However, neither of these micro-satellites can observe a significant sample of B stars because they are limited to very bright stars ($m_V < 6$).

In contrast to the above programs, *Kepler* simultaneously monitors the light variations of about 150,000 stars. Although its primary mission is to search for eclipses caused by transiting Earth-like planets, dozens of high quality B-star light curves are also being acquired. The potential that *Kepler* holds for the study of B-star variability was amply demonstrated by the investigation of Balona et al. (2011). Among the 48 light curves they examined, fifteen were found to be pulsators. This study expands on that pioneering work by examining a much larger set of *Kepler* B stars and classifying their variability. Therefore, this study is limited to a discussion of the *Kepler* B-star frequency spectra. The relation between these spectra and a star's position in the HR diagram will be the subject of a later paper.

This paper is organized in the following fashion. In Section 2 the *Kepler* data set is described. Section 3 provides an overview of the frequency analysis. Section 4 provides a discussion of the frequency spectra of our target stars and Section 5 consists of a summary of our findings.

2. DATA

The *Kepler* satellite was launched on 2009 March 6. It monitors the brightness variations of about 150,000 stars in a 105 deg^2 region in the constellations of Cygnus and Lyra. In preparation for its launch, Brown et al. (2011) obtained multi-band photometry (*griz*, DD051, and *JHK* from Two Micron All Sky Survey) for more than 4 million stars in this field. These colors were used to assign each star an effective temperature $T_{\rm eff}$,

Table 1
KIC Numbers of Non-variable Stars in Sample

1028085	4678193	6761643	8758259	10685044*
1721361	4829241	6853881	9005047*	10789011
2020175	5109770	6860325*	9032986*	10816401
2308039	5288186	6946179*	9141584*	11075420*
2581243	5372254	6950240	9151452	11351218
2830941	5544772*	7104168	9718641	11395846
2987372	5557097	7188447	9718683	11403244
3112242	5612463*	7353409	9725496	11456087
3343613	5951261*	7358074*	9826266	11565279
3345780	5960374	7549771	9948188	11652092*
3353239	6204719	7918401*	9957741	11713245*
3442422	6205507	7966886	10272154	11719437
3459901	6214434	8037519	10292000	11719549
3544662	6267975	8077281	10340843	11817929†
3545048	6293167	8167479	10389280*	11822535
3858566*	6371916	8442729*	10415184	12060050
4166305	6391844*	8523491	10449976	12066844
4366757*	6460385*	8559392	10483888	12366417
4457244	6688779	8609006	10535643*	12453485*
4660027	6752816	8682822	10671396	12885346

Notes.
* Denotes that pulsations might be present but are below the 20 ppm level.
† Denotes stars in common with Balona et al. (2011).

surface gravity log(g), visual absorption A_V, metallicity, and radius. The *Kepler* team then selected about 150,000 of these stars whose light curves would be continuously measured. The measurements were obtained in a single filter whose effective wavelength is close to that of the Johnson R filter. Magnitudes in this bandpass are referred to as *Kepler* magnitudes (K_p) in the Kepler Input Catalog (KIC). Light curve points were obtained at a cadence of 30 minutes (long cadence) or 1 minute (short cadence). The stars monitored each quarter may change as the *Kepler* team refines their planet search targets and as new objects are added by participants in the Kepler Guest Observers program. Targets are given a unique identification number ranging from 757076 to 12984227.

This study targets B stars. Program objects were identified by requiring (1) that they have a $T_{\rm eff} > 10{,}000$ K in the KIC, or (2) a position in a KIC color–color plot that is close to that of a B star. The latter criterion was adopted because the *Kepler* temperatures of upper main sequence stars are not very precise (Lehmann et al. 2011). As a consequence of criterion 2, our initial sample was expected to contain some early-type A stars. In Figure 1 we compare the effective temperature of B stars whose temperatures were measured spectroscopically in the Balona et al. (2011) study to those listed in the KIC. In general the *Kepler* B-star effective temperatures are too low by about 3000 K, however, in extreme cases these temperatures can differ by a factor of two. Because the error in log(g) is relatively large, no restriction was placed on its value when creating our initial list of B-star candidates. The application of these criteria resulted in a sample size of 252 stars. An examination of their power spectra revealed that many (100) candidates were not light variables or possessed a very low level of variability. The KIC numbers of these stars are listed in Table 1. If their number is followed by an asterisk, they might be variable at a level of less than about 0.02 mmag. The properties of the remaining 152 stars in our sample are listed in Table 2. The first column provides their KIC number. The remaining columns provide the star's *Kepler* magnitude (K_p), Sloan g magnitude and $g - i$ color, its proper

Table 2
B-type Star Target List with General Parameters

KIC	K_p	g	$g - i$	$\mu_\alpha \cos\delta$ (mas yr^{-1})	μ_δ (mas yr^{-1})	M_μ
1430353	12.39	12.320	−0.26	−3.5	−4.7	12.45
1718290	15.49	15.323	−0.43	−6.2	−6.3	16.94
1868650	13.45	13.453	−0.71	4.7	−14	18.93
2697388	15.39	15.130	−0.64	0.9	−7.6	18.89
2708156	10.67	10.672	−0.04	1.9	−7.4	14.74

Note.
† Denotes stars in common with Balona et al. (2011).

(This table is available in its entirety in machine-readable and Virtual Observatory (VO) forms in the online journal. A portion is shown here for guidance regarding its form and content.)

motion in right ascension and declination, and a pseudo absolute magnitude, M_μ, that is used later in the text. A histogram of their K_p magnitudes is shown in Figure 2. All of the light curves for our program stars were obtained in the long-cadence mode.

3. FREQUENCY ANALYSIS

The light curves for all 252 program stars were analyzed in a consistent way. All the light-curve measurements were obtained from the MAST database. We experimented with using the recently released target pixel files and corrections to it, but found that the corrected light curves were more useful for our purposes.

We handled the different epochs by analyzing all available quarters (n_q) for each star as well as the entire time series separately, to give $n_q + 1$ frequency spectra per star. Outlier points in all light curves were removed, and each time series was interpolated onto an equidistant time grid. Light curves were then put into units of parts-per-million (ppm), using the transformation from the original *Kepler* flux ($F_{\rm K}$) as $f(t) = 10^6(F_{\rm K}/y - 1)$, where y was either the mean value of the total light curve or a low-order polynomial fit to the light curve, depending on any artifacts present in the data. This fitting did well in removing long-term trends in the light curves that are likely non physical in origin. A similar approach was carried out in Uytterhoeven et al. (2011).

For each case, oversampled power spectra were computed and the frequency of maximum power and its corresponding amplitude were used in a minimization procedure to determine the true frequency, amplitude, and phase (and errors in all three parameters) of a sine function that models the mode. After each iteration, the data were pre-whitened, and the routine continued to determine the frequency set iteratively until an undesirable signal-to-noise (S/N) ratio of $\leqslant 5$ was reached. This S/N was defined as the amplitude of the pulsation compared to the median amplitude of the very high frequency regime.

