Analysis of *Kepler* B stars: Rotational modulation and Maia variables

L. A. Balona$^1$, A. S. Baran$^2$, J. Daszyńska-Daszkiewicz$^3$, P. De Cat$^4$

$^1$South African Astronomical Observatory, P.O. Box 9, Observatory 7935, Cape Town, South Africa

$^2$Universytet Pedagogiczny w Krakowie, ul. Podchorazych 2, 30-084, Kraków, Poland

$^3$Instytut Astronomiczny, Uniwersytet Wrocławska, Kopernika 11, 51-622 Wroclaw, Poland

$^4$Royal Observatory of Belgium, Ringlaan 3, B-1180 Brussel, Belgium

Accepted .... Received ...

ABSTRACT

We examine 4-yr almost continuous *Kepler* photometry of 115 B stars. We find that the light curves of 39 percent of these stars are simply described by a low-frequency sinusoid and its harmonic, usually with variable amplitudes, which we interpret as rotational modulation. A large fraction (28 percent) of B stars might be classified as ellipsoidal variables, but a statistical argument suggests that these are probably rotational variables as well. About 8 percent of the rotational variables have a peculiar periodogram feature which is common among A stars. The physical cause of this is very likely related to rotation. The presence of so many rotating variables indicates the presence of star spots. This suggests that magnetic fields are indeed generated in radiative stellar envelopes. We find five $\beta$ Cep variables, all of which have low frequencies with relatively large amplitudes. The presence of these frequencies is a puzzle. About half the stars with high frequencies are cooler than the red edge of the $\beta$ Cep instability strip. These stars do not fit into the general definition of $\beta$ Cep or SPB variables. We have therefore assumed they are further examples of the anomalous pulsating stars which in the past have been called “Maia” variables. We also examined 300 B stars observed in the K2 Campaign 0 field. We find 11 $\beta$ Cep/Maia candidates and many SPB variables. For the stars where the effective temperature can be measured, we find at least two further examples of Maia variables.

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

1 INTRODUCTION

The *Kepler* mission has been an outstanding success, not only in the detection of extra-solar planets by the transit method, but also in the general field of astrophysics and asteroseismology. The superb photometric precision and almost continuous 4-yr coverage of over 100000 stars has led to many surprises. The center of the *Kepler* field is about 13$^\circ$ above the galactic plane. B-type main sequence stars are to be found very close to the galactic plane and, as a result, only a few of the nearest, brightest, main sequence B stars are visible in the *Kepler* field. There are a few hundred stars which have effective temperatures $T_{\text{eff}} > 10000 \text{K}$ according to the *Kepler Input Catalogue* (KIC, [Brown et al. 2011]). Most of these have high proper motions and probably are faint, hot subdwarfs. Unfortunately, the multicolour photometry used to derive the stellar parameters in the KIC does not include the U band. As a result, the effective temperatures for B stars cannot be trusted. Therefore some B stars may have been assigned low temperatures in the KIC, placing them among the A stars.

[Balona et al. 2011] presented the first major study of *Kepler* main sequence B stars based on the first year of operation. Among the 48 B stars, 15 stars show the characteristics of SPB variables, 7 of which could be considered as hybrid $\beta$ Cep/SPB variables. The data indicate that non-pulsating stars exist in the $\beta$ Cep and SPB instability strips. Apart from the pulsating stars, several different classes of variables can be identified based on frequency groupings, but the nature of the variability is unclear. Subsequently, [McNamara et al. 2012] analyzed the *Kepler* light curves of B star candidates to further characterize B-star variability. They found 10 $\beta$ Cep variables and 54 SPB stars among the sample. However, many of the $\beta$ Cep candidates are now known from spectroscopic observations to be hot compact objects and not main sequence B stars.

The loss of a second spacecraft reaction wheel effectively ended data collection in the original *Kepler* field after four
years of continuous monitoring. By pointing near the ecliptic plane, the *Kepler* spacecraft is able to minimize pointing drift, allowing data collection to proceed with much reduced photometric precision. This mode of operation is called the K2 project. A preliminary test of this mode for science purpose, Campaign 0, was made during 2014 Mar 8–27. The K2 Campaign 0 field, which we will call the K2-0 field, is closer to the galactic plane ($b = 6^\circ$) and contains many more B stars. However, ground based photometry is very limited and it is not possible to estimate effective temperatures for most of the stars.

In this paper we examine in more detail the light curves of B stars observed in the original *Kepler* field using all available (Q0–Q17) data. We also include 300 B stars observed in the K2-0 field. Our aim is to detect pulsating main sequence B stars in these two fields by examining the light curves and periodograms and to classify them according to variability type as best as we can.