After the frequency analysis of all quarters of all stars, it was necessary to attempt to determine which frequencies were real by eliminating those that could have had instrumental origin. The criterion we used was that a frequency had to be present in each quarter as well as the entire time series spectrum. Additionally, to ensure the robustness of the frequencies reported in this study, only those having an amplitude within 20% of the largest amplitude mode were considered. This step certainly under counts the number of frequencies present in many of the stars, but is adequate for determining the type of variability these stars possess. In our view, additional work on the removal

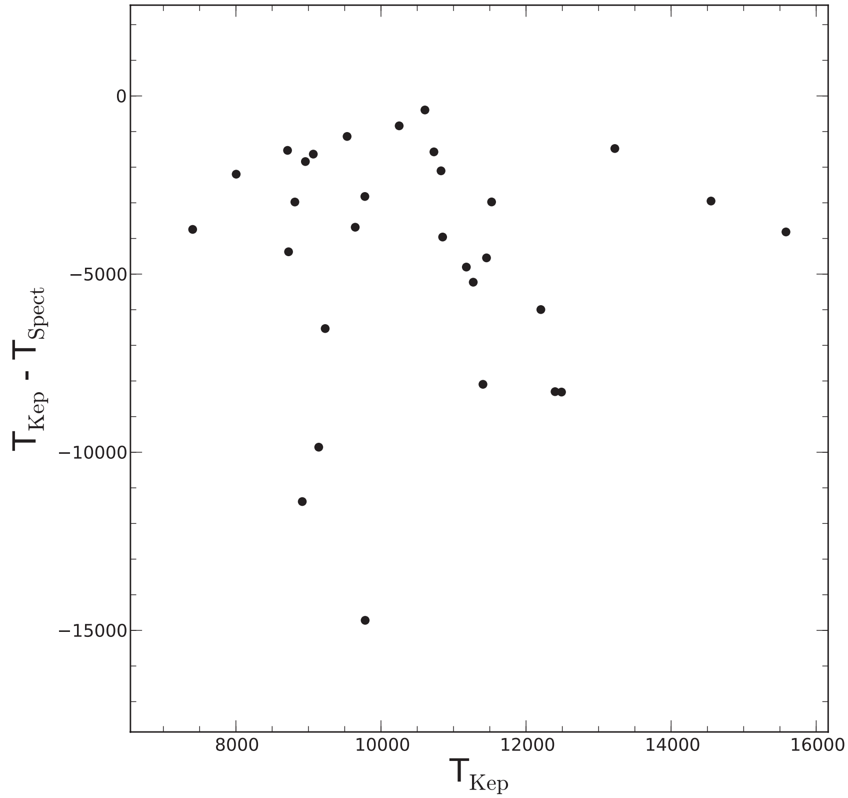

Figure 1. Difference in the *Kepler* and spectroscopic temperature of a B star vs. its *Kepler* temperature. For hot stars, the effective temperatures in the *Kepler* database are too low by about 3000 K, but some temperatures can be underestimated by more than 10,000 K.

of instrumental effects and further high-quality measurements are needed to confirm the presence of the lower-amplitude frequencies.

4. DISCUSSION

The Balona et al. (2011) study classified the variable B stars into four groups: SPB stars, SPB/β Cep hybrids, stars with frequency groupings, and stars with variations due to binarity or possibly rotation-modulated magnetic activity. To distinguish between white dwarfs, hot subdwarfs, and main-sequence B stars, they used proper motions in the UCAC3 catalog (Zacharias et al. 2009). Statistically, stars with large proper motions are expected to be closer to Earth than stars with smaller motions. B stars are rare, therefore, the nearest is expected to be far from us and have a small proper motion. Proper motions for all but six stars in our sample stars are contained in the UCAC3 catalog. Figure 3 shows their vector point diagram. If we only consider stars classified as a B star in the previous studies (Balona et al. 2011; Lehmann et al. 2011; Østensen et al. 2010), their average motion is $(-4.1, -5.1)$ mas yr^{-1} with a 1σ dispersion of about 1.3 mas yr^{-1}. This centroid is close to the value found by Balona et al. (2011; -4.3, -5.4), and consistent with that expected of a young star group in the direction of the *Kepler* field-of-view (Kharchenko et al. 2003), so we adopt it for this study. The location of a star in this diagram provides a crude way of distinguishing B stars from other stellar types. B stars in the upper-right quadrant of the figure have motions consistent with membership in the Gould belt, a partial ring of stars inclined by about 18 deg to the galactic plane.

The above procedure was further refined by examining the position of a star in a pseudo HR diagram. The construction of this diagram is described in the Balona et al. (2011) paper so

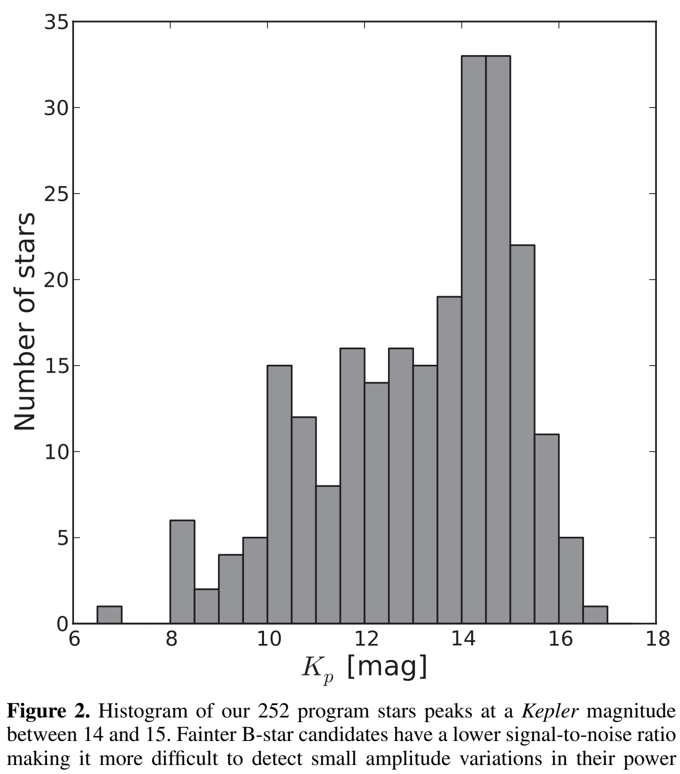

Figure 2. Histogram of our 252 program stars peaks at a *Kepler* magnitude between 14 and 15. Fainter B-star candidates have a lower signal-to-noise ratio making it more difficult to detect small amplitude variations in their power spectra.

we only provide an overview of it here. Using a star's proper motion as a proxy for its distance, a pseudo absolute magnitude is computed from the relation: $M_\mu = g + 5\log(\overline{\mu})$, where g is the Sloan magnitude listed in the KIC, $\overline{\mu} = \Delta\mu/(1\text{mas yr}^{-1})$, and