It turns out that a large fraction of B stars appear to be rotational variables. This is surprising because B star atmospheres are radiative which are thought not to be capable of generating the magnetic field necessary to produce a star spot. We also find an extraordinary number of supposedly ellipsoidal variables. Many of these may be rotational variables as well. Furthermore, we show that the strange periodogram feature, first found among A stars and described by Balona [2013a], is also present among the B stars. Finally, we detect several B stars containing high frequencies but which are too cool to be classified as $\beta$ Cep variables. In citetBalona2011b it was speculated that these anomalous pulsating stars may be binaries in which the primary is a B star and the secondary a $\delta$ Scuti variable. However, the sheer number of such anomalous variables as well as recent CoRoT and ground-based observations do not support this conclusion. Because these stars cannot be considered as $\beta$ Cep or SPB stars and are too hot to be $\delta$ Scuti variables, we decided to call them Maia variables. This name has been used for such pulsating variables in the past, but no definite proof of their existence has been found. Although they may eventually be explained by known mechanisms, we feel that until this is done, it is important to distinguish them from the $\beta$ Cep and SPB variables.

2 THE DATA

The *Kepler* light curves are available as uncorrected simple aperture photometry (SAP) and with pre-search data conditioning (PDC) in which instrumental effects are removed [Stumpe et al. 2012; Smith et al. 2012]. The vast majority of the stars are observed in long-cadence (LC) mode with exposure times of about 30 min. Several thousand stars were also observed in short-cadence (SC) mode with exposure times of about 1 min. These data are publicly available on the Barbara A. Mikulski Archive for Space Telescopes (MAST, archive.stsci.edu).

In selecting our sample of known and possible B stars observed by *Kepler* we first included all stars with effective temperatures $T_{\text{eff}} \geq 10000$ K in the *Kepler* Input Catalogue (KIC, Brown et al. 2011). We also added stars in Table 1 of Balona et al. [2011] which do not have effective temperature measurements in the KIC but which are known B stars. Finally, we performed a literature search on all stars in this list and removed compact objects. The list of stars which we consider to be mostly B-type main sequence objects is shown in Table I. Since the KIC effective temperatures are not reliable for B stars, some stars in the table may be cooler than B9 and a few may still be unrecognized compact objects.

In this table, spectroscopic measurements of $T_{\text{eff}}$, and surface gravity, $\log(g)$, are used whenever possible. Failing this, values derived from Strömgren photometry are listed. These parameters are from Balona et al. [2011] which are mostly derived from Catanzaro et al. [2010] and Lehmann et al. [2011]. Further spectroscopic data by McNamara et al. [2012] and Tkachenko et al. [2013a,b] were also used to update the effective temperatures and surface gravities. When spectroscopic or Strömgren values are not available, the KIC values are shown marked by a colon. The luminosity $\log(L/L_\odot)$ is calculated from $T_{\text{eff}}$ and $\log(g)$ using the relationship in Torres et al. [2010]. For those stars where only the KIC values are available, the luminosity was derived from the KIC effective temperature and radius. We emphasize, once again, that the KIC values are highly unreliable for B stars and they serve merely as indicators that the stars may be of type B and nothing more. Further observations are required to ascertain their effective temperatures and surface gravities. In Fig. I we plot all the stars of Table I in the theoretical H-R diagram.

3 CLASSIFICATION OF VARIABILITY TYPE

Classification of variability type is an essential first step in this study. We only have the light curve and periodogram, but in most cases this is sufficient to enable a variability type to be assigned. We discuss the types of variable star that might be found among the B stars.

Eclipsing binaries are easily classified into two main groups: detached systems (Algol type, EA) or semi-detached ($\beta$ Lyr systems, EB). In EA systems the components are...
spherical or slightly ellipsoidal and it is easy to specify the beginning and end of the eclipses. Between eclipses the light remains almost constant. In EB systems the stars are tidally distorted and it is impossible to specify the exact times of onset and end of eclipses because of a continuous change of the combined brightness between eclipses.

The ellipsoidal variables (ELL) are close binary systems with tidally distorted components. Due to the low inclination of the orbital axis, there are no eclipses, but the changing aspect towards the observer results in light variations. The light variations are a combination of tidal distortion, reflection and beaming. Beaming is induced by the stellar radial motion which results in an increase (decrease) in brightness when the star is approaching (receding from) the observer. The period of the reflection and beaming contributions is the same as the orbital period whereas the ellipsoidal effect has half the orbital period.

There is also the possibility of rotational modulation in single stars (ROT). All stars rotate, so it is natural to expect light variations if the photospheric surface brightness is not perfectly uniform in longitude. Several types of Bp stars are known to have photospheric spots, though these are supposedly surface abundance variations and not comparable to sun spots. We take the view that spots of any description must be a permissible option, even though we may not know how they may be formed. The extraordinary photometric precision attained by Kepler allows detection of very small surface brightness variations which may have escaped ground-based observations. We should also allow for the possibility of differential rotation which could result in multiple closely-spaced frequency peaks in the periodogram.
There is a degeneracy between the ELL and ROT classes because it is not possible to distinguish between orbital and rotational variations without additional information from spectroscopy. We assume that if the amplitude of the periodic variation changes in a relatively short time scale (perhaps a few months), then it is perhaps more likely to be a result of a star spot. Orbital variations typically have a longer time scale. Of course, it is equally true that long-lived spots may mimic the light curve of the ELL class.