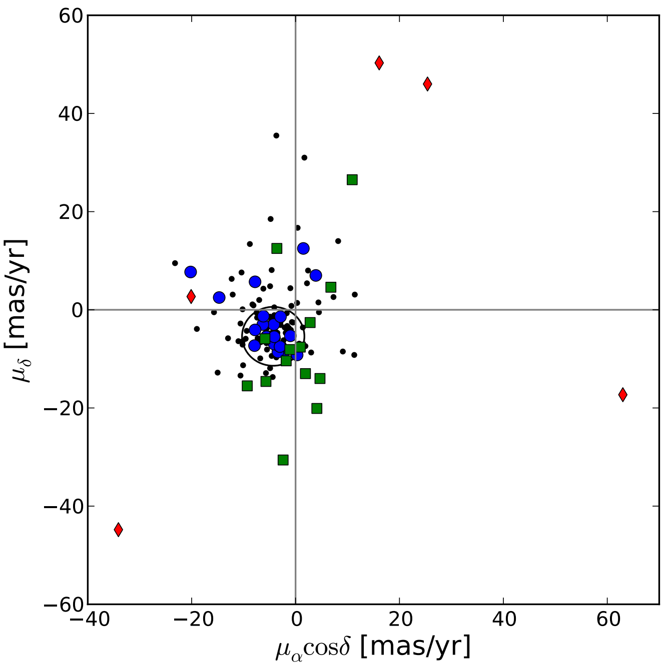

Figure 3. Proper motion in right ascension vs. the proper motion in declination of the stars listed in Table 2, as well as spectroscopically classified non pulsators. Motions were taken from the catalog of Zacharias et al. (2009). The circle near the center of this figure, at coordinates (−4.3, −5.4) mas yr^{-1} and with radius 6 mas yr^{-1}, shows the location of spectroscopically classified B stars denoted as large blue dots. Squares denote spectroscopically classified hot subdwarfs and diamonds denote white dwarfs. Program stars that have not been spectroscopically classified are denoted by small black circles.

(A color version of this figure is available in the online journal.)

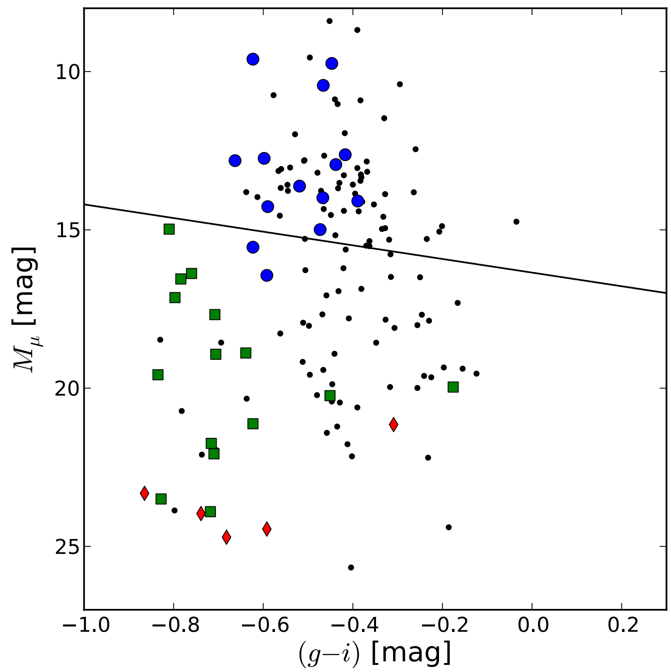

Figure 4. Pseudo HR diagram of the program stars listed in Table 2 using the proper-motion measure M_μ and $g - i$ color. Spectroscopically classified hot subdwarfs are denoted by squares and white dwarfs by diamonds. Program stars that have not been spectroscopically classified are denoted by small black circles. The solid line separates main-sequence B stars from hot subdwarfs and is taken from Balona et al. (2011). This figure provides an excellent tool for distinguishing main-sequence B stars from hot subdwarfs and white dwarfs.

(A color version of this figure is available in the online journal.)

$\Delta\mu$ is the difference between the stars's proper motion and the center of the B-star concentration. This absolute magnitude is then plotted against the star's $g - i$ color. Using stars of known MK spectral type, Balona et al. (2011) were able to identify a boundary between main-sequence B stars and other stellar types in this pseudo HR diagram. Since our sample is an extension of the one used in their study, we adopt this same boundary in our study. Figure 4 shows the pseudo HR diagram of our stars. Stars with known spectral types are given special symbols that are discussed in the figure caption. A major difference between our figure and its counterpart in Balona et al. (2011) is the number of subdwarfs redder than $g - i = -0.4$. This difference arises from the presence of a sizable number of A stars that were included in our study. As discussed earlier, the KIC hot star effective temperatures are not very precise. Therefore, to capture as many B stars as possible, our sample extended to stars that have KIC colors appropriate to the early A stars. Figure 4 provides a natural way of separating main-sequence B stars from hot subdwarfs and white dwarfs.

To make our results compatible to those obtained by Balona et al. (2011), we classified stars using the same scheme suggested by those investigators. β Cep stars are defined as stars whose pulsation frequencies extend from about 3.5 to 20 day^{-1}. SPB stars are defined as B stars that pulsate with frequencies between 0.5 and 3.5 day^{-1}. To be classified as a β Cep/SPB hybrid, a B star must possess modes of both of these classes, i.e., between 0.5 to 20 day^{-1}. The power spectra of stars with frequency groupings show distinct groupings of many modes around specific frequencies in their power spectra. Stars with variations due to binarity or rotation show relatively smooth light curves where the variability arises from rotation or proximity effects in a binary system such as light reflection, deformation of the components, or Doppler beaming. For completeness hot subdwarf and white dwarf candidates are also included in Table 3.

Table 3 shows the classification assigned to each of our program stars. We assign the columns to KIC number, quarters observed, our variable classification, the frequency of the waveform with the largest amplitude ($\nu_{\rm max}$), the amplitude of this frequency ($A_{\rm max}$), number of waveforms detected with a amplitude greater the 20% of the largest amplitude ($N_{\rm freq}$), and associated notes. In cases where it was not possible to distinguish a real variation from the low frequency noise, the frequency information is left blank. When the value for $N_{\rm freq}$ has a colon attached to it, this uncertainty is associated with this noise. The presence of a frequency grouping is denoted in the notes column by the "Fg." When a star's proper motion is large, this is also noted since it is used to differentiate variable classes. Representative members of the each stellar group are discussed below.