Among the sample of stars there are a number of chemically peculiar stars. These stars have spots of some kind (perhaps of different abundances) and are known as \( \alpha \) CVn variables (ACV).

We know of two types of pulsating main sequence B stars: the \( \beta \) Cep (BCEP) variables (high pulsation frequencies) and the slowly pulsating B stars (SPB stars with low frequencies). We selected the dividing line between low and high frequencies to be around \( 5 \, \text{d}^{-1} \) because very few known \( \beta \) Cep pulsate with lower frequencies and few SPB stars pulsate with higher frequencies.

Some stars break this rule: there are stars with high frequencies which are cooler than the red edge of the BCEP variables. It is possible that such stars are binaries in which the pulsating component is the cooler companion of a B star primary. In this way one could explain these anomalous pulsating stars as an A-type \( \delta \) Sct star orbiting a more luminous non-pulsating B star (Balona et al. 2011). However, it is difficult to sustain this explanation in the face of the large number of such variables. In this paper we have provisionally classified such anomalous pulsating stars as MAIA variables, a term which is discussed below. We classify a star as a MAIA variable if it is a B star with high frequencies that is cooler than the coolest known \( \beta \) Cep variable. This does not necessarily imply that Maia variables require a separate driving mechanism. We use the term because these stars violate the definitions of existing classes.

It is not always possible to distinguish between the SPB and ROT classes. It would be incorrect to dismiss the presence of rotational modulation in any star so that multiple close low frequencies might be a sign of differential rotation and need not automatically imply pulsation. We generally assume that pulsation is responsible unless we see at least one harmonic, in which case rotation is to be preferred. The reason is that harmonics of pulsation modes are not normally visible unless the amplitude is large, whereas harmonics are a natural consequence of localized spots.

With the above considerations in mind, we assigned a variability type to each star as best as we could. Results for the B stars in the Kepler field are shown in Table 1. Nearly all the stars in Balona et al. (2011) are listed in this table. However, KIC 8087269, 8161798, 8488717 and 12207099 are blue horizontal branch stars (R.H. Østensen, priv. comm.), while KIC 10536147 is a pulsating white dwarf (McNamara et al. 2012). These stars are omitted.

![Figure 3](https://example.com/figure3.png)

**Figure 3.** Periodograms in the region of the broad and narrow peaks for stars showing the pattern described by Balona (2014).
Table 1. Candidate main sequence B stars in the *Kepler* field. The KIC number and a variable star classification is shown in the first two columns. Stars showing little signs of variability are indicated by a dash in the type column. The Kp magnitude, effective temperature, $T_{\text{eff}}$ and surface gravity, log($g$), are from the KIC if followed by a colon, otherwise it is from Balona et al. (2011). The luminosity log $L/L_\odot$, photometric rotation period and the projected rotational velocity, $v\sin i$, are also shown. Remarks are given in the last column.