4.1. β Cephei Stars

The *Kepler* power spectra of these stars generally possess dozens of frequencies above about 3.5 day^{-1}. Few, if any, of these pulsations would have been detected in ground-based studies because of their small amplitudes. Their spectra often resemble those of hot subdwarfs. Therefore, it is possible that some hot subdwarfs have been incorrectly classified as β Cep stars. To minimize this possibility, a candidate star's position in Figures 3 and 4 were used to distinguish hot subdwarfs/white dwarfs from B stars. The power spectra of β Cep stars can also resemble that of a δ Scuti star. In addition, as shown by Figure 1, the *Kepler* KIC effective temperatures for hot stars

Table 3
Variable Classifications

KIC	Quarters	Class	ν_{max} (c day^{-1})	A_{max} (ppm)	N_{freq}	Notes
2856756	0123	BCEP	17.86	151	19	
6614501	35	BCEP	6.35	231	6	
7204794	23	BCEP	3.87	3222	3	Possible δ Scuti
7668647	235	BCEP	12.59	286	24	
8302197	35	BCEP	24.47	432	10	
10118750	123	BCEP	3.63	1360	20	Fg
10553698	45	BCEP	17.45	1135	11	
10670103	25	BCEP	11.93	1858	29	
11045341	2345	BCEP	7.42	3412	6	Possible δ Scuti
11558725	35	BCEP:	11.33	330	52	Possible sdB, large μ
1430353	0123	SPB	0.98	4188	7	
3443222	23	SPB	1.10	981	12	Possible A star
3459297	0123	SPB	0.99	4074	8	
3756031†	0123	SPB	0.40	574	40	
3839930†	123	SPB	0.86	8999	3	
3862353	23	SPB	0.44	651	19	
3865742†	0123	SPB	0.24	7783	4	
4077252	0123	SPB	0.25	705	10	
4373195	0123	SPB	0.31	18	12	Noisy low freq. spectrum
4663658	0123	SPB	1.32	9	11	Fg
4931738	0123	SPB	0.75	5311	8	
4936089	123	SPB	0.87	5391	5	
4939281	0123	SPB	0.27	1126	9	Possible Hybrid
5084439	23	SPB	1.71	3492	16	Fg
5477601	023	SPB	0.19	320	12	
5941844	0123	SPB	1.31	12994	4	
6780397	0123	SPB	1.18	357	5	
7630417	123	SPB	2.03	613	15	
8054179	345	SPB	0.24:	114	239	Fg, large μ, high g
8087269†	0123	SPB	1.61	1011	11	Fg, possible Hybrid
8167938	23	SPB	0.83	5725	8	
8362546	123	SPB	0.9	1287	2	High g
8766405†	0123	SPB	1.83	1424	5	Fg
9075895	2345	SPB	1.94	190	12	Fg
9211123	35	SPB	0.17	406	39	Fg
9227988	0123	SPB	0.17	2297	8	
9278405	0123	SPB	1.78	9	16	Low amplitude
9468611	0123	SPB	2.14	33	8	Single Fg
9582169	0123	SPB	2.5	24	2	Low freq. noise
9663239	2345	SPB	0.38	280	2	Possible sdB, large μ
9715163	0123	SPB	0.38	9	29	
9715425	0123	SPB	1.71	2628	15	Fg, low freq. noise
9884329	0123	SPB	2.71	34	5	
9910544	0123	SPB	0.72	19	23	Fg, low freq. noise
10207025	35	SPB	1.45	54	254	Fg, noisy
10220209	2	SPB	1.24	1299	9	Possible Hybrid, large g
10526294	123	SPB	0.57	11133	10	
10658302†	0123	SPB	0.19	2127	12	Fg, high g
10790075	0123	SPB	0.26	51	21	Low freq. noise
10797526†	0123	SPB	0.37	1842	19	
11152422	2345	SPB:	0.94	500	5	Possible A star
11454304†	0123	SPB	0.62	397	37	Large g
11671923	0123	SPB	1.72	38	12	
11912716	123	SPB	1.51	97	8	
11957098	0123	SPB	0.58	129	8	
12021724	45	SPB	1.48	397	3	Modest μ
1868650	0123	BIN/ROT	3.42	22946	1	Modest μ
2708156	0123	BIN/ROT	0.53	110297	8	
2853320	123	BIN/ROT	0.2	3684	9	
2987640	123	BIN/ROT	0.23	343	2	
3216449	0123	BIN/ROT	1.06	2033	2	
3443582	45	BIN/ROT	0.92	3838	2	Large g
3763002	123	BIN/ROT	0.58	245	32	Possible SPB, low freq. noise

Table 3
(Continued)

KIC	Quarters	Class	ν_{max} (c day^{-1})	A_{max} (ppm)	N_{freq}	Notes
4064365	123	BIN/ROT	0.11	15290	1	
4373805	0123	BIN/ROT	0.13	166	19	
4476114	12	BIN/ROT	0.34	2601	3	
4828345	0123	BIN/ROT	1.19	14072	2	High *g*
4831616	23	BIN/ROT	0.48	4252	2	
5352328	23	BIN/ROT	0.97	105	7:	
5450881	0123	BIN/ROT	3.68	934	4	
5473826	0123	BIN/ROT	0.95	10800	2	
5479821†	0123	BIN/ROT	0.59	12844	2	
5530935	0123	BIN/ROT	1.27	65	2	
5687841	0123	BIN/ROT	0.61	18	10	Fg, possible SPB
5706079	123	BIN/ROT	0.24	3257	2	
5775128	0123	BIN/ROT	0.52	7677	4	High *g*
5942605	123	BIN/ROT	1.56	6593	2	High *g*
6278403	0123	BIN/ROT	0.84	2643	2	
6363494	23	BIN/ROT	1.1	872	4	Possible A star
6864569	0123	BIN/ROT	0.43	10933	2	
6878288	35	BIN/ROT	0.33	3552	5	
6950556	12	BIN/ROT	1.32	6695	2	
6953047	23	BIN/ROT	0.58	5595	2	
6954726†	0123	BIN/ROT	1.03	9076	43	Low freq. noise
7022658	23	BIN/ROT	0.64	5670	2	Possible A star
7282265	23	BIN/ROT	0.89	3418	5	
7335517	35	BIN/ROT	7.29	18094	4	Large μ
7434250	25	BIN/ROT	0.24	549	65	sdB?, low freq. noise, modest μ
7599132†	0123	BIN/ROT	0.77	8056	2	
7749504	0123	BIN/ROT	3.53	1260	2	
7778838	0123	BIN/ROT	0.17	9732	1	
8129619	123	BIN/ROT	1.05	515	1	
8161798†	0123	BIN/ROT	0.91	36288	2	
8183197	0123	BIN/ROT	0.27	264	1	Low freq. noise
8233804	123	BIN/ROT	1.51	5977	3	High *g*
8488717†	0123	BIN/ROT	0.31	247	1	
8619436	123	BIN/ROT	0.32	8884	1	
8754603	35	BIN/ROT	6.76	11630	3	Modest μ
8759258	0123	BIN/ROT	1.05	6509	3	Modest μ
8871494	123	BIN/ROT	1.17	316	1	
9202990	34	BIN/ROT	0.08	51338	26	Low freq. noise, large μ, possible A star
9472174	0123	BIN/ROT	7.95	53559	1	
9958053	0123	BIN/ROT	0.73	3581	2	
10090722	0123	BIN/ROT	0.17	3033	4	
10130954†	0123	BIN/ROT	0.45	370	2	High *g*
10281890	0123	BIN/ROT	0.08	13236	1	
10551350	2345	BIN/ROT	0.9	8095	2	Large μ
10657664	0123	BIN/ROT	0.61	392	10	Possible Hybrid
10937527	123	BIN/ROT	1.31	7396	4	Modest μ, high *g*
10966623	345	BIN/ROT	1.38	4090	5	High *g*
11038518	123	BIN/ROT	1.31	3600	4	
11287855	2345	BIN/ROT	2.28	296	8	Large μ
12207099†	0123	BIN/ROT	0.70	14896	2	
12217324†	0123	BIN/ROT	0.15	17	22	Very bright, low freq. noise
12268319	0123	BIN/ROT	0.28	393	7	Low freq. rise
2860851	0123	H	3.71	346	10	
4547333	35	H				Noisy spectrum, possibly nonvariable
5172153	23	H	3.14	621	20	Possible δ Scuti, Fg
5643103	0123	H	5.53	1100	4	
6777127	23	H	11.73	180	4	Large μ, possible A star
7108883	0123	H	6.18	259	4	Large μ
7664467	25	H	0.25	163	60:	Possible BCEP
8264293	0123	H	2.96	104	13	
10285114†	0123	H	5.41	1282	7	Fg, high *g*
11293898	0123	H	2.35	1486	18	Fg
11360704†	0123	H	2.07	1972	16	Fg
11971405	0123	H	4.01	3292	6	Fg