| KIC      | Type       | Kp  | $T_{\text{eff}}$ | log($L/L_\odot$) | log($g$) | $P_{\text{rot}}$ | $v\sin i$ | Notes         |
|----------|------------|-----|-----------------|-------------------|---------|-----------------|----------|---------------|
| 1029085  | ELL        | 12.649 | 10721 | 3.64: 2.30: 0.5456 |
| 1430353  | SPB/ROT    | 12.391 | 10765 | 3.65: 2.30: 1.0179 |
| 2987640  | MAIA       | 12.641 | 10985 | 4.13: 1.81: |
| 3216449  | ELL        | 11.821 | 10232 | 4.40: 1.32: 0.9436 |
| 3240411  | SPB/BCEP   | 10.241 | 20980 | 4.01 3.54 42.6 B2 V |
| 3343239  | MAIA       | 14.420 | 10691 | 3.93: 1.97: |
| 3442422  | ROT        | 11.954 | 10732 | 4.02: 1.88: 14.286 |
| 3459297  | MAIA       | 12.554 | 10592 | 4.63: 1.14: |
| 3839930  | SPB        | 10.864 | 16500 | 4.20 2.73 |
| 3848385  | ROT        | 8.958  | 11680 | 3.76 2.46 0.9709 B8 V |
| 3865742  | SPB/ROT    | 11.130 | 19500 | 3.70 3.75 4.1118 133.0 |
| 4064365  | ELL        | 12.296 | 11281 | 4.17: 1.84: 8.9606 |
| 4077252  | ELL        | 12.314 | 10514 | 3.95: 1.91: 3.9754 KOI 5038.01 |
| 4276892  | ELL/ROT    | 9.185  | 10800 | 4.10 1.86 6.4309 10.0 B8/A0 |
| 4366757  | ROT        | 13.543 | 11087 | 4.12: 1.84: 7.1429 |
| 4373805  | ROT        | 11.836 | 11423 | 4.37: 1.63: 3.169 |
| 4931738  | SPB        | 11.645 | 10136 | 4.42: 1.27: |
| 4936089  | SPB        | 11.928 | 11295 | 4.28: 1.71: |
| 5450881  | ROT        | 12.468 | 10197 | 3.41 2.93 0.8391 200.0 B9/A5 |
| 5458880  | ROT        | 7.824  | 24070 | 3.18 4.95 3.5112 |
| 5530935  | SPB        | 8.040  | 10203 | 4.20 1.61 0.5028 |
| 5557097  | -          | 14.545 | 10454 | 3.60: 2.28: |
| 5687841  | ROT-d      | 10.392 | 10670 | 3.86 2.13 0.4654 155.0 B9 IV/V |
| 5706079  | ROT-d      | 10.385 | 10708 | 3.64: 2.30: 1.4885 |
| 5886771  | ELL        | 9.429  | 11790 | 3.41 2.93 0.8391 237.0 B8.5 III |
| 5941844  | SPB        | 9.172  | 13100 | 3.90 2.55 0.9907 180.0 B4-B8 |
| 5948880  | ROT        | 12.543 | 11087 | 4.12: 1.84: 7.1429 |
| 5977601  | SPB/ROT    | 12.894 | 10988 | 3.70 3.75 4.1118 133.0 |
| 6065699  | SPB        | 11.928 | 11295 | 4.28: 1.71: |
| 6070977  | -          | 14.545 | 10454 | 3.60: 2.28: |
| 6214344  | ROT-d      | 10.392 | 10670 | 3.86 2.13 0.4654 155.0 B9 IV/V |
| 6278403  | ELL        | 8.758  | 10687 | 4.01: 1.88: 1.1911 B9 |
| 6780397  | ROT        | 10.051 | 11166 | 4.17: 1.81: 0.8529 B9 |
| 6845529  | SPB        | 10.734 | 14300 | 3.80 3.60 10.0 |
| 6905555  | ELL        | 12.751 | 10942 | 3.70: 2.28: 1.5116 |
| 6954726  | BE         | 11.930 | 10900 | 4.08 1.95 1.3036 63.0 B8.5 V |
| 7599132  | ELL        | 9.384  | 11090 | 4.08 1.95 1.3036 63.0 B8.5 V |
| 7749504  | ROT        | 12.723 | 11064 | 3.73: 2.28: 0.2700 |
| 7778838  | ELL        | 11.868 | 11090 | 4.18: 1.76: 5.8754 |
| 7974841  | ELL/ROT    | 8.198  | 10650 | 3.87 2.11 2.8433 33.0 B8 V, B7 IV/V |
| 8035614  | SPB/MAIA   | 8.006  | 11089 | 3.78: 2.23: 0.5988 B8 V |
| 8057661  | BE/BCEP    | 11.609 | 21360 | 4.23 3.33 49.0 Be |
| 8129619  | ELL        | 10.992 | 10203 | 4.49: 1.20: 0.9519 KOI 6052.01 |
| 8167038  | SPB        | 10.846 | 11167 | 4.23: 1.74: |
| KIC  | Type      | Kp  | T$_{\text{eff}}$ | log($L_\odot$) | log(g) | P$_{\text{rot}}$ | v$_\sin i$ | Notes                  |
|------|-----------|-----|-----------------|----------------|--------|----------------|-----------|------------------------|
| 8177087 | SPB | 8.093 | 13330 | 3.42 | 3.21 | 22.2 | B7 III He-strong |
| 8183197 | ELL | 11.233 | 10822 | 4.07 | 1.84 | 3.6914 |
| 8264293 | ROT | 11.310 | 10038 | 4.46 | 1.21 | 0.3400 |
| 8324268 | ACV | 7.955 | 11370 | 3.35 | 2.93 | 2.0090 | | |
| 8351193 | ROT | 7.598 | 9960 | 3.80 | 2.05 | 0.5685 | 180.0 | B9 V Si |
| 8381949 | SPB/BCEP | 11.104 | 24500 | 4.30 | 3.59 |
| 8399948 | ROT-d | 9.220 | 10240 | 3.86 | 2.03 | 1.0060 | 142.0 | B9.5 V/IV |
| 8442729 | ELL | 10.905 | 10753 | 3.95 | 1.96 | 1.6576 |
| 8458989 | SPB | 8.730 | 15760 | 3.81 | 3.10 | 22.2 | B7 III He-strong |
| 8559392 | ROT | 12.983 | 10510 | 5.23 | 0.42 | 3.0000 |
| 8619436 | ELL | 11.806 | 10694 | 3.81 | 3.10 | 53.0 | B4.5 IV, SB2? |
| 8692626 | ELL | 8.342 | 9826 | 4.71 | 0.98 | 1.6483 |
| 8714886 | SPB/MAIA | 10.945 | 19000 | 4.30 | 2.96 |
| 8766405 | ROT | 8.875 | 12930 | 3.16 | 3.48 | 0.5457 | 240.0 | B7 III |
| 8881883 | ELL | 12.441 | 10710 | 3.63 | 2.31 | 3.3234 |
| 9005047 | ROT | 11.686 | 10477 | 3.61 | 2.28 | 1.3167 |
| 9227988 | SPB | 12.845 | 10890 | 4.02 | 1.91 |
| 9278405 | ROT | 10.243 | 11486 | 4.20 | 1.84 | 0.5590 |
| 9468611 | ELL | 12.441 | 11063 | 3.73 | 2.27 | 0.4559 |
| 9582169 | ELL | 12.051 | 11373 | 3.79 | 2.28 | 0.4006 |
| 9655433 | MAIA/ROT-d | 11.930 | | | | 0.8361 | | NGC 6811, B7/A3 |
| 9715425 | SPB | 13.065 | 11199 | 4.11 | 1.88 |
| 9716301 | ROT | 11.622 | 7822 | 3.63 | 1.55 | 1.9940 | | | |
| 9716306 | ELL | 11.980 | 10353 | 3.94 | 1.26 | 0.3417 |
| 9725496 | ELL | 12.256 | 10257 | 4.46 | 1.25 |
| 9884329 | ELL | 12.144 | 10695 | 3.57 | 2.37 | 0.3692 |
| 9958053 | ELL | 11.727 | 10225 | 4.01 | 1.77 | 2.7334 |
| 9964614 | SPB/BCEP | 10.806 | 20300 | 3.90 | 3.59 |
| 10090722 | ELL | 12.998 | 11383 | 3.78 | 2.29 | 6.0100 |
| 10118750 | SPB/ROT | 13.897 | 11147 | 3.75 | 2.28 | 0.2700 |
| 10130954 | ELL | 11.134 | 19400 | 4.00 | 3.36 | 2.2467 |
| 10220209 | SPB | 14.120 | 15969 | 6.10 | 0.63 |
| 10285114 | SPB/MAIA | 11.232 | 18200 | 4.40 | 2.74 |
| 1041584 | - | 14.464 | 10265 | 3.99 | 1.80 |
| 10526294 | SPB | 13.033 | 11072 | 3.74 | 2.27 |
| 10657664 | ELL | 13.234 | 10564 | 3.99 | 1.87 | 3.2733 | KOI 964.01 |
| 10658320 | SPB | 13.125 | 15900 | 3.90 | 3.01 |
| 10763966 | SPB | 10.479 | 11030 | 4.12 | 1.84 |
| 10864843 | - | 10.472 | 10000 | 4.04 | 1.68 |
| 10790075 | ROT? | 12.808 | 11396 | 3.77 | 2.31 | 3.9060 |
| 10797526 | SPB | 8.342 | 20873 | 3.22 | 4.54 | | B5/A5 |
| 10906750 | SPB/BCEP | 9.844 | 19960 | 3.91 | 3.54 | 253.0 | B2.5 V |
| 10965032 | SPB/ROT | 14.647 | 11488 | 3.82 | 2.27 | 0.3000 |
| 11038518 | ELL | 13.554 | 11224 | 3.75 | 2.29 | 0.7646 |
| 11075420 | ROT-d | 11.604 | 11089 | 3.74 | 2.28 | 0.3417 |
| 11360704 | SPB/ROT | 10.738 | 20700 | 4.10 | 3.40 | 0.4060 |
| 11454304 | SPB/MAIA | 12.951 | 17500 | 3.90 | 3.23 |
| 11565279 | - | 12.324 | 11374 | 4.17 | 1.85 |
| 11671923 | SPB | 10.679 | 10044 | 4.24 | 1.46 |
| 11817929 | - | 10.381 | 16000 | 3.70 | 3.27 | | A0 |
| 11912716 | SPB/ROT | 6.602 | 10386 | 3.61 | 2.26 | 1.5106 | | B9 III |
| 11957688 | ELL | 12.887 | 11183 | 3.78 | 2.26 | 1.7967 |
| 11973705 | MAIA | 9.116 | 11150 | 3.96 | 2.11 | 103.0 | B8.5 V/IV, SB2 |
| 12060005 | ROT | 13.671 | 10825 | 3.67 | 2.29 | 3.0300 |
| 12217324 | ROT | 8.312 | 10380 | 3.75 | 2.20 | 6.6600 | 19.0 | B9.5 IV |
| 12258330 | SPB/MAIA | 9.517 | 14700 | 3.85 | 2.88 | 130.0 | B5 V |
| 12268319 | ELL | 11.628 | 10763 | 4.03 | 1.87 | 3.6311 |
| 12453485 | ROT | 12.361 | 10317 | 3.79 | 2.05 | 0.4135 |
4 ECLIPSING BINARIES