Table 3
(Continued)

KIC	Quarters	Class	ν_{max} (c day^{-1})	A_{max} (ppm)	N_{freq}	Notes
12116239	2345	H	23.71	172	59	Likely A star
12258330†	0123	H	2.49	662	4	Large μ
3527751	25	sdB	22.09	140	69	Possible β Cep star
3561700	23	sdB	1.05	3555	8	Possible SPB, but large μ
5807616	25	sdB	14.5	418	27	Large μ
6188286	2	sdB	0.21	194	8	Possible SPB
6848529	0123	sdB				Large μ, low freq. rise, sdB?
7098125	23	sdB	0.34	129	6	Large μ, noisy
7353409	25	sdB				Low freq. rise, modest μ
7755741	123	sdB	0.34	229	17	Possible H
9543660	123	sdB				Large μ, low freq. noise, high g, sdB?
10139564	25	sdB	21.63	691	128	Large μ, low freq. rise
10904353	2345	sdB	1.45	28	6:	Large μ
10982905	34	sdB	0.96	144	18	Possible A star, noisy
1718290	123	WD	7.94	295	46	
2697388	25	WD	17.33	1271	57:	Low g, β Cep?
3544662	12	WD	0.19:	94	15:	Low amp. signals, constant?
6866662	0123	WD	3.22	626	9	Fg
7540755	23	WD	3.80	482	13	Fg
8619526	15	WD	0.89	142	6	Large μ, single freq?, low g
9020774	123	WD	1.90	7796	4	SPB?
10536147†	0123	WD	0.22	1872	4	SPB?
10799291	123	WD	2.90	1908	13	SPB?, Fg
11302565	123	WD	1.37	539	15	SPB?, Fg
11953267	0123	WD	2.70	2557	54	Low freq. rise in power spectrum, poss Fg

Note. † Denotes stars in common with Balona et al. (2011).

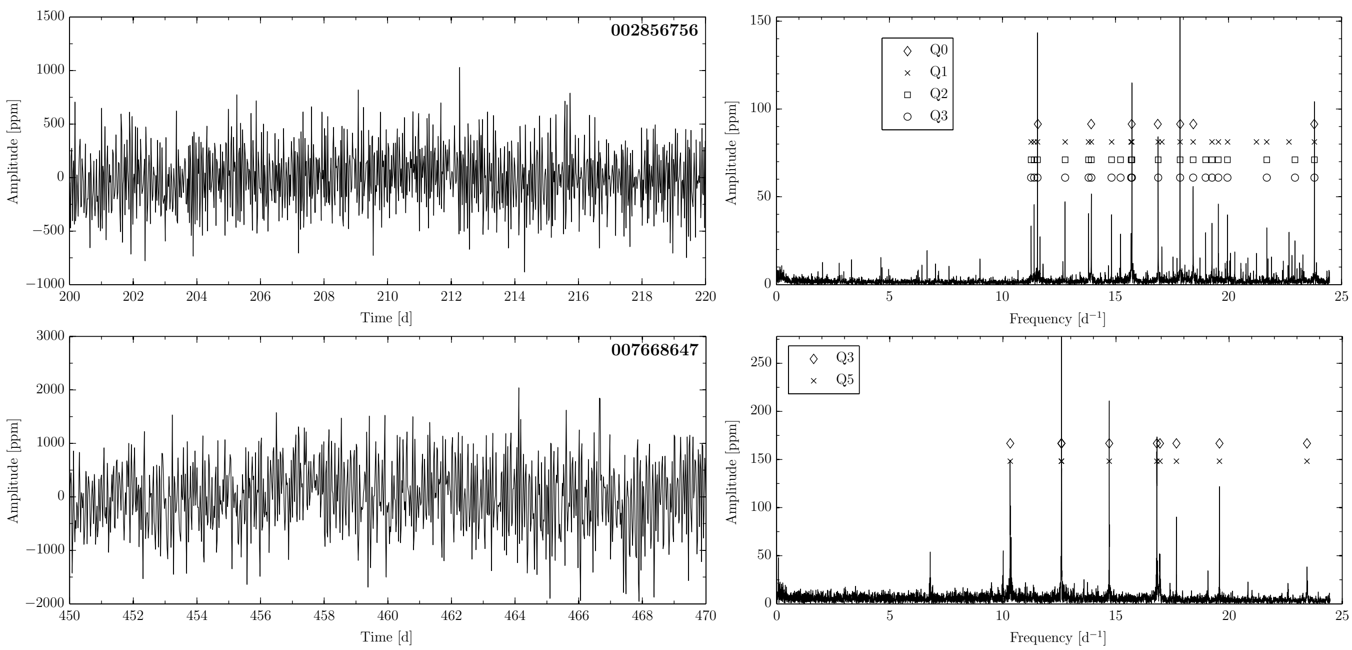

Figure 5. β Cep candidate stars. A portion of the *Kepler* light curves for KIC 002856756 (top) and KIC 007668647 (bottom) and their associated amplitude spectra are shown. The quarters for which data were available and analyzed for each star is labeled at the top of the light curves. Symbols attached to the major peaks in the power spectra show the quarters in which the frequency was detected. To avoid confusion, these symbols are only shown for the frequencies that have an amplitude within 20% of the maximum amplitude.