There are surprisingly few eclipsing binaries - only one in our sample of 115 stars. KIC 8018827 shows the characteristic light curve of a contact binary with a secondary eclipse that is approximately one-quarter the depth of primary eclipse. The orbital period $P = 0.3979 \text{ d}$ is very short (Tkachenko et al. 2013]. If the stellar mass is approximately $3 M_\odot$ the semi-major axis will be approximately $3.3 R_\odot$. It is classified as a rotational variable in Balona et al. (2011).

5 ELLIPSOIDAL VARIABLES

The periodogram of an ellipsoidal binary consists of sharp peaks at the fundamental frequency and its harmonics. Usually only the first harmonic is visible. Sometimes the fundamental has a lower amplitude than the first harmonic. As a consequence of differences in harmonic content, the shapes of the light curves can be very different. About half the ellipsoidal variables in Table 1 have almost sinusoidal light curves. Examples of ELL variables with non-sinusoidal light curves are shown in Fig. 2. These were obtained by phase-fitting the light curve with the fundamental period and averaging the phase curve in twenty phase bins. The large number of ELL variables is rather surprising because one expects rather few systems at low inclinations. The highly non-sinusoidal light curves in Fig. 2 may be a result of a strong reflection effect and/or beaming. A study of the stellar parameters required to produce such light curves is beyond the scope of this paper, but is clearly of great interest given the considerable number of these systems among the Kepler B stars.

In KIC 3216449 the amplitude increases gradually from about 2.5 ppt (parts per thousand) to 3.5 ppt over the 4-yr observing period. In KIC 4077252 the amplitude decreases from 12 to 9 ppt over the 4-yr period. In KIC 4064365 there is a single strong peak at 0.1116 $\text{d}^{-1}$ and another much weaker one at 0.0881 $\text{d}^{-1}$. The secondary peak could indicate non-synchronous rotation. In KIC 4276892 the dominant peak is $\nu = 0.1555 \text{d}^{-1}$ with a much weaker peak at 0.0439 $\text{d}^{-1}$. Both peaks are fairly broad and the light curve is rather complex. It is difficult to understand the variation in terms of a simple ellipsoidal system and perhaps this star should be classified as a rotational variable.

The stars classified as ELL in Table 1 are nearly always classified as probable binaries in Balona et al. (2011). With the much larger data set used here, one is able to determine the orbital period and shape of the light curve quite accurately. For KIC 7974841 Balona et al. (2011) adopt a classification of ROT/SPB. The periodogram shows a sharp peak ($P = 2.8433 \text{d}$) and harmonic, but also a broad peak at $P = 4.0 \text{d}$ and its harmonic. This does not look like the frequency pattern of an SPB star but could be a spotted companion in a non-synchronous orbit. Tkachenko et al. (2013) could not find evidence for binarity from their two spectra. We give it the classification ELL/ROT.

6 ROTATIONAL VARIABLES

A characteristic of the ROT type is a variation in amplitude on a timescale of months. Often there are beating effects and traveling features in the light curve which is a characteristic feature of late-type variables with star spots. An interesting subset of the rotational variables consists of a pattern first described in Balona (2014). Examples of this pattern are shown in Fig. 3. As can be seen, there is a broad peak flanked by a sharp peak at a slightly higher frequency. For convenience we classify stars with this pattern as ROT-d because the pattern is similar to the letter d.

Balona (2013) discovered that about 20 percent of Kepler A stars are ROT-d variables. Balona (2014) suggested that the broad feature is due to differential rotation and the sharp peak a result of reflection from a planet in a co-rotating orbit (not necessarily transiting). Whatever the reason, ROT-d variables are very common and require an explanation. Fig. 5 shows the periodograms of all ROT-d stars in our sample.

In KIC 9655433 three of four peaks with amplitudes in the range 0.2–1.2 ppt can be seen with $\nu > 22.5 \text{d}^{-1}$. The high frequencies and low temperature means that this is a MAIA variable. There are scattered low-amplitude peaks all the way to zero frequency. There is also a ROT-d pattern with the sharp peak at 1.1960 $\text{d}^{-1}$ and broad peak at $\nu_B = 1.14 \text{d}^{-1}$ and a hint of the harmonic.

In KIC 4366757 there are two sharp, low-amplitude peaks at $\nu_1 = 0.3155$ and $\nu_2 = 2.7905 \text{d}^{-1}$. The lower of the two frequencies is embedded in a broad peak and there is some weak structure at 2$\nu_1$ suggesting rotational modulation. In KIC 4373805 there is just a single, broad, very weak peak at 0.140 d$^{-1}$, though no harmonic is visible. This period is clearly visible in the light curve which is characterized by variable amplitude and an overall decrease in amplitude from about 0.9 to 0.6 ppt over four years.