are generally much lower than a star's spectroscopically derived temperature. Therefore, stars whose *Kepler* temperatures would normally be too low to be considered a B star were included in our study. Both of these features make it likely that some of our B-star candidates are actually early A-type stars. The number of β Cep stars known prior to 2004 is about 93 (Stankov & Handler 2005). We were able to identify 10 additional β Cep candidates. In Figure 5, we provide the amplitude spectra, light curves, and stability maps of two of these stars. The stability of the detected oscillations from quarter to quarter is useful in

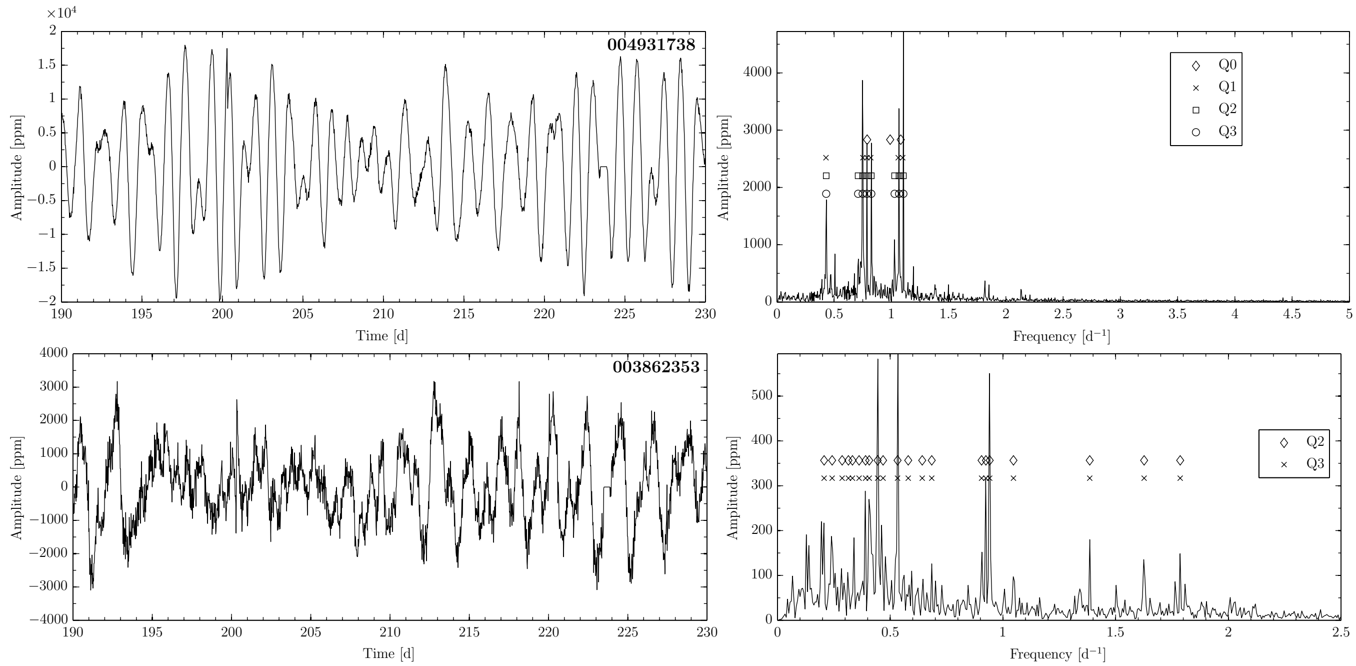

Figure 6. SPB candidate stars. A portion of the *Kepler* light curves for KIC 004931738 (top) and KIC 003862353 (bottom) and their associated amplitude spectra are shown. The quarters for which data were available and analyzed for each star is labeled at the top of the light curves. Symbols attached to the major peaks in the power spectra show the quarters in which the frequency was detected. To avoid confusion, these symbols are only shown for the frequencies that have an amplitude within 20% of the maximum amplitude.

identifying possible transient signals. Additional information about these stars is provided below.

KIC 002856756. In the KIC this star has a *Kepler* magnitude of 10.2 and has an effective temperature of 10333 K. Its amplitude spectrum based on the data collected during quarters 0–3 is shown in Figure 5. Its strongest pulsation mode has an S/N of 69 and is located at 17.85 day^{-1} (or a period of 1.34 hr). Although a prominent feature in the amplitude spectrum, the amplitude of this mode is only 0.15 mmag. An examination of its frequency spectrum shows that 19 frequencies have an amplitude of 20% of the maximum value. The stronger modes appear to be stable over the time period covered by the *Kepler* measurements, but this may not be the case for some of the weaker modes. Two frequencies located near 22 day^{-1} were only detected in the Q1 data. Additional measurements are needed to investigate whether some weaker modes are actually transient or are the result of instrumental effects. Although we are using this star are an example of a β Cep star, their is some evidence for several small amplitude (less than 20 ppm) modes with frequencies of less than 3.5 day^{-1}. If confirmed, this star would then be a hybrid. One wonders if classically defined β Cep stars were re-examined using high S/N data sets like those available from *Kepler*, whether many of them would be re-classified as hybrids.

KIC 007668647. In the KIC this star has a *Kepler* magnitude of 15.4 and an effective temperature of 10668 K. Its strongest mode has a frequency of 12.59 day^{-1} and an amplitude of 0.29 mmag. Twenty-four frequencies were detected within 20% of this maximum amplitude. Many of the detected modes are closely spaced in frequency and are not obvious in Figure 5. Some of these may be artifacts of this star's relatively complex window function. All of the stronger frequencies found in this star appear to be stable over the time period covered by *Kepler* Q3 and Q5.

4.2. SPB Stars

To be classified as an SPB a star had to meet three criteria: (1) all of the frequencies in its power spectrum had to be $\leqslant$3.5 day^{-1}; (2) its positions in Figures 3 and 4 had to be consistent with that of a B star; and (3) its power spectrum had to contain more than two frequencies. The last criterion was imposed to distinguish SPB stars from stars classified as binary/rotation (Bin/Rot). It was assumed that frequencies arising from rotation or binary activity will be few in number. Although special cases may arise where this assumption is not valid, it conforms to the scheme used to classify stars in the Balona et al. (2011) study. Approximately 51 SPBs were known to exist prior to about 2007 (De Cat 2007). We identified an additional 46 potential members of this class. Example amplitude spectra, light curves, and stability maps of two members of this group are shown in Figure 6 and are discussed below.

KIC 004931738. This star has a *Kepler* magnitude of 11.6 and KIC effective temperature of 10136 K. Its light curve extends for approximately 225 days and includes measurements made during quarters 0–3. Its largest amplitude signal (5.3 mmag) is at a frequency of 0.75 day^{-1}. Seven other frequencies have amplitudes that are within 20% of this peak amplitude. Frequencies are present out to at least 1.8 day^{-1}. The spectrum consists of three frequency groupings, separated by about 0.31 day^{-1}, centered at 0.43 day^{-1}, 0.75 day^{-1}, and 1.06 day^{-1}. The strongest frequencies within these groups are separated by about 0.038 day^{-1}. Figure 6 shows that the stronger amplitude frequencies are present in each of the quarters for which we have *Kepler* data, with the exception of quarter 0 which was only 10 day long, and thus appear to be quite stable.

KIC 003862353. This star has a *Kepler* magnitude of 14.4 and a KIC listed effective temperature of 10738 K. Measurements were obtained during quarters 2 and 3 and cover about 180 days. The strongest mode has a frequency of 0.44 day^{-1} and an

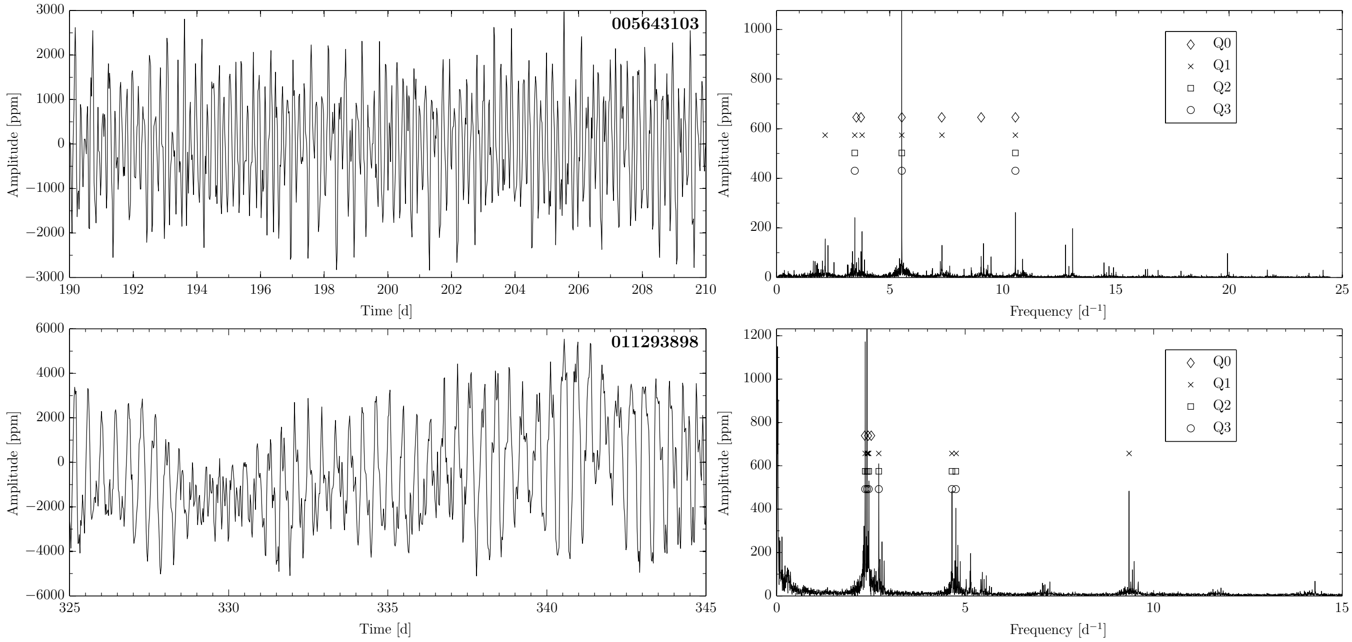

Figure 7. β Cep/SPB hybrid candidate stars. A portion of the *Kepler* light curves for KIC 005643103 (top) and KIC 011293898 (bottom) and their associated amplitude spectra are shown. The quarters for which data were available and analyzed for each star is labeled at the top of the light curves. Symbols attached to the major peaks in the power spectra show the quarters in which the frequency was detected. To avoid confusion, these symbols are only shown for the frequencies that have an amplitude within 20% of the maximum amplitude.

amplitude of 0.65 mmag. Smaller amplitude modes are present out to a frequency of at least 2.8 day^{-1}. Its spectrum in Figure 6 is more complex than for KIC 4931738, but no regular frequency spacings are evident. Eighteen frequencies were found that have an amplitude at least 20% as strong as that of the primary mode.

4.3. SPB/β Cep Hybrid Stars

Hybrid stars pulsate with frequencies typical of both the SPB stars and β Cep stars, i.e., within the frequency range 0.5–20 day^{-1}. About a third of the stars we identified in this group possess frequency groupings. Prior to about 2007 only about six hybrids were known (De Cat 2007). Fourteen stars in our sample are classified as hybrid pulsators. The light curves, amplitude spectra, and stability maps of two of them are shown in Figure 7. Some additional discussion of these stars is provided below.

KIC 005643103 (β Cep/SPB). The star was observed by *Kepler* for quarters 0–3, providing nearly 230 days of continuous measurements. Its *Kepler* magnitude and effective temperature are 9.74 and 10225 K, respectively. Its primary frequency at 5.53 day^{-1} has an amplitude of 1.1 mmag. The star has power at frequencies extending from 1.6 day^{-1} to about 22 day^{-1} although only three other modes have amplitudes greater than 20% that of its primary mode. Its power spectrum possesses several frequency groupings, but their spacing is not even. Two groupings near 7 day^{-1} were not detected in quarters 2 and 3.

KIC 011293898 (SPB/β Cep). This star has a *Kepler* magnitude of 13.4 and a KIC effective temperature of 15072 K. Measurements were obtained in quarters 0–3 and cover about 230 days. The highest peak in the amplitude spectrum has a frequency of 2.35 day^{-1} and an amplitude of 1.49 mmag. Approximately 17 other frequencies have an amplitude that is within 20% of this value. Frequency groupings starting at 2.35 day^{-1} and spaced at integer multiples of this frequency are present. The pattern of the power within these frequency groupings, however, differs. The higher amplitude modes are stable over our observing period for this star, but at least one low amplitude mode near 5 day^{-1} was detected only in quarter 0. The frequency grouping near 10 day^{-1} was only detected in quarter 1.

4.4. Binary/Rotation Modulated Stars

The light curves of stars within this group vary smoothly. Their power spectra show few peaks and these are thought to be connected to the star's rotation or binarity rather than pulsation. We identified 67 members of this group. Eight of these stars have high surface gravities and two have A-star effective temperatures in the KIC. The light curves, amplitude spectra, and stability maps of two of these stars are shown in Figure 8. Each is briefly described below.

KIC 012216706. The *Kepler* magnitude and effective temperature of this star are 10.7 and 11061 K. Its light curve is typical of a binary system of one large star and one small companion. The strongest mode present in the power spectrum has a frequency and amplitude of 0.53 day^{-1} and 0.11 mag, respectively. Other frequencies in the power spectrum are integer multiples of this primary frequency. This frequency is stable over the time period of our data set which consists of quarters 0–2.