In KIC 4476114 the highest peak is at $\nu_1 = 0.3390 \text{d}^{-1}$ with smaller peaks at $\nu_2 = 0.1647$ and $\nu_3 = 0.8250 \text{d}^{-1}$. There is no obvious relationship between these three frequencies except $\nu_3 = 5\nu_2$. If the term SPB is a catch-all for unexplained peaks, then perhaps this could be classified as a peculiar SPB with only three unstable frequencies. However, the light curve is typical of late-type stars with spots, so perhaps this is a manifestation of rotational modulation. The light curve of KIC 5450881 also looks very much like that of a late-type spotted star. The periodogram is dominated by three peaks $\nu_1 = 3.6787$, $\nu_2 = 3.2700$, $\nu_3 = 4.0874 \text{d}^{-1}$ and the harmonic 2$\nu_1$.

In KIC 8264293 there is a tight group of equidistant peaks at $\nu = 2.9556$, 3.1295, 2.4091, 2.9309, 2.4228, 2.8519 d$^{-1}$, with equal spacing ($\delta \nu = 0.023 \text{d}^{-1}$). The first harmonics of these peaks are also visible. This may be a rotational variable with splitting caused by the proximity effect of a binary with orbital frequency 0.023 d$^{-1}$.

In the B7 III star KIC 8766405 there are about a dozen peaks below 6 d$^{-1}$ with the highest at $\nu_1 = 1.8326 \text{d}^{-1}$, amplitude 1.7 ppt. A strong harmonic is present for $\nu_2 = 0.8658$, which suggests that this may be the rotation frequency. The peak at $\nu_3 = 1.9774$ is also strong. The harmonics 2$\nu_1$ and 2$\nu_2$ have relatively large amplitudes. All this is more suggestive of differential rotational modulation than SPB pulsation, but either (or both) is possible.
A logarithmic amplitude scale is used to show the very weak high frequencies.

Figure 4. Periodograms of stars classified as SPB/β Cep hybrids. A logarithmic amplitude scale is used to show the very weak high frequencies.

7 CHEMICALLY PECULIAR STARS

There are four known chemically peculiar stars in our sample and all show rotational modulation. The only star of the four which has been given the designation ACV in the General Catalogue of Variable Stars (Samus et al. 2004) is KIC 8324268, but the other three stars should probably be given the same classification. KIC 8324268 is a B9pSiCr star with a peak at $\nu = 0.4977 \text{ d}^{-1}$ and amplitude 12 ppt. Tkachenko et al. (2013) find line profile variations consistent with abundance spots.

Tkachenko et al. (2013) find that KIC 8351193 has a metallicity, $[\text{M/H}] < -0.8$ dex, with nearly solar helium abundance and overabundance of Mg compared to the derived Fe content. In addition, there is a strong enhancement of Si. The light curve shows a very low amplitude (2 ppm) rather broad peak at $\nu = 1.7589 \text{ d}^{-1}$ and its harmonic which we interpret as rotational modulation.

KIC 5479821 is a B5.5 V He-weak star (Lehmann et al. 2013). The periodogram shows a dominant peak at $\nu_1 = 0.5878 \text{ d}^{-1}$ and first harmonic. Higher harmonics are present but very weak. In addition, there is another peak at $\nu_2 = 0.1841 \text{ d}^{-1}$ which bears no relationship to $\nu_1$. The light curve is sinusoidal with minima and maxima of slightly different amplitude superimposed on the low-frequency $\nu_2$ variation. We presume that $\nu_1$ is the rotation frequency.

KIC 6128830 is a sharp-lined B6HgMn star (Catanzaro et al. 2013). There is only one frequency $\nu = 0.2065 \text{ d}^{-1}$ and its harmonic.

8 β CEP VARIABLES

Pulsations in β Cep and SPB stars are driven by the $\kappa$ opacity mechanism due to the iron-group opacity bump at about 200 000 K. This mechanism can destabilize p modes in β Cep stars and g modes in SPB stars. Driving of pulsations can only occur if certain criteria are met. One of these criteria is that the pulsation period is of the same order as the thermal timescale, otherwise the driving region remains in thermal equilibrium and cannot absorb/release the heat required for driving the pulsations. Another requirement is that the pressure variation is large and varies only slowly within the driving region. This criterion is satisfied for low radial order p modes in β Cep stars. In the relatively shallow partial ionization zone of iron-group elements the thermal timescale is well below 1 d. It turns out the timescale constraint is fulfilled only for p modes of low radial and mixed modes as well as for g modes with $l \geq 4$, though it is possible to find unstable g modes with $l$ as low as $l = 2$ for models close to the core hydrogen burning phase. In less massive stars, the iron opacity bump is located deeper and, in addition, the luminosity is lower. Both factors contribute to an increase in the thermal timescale. Consequently, all p modes are stable because their periods are much shorter than the thermal timescale, while g modes fulfill the timescale and pressure amplitude constraints and are unstable. Thus we find two instability regions among the B stars: the β Cep instability strip and, at lower masses, the SPB instability strip.

In general, g modes are heavily damped in B stars of high mass because they have high amplitudes in the deep layers just above the convective core. The temperature variation gradient is very large in this region, leading to significant heat loss and damping of the pulsations. However, the structure of the eigenfunction plays an important role and for some modes driving due to the iron-group opacity bump exceeds damping in the inner layers. Hence some low-frequency g modes can occur together with high frequency p modes in the same star. Stars where both low-frequency SPB pulsations and high-frequency β Cep pulsations are present are called SPB/β Cep hybrids.

In Table 1 there are four stars which show high frequencies and lie within the known β Cep instability strip. The periodograms of these stars are shown in Fig. 1. In addition, the Be star KIC 8057661 discussed below appears to be a β Cep variable. KIC 3240411 is a sharp-lined B2 V star whose effective temperature was measured spectroscopically by Lehmann et al. (2011). The star has a large number of peaks below 2 d$^{-1}$, although significant very low-amplitude peaks are present up to 17 d$^{-1}$. The star would have been classified as a simple SPB if only peaks with amplitudes greater than 50 ppm are considered, but otherwise as a SPB/β Cep hybrid.

KIC 10960750 is a rapidly-rotating B2.5 V star (Lehmann et al. 2011). Peaks as high as 21 d$^{-1}$ are visible, though most of the higher amplitudes are in the range 0–4 d$^{-1}$. KIC 8381949 shows quite a rich frequency spectrum with significant peaks at least as high as 15 d$^{-1}$ and a moderate amplitude group in the interval 7–10 d$^{-1}$.

9 THE MAIA VARIABLES

Struve (1955) suggested the possibility of a new class of
short-period late B or early A variable stars on the basis of radial velocity observations of the star Maia, a member of the Pleiades. Later, Struve et al. (1953) disclaimed such variability in Maia, although short-term variations were found in the strengths of the helium lines. Since that time, several attempts have been made to detect short-term periodic variability in stars lying between the $\beta$ Cep and $\delta$ Sct instability strips without success (McNamara 1985; Scholz et al. 1998; Lehmann et al. 1995). Several hundred $\delta$ Sct instability strips without success (McNamara 1985; Scholz et al. 1998; Lehmann et al. 1995). Several hundred $\delta$ Sct instability strip stars were subsequently observed by De Cat et al. (2007), but all were reclassified into other variability classes.

In spite of these failures, there are persistent reports that such variables do exist. A good example is $\alpha$ Dra, an A0III Maia candidate with a period of about 53 min and very small amplitude (Kallinger et al. 2004). Further examples of possible Maia candidates are provided by CoRoT observations of B-type variables (Degroote et al. 2003). These stars have a very broad range of frequencies and low amplitudes. In addition, several SPB stars with residual excess power at frequencies typically a factor three above their expected g-mode frequencies were found by CoRoT. The high frequencies found in some SPB stars observed by Kepler (Balona et al. 2011) may be taken as further examples of these anomalous variables.

There is no doubt that cool B stars with high frequencies do exist, although they have not been given the name “Maia” variables. It may be argued that perhaps the temperatures of these stars are not correct or perhaps some are binary systems in which the fainter component is a $\delta$ Sct star. It would certainly be important to obtain spectroscopic observations of these stars to detect the supposed $\delta$ Sct companion. However, the sheer number of such stars now known argues strongly against such an interpretation.

Further evidence indicating the existence of these anomalous pulsating stars has recently been found by Mowlavi et al. (2013) in photometric observations of the young open cluster NGC 3766. They found a large population (36 stars) of new variable stars between the red edge of the SPB instability strip and the blue edge of the $\delta$ Sct instability strip. Most stars have periods in the range 0.1–0.7 d, with amplitudes between 1–4 mmag. About 20 percent of stars in this region of the H-R diagram were found to be variable. They suggest that rapid rotation may be a requirement for the presence of these modes.

Since there is a possibility of some unknown pulsation mechanism operating in these stars and since high frequencies in late B stars are unexplained in terms of our current understanding (see below), we decided to classify all stars with high frequencies cooler than about 20000 K as MAIA variables. Whether such stars require a separate driving mechanism is, as yet, not clear. It may be possible that they could be assimilated into the SPB class when rapid rotation is taken into account. Periodograms of some of these stars are shown in Fig. 5.

KIC 3756031 is a sharp-lined B5V/IV star (Lehmann et al. 2011). Most peaks are in the range $\nu < 2 \text{d}^{-1}$, but significant peaks are visible as high as $\nu = 10 \text{d}^{-1}$. In KIC 11454304 peaks up to 20 d$^{-1}$ are visible, but most peaks are below 5 d$^{-1}$. KIC 12258330 is a He-strong star (Lehmann et al. 2011). Peaks up to 14 d$^{-1}$ are present.

10 SPB VARIABLES

There are 25 stars in Table I which could be considered pure SPB variables. Periodograms of some of these stars are shown in Figs. 6. We discuss some of the more interesting stars.

In KIC