KIC 005473826. This star has a *Kepler* magnitude of 10.9 and a KIC effective temperature of 10927 K. Its light curve is smoothly varying and its power spectrum shows only two dominant modes at 0.95 day^{-1} and 1.90 day^{-1}. The latter is simply a harmonic of the first frequency, indicating that this waveform has a non-sinusoidal shape. Both of these frequencies, which have amplitudes of 10.80 mmag and 6.03 mmag, respectively, are stable over the time period (quarters 0–3) covered by our data. The light curve is suggestive of magnetic spot modulation.

4.5. Pulsating Hot Subdwarfs and White Dwarfs

Candidates for these two classes of stars are presented because of their astrophysical importance. The power spectra of hot

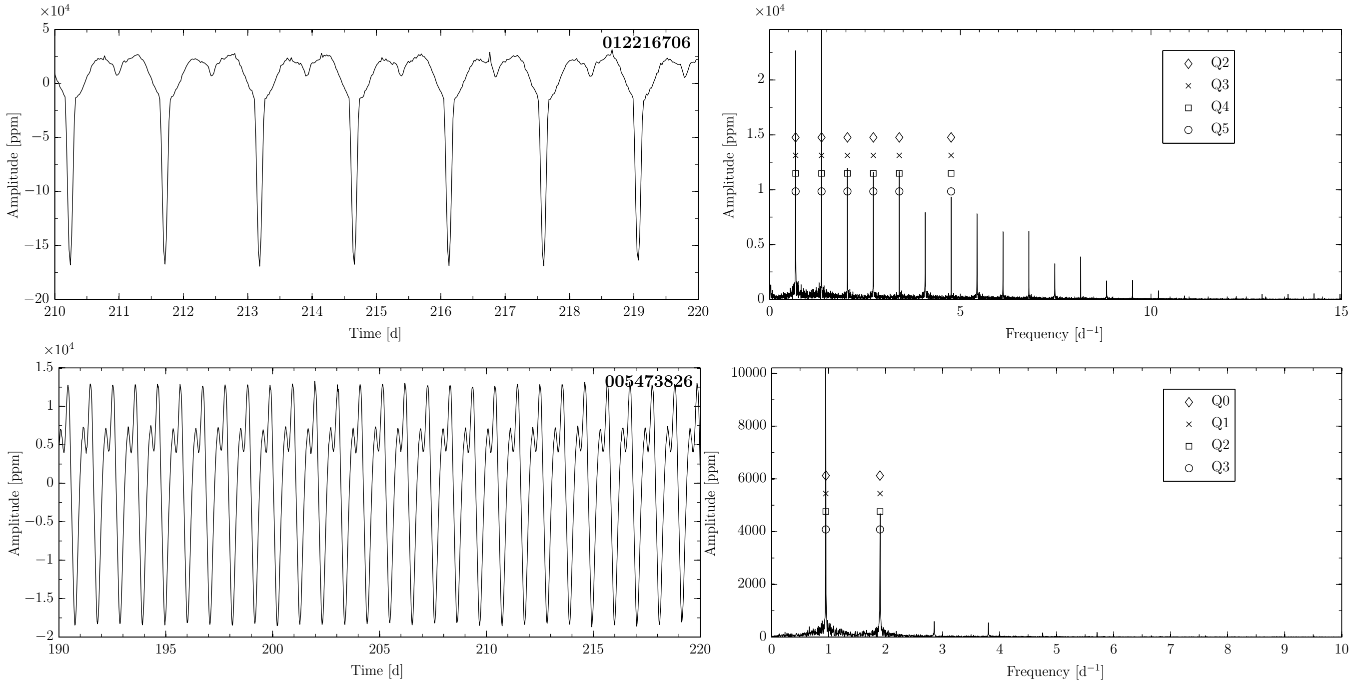

Figure 8. Bin/Rot candidate stars. A portion of the *Kepler* light curves for KIC 012216706 (top) and KIC 005473826 (bottom) and their associated amplitude spectra are shown. The quarters for which data were available and analyzed for each star is labeled at the top of the light curves. Symbols attached to the major peaks in the power spectra show the quarters in which the frequency was detected. To avoid confusion, these symbols are only shown for the frequencies that have an amplitude within 20% of the maximum amplitude.

horizontal branch stars provide information about the structure of evolved stars, while white dwarfs are a major end product of stellar evolution. Stars are classified as pulsating hot subdwarfs or pulsating white dwarfs based on either their location in Figure 4 or their spectroscopic classification (Østensen et al. 2010). Membership in either of these classes is highly uncertain. Many of these stars may be misclassified β Cep or SPB stars. Generally they possess a large proper motion and nearly all of the pulsating white dwarf candidates have a KIC log(g) 5. In Table 3 we classify 12 stars as pulsating sdB stars and 11 stars as pulsating white dwarfs. The discovery of pulsating white dwarfs in the *Kepler* field is interesting since only a few (one?) of these stars are currently known. Many of the white dwarf candidates possess frequency groupings. For two sdB stars, KIC 6848529 and 9543660, we do not provide frequencies. In both cases the light curves are affected by unresolved calibration issues that cause a rapid rise in power at low frequencies. It is likely that the star KIC 006848529 has a stable mode at 0.92 day^{-1} with an amplitude of about 0.13 mmag, but a cleaner data set is needed to confirm this value. The amplitude spectrum of KIC 009543660 has several peaks below 1 day^{-1}, but their amplitudes are very small ($\leqslant$0.03 mmag) and a confirming data set is required.

5. SUMMARY

In this study we have examined the light curves of 252 B-star candidates in the *Kepler* catalog. Variable stars in this sample have been classified using the criteria adopted by Balona et al. (2011). These groupings include: the β Cep stars, the SPB stars, hybrid pulsators whose power spectra contain frequencies present in both of these pulsators, and B stars whose variability is likely related to their rotation or presence in a binary. Proper motions obtained from the UCAC3 catalog (Zacharias et al. 2009) and the position of these stars in a pseudo HR diagram were used to distinguish between likely main-sequence B stars, hot subdwarfs, and A stars. Because the *Kepler* temperatures of hot stars are poorly known, the stars classified in this study should only be considered to be candidates for each of their variable classes. The primary result of this study has been to increase the number of B-star variables identified using *Kepler* light curves. Using Balona et al. (2011) as a reference and the variable candidates studied here for inclusion within their respective classes, the number of β Cep candidates has been increased from 0 to 10, the number of SPB stars from eight to 54, the number of hybrids from seven to 21, the number of Bin/Rot B stars from 23 to 82. For comparison purposes the number of confirmed SPBs and hybrids known prior to 2007 were about 51 and six, respectively (De Cat 2007). The number of confirmed β Cep stars know prior to 2004 was 93 (Stankov & Handler 2005). A secondary result of this study is the identification of an additional 11 white dwarf candidates, four of which possess frequency groupings.

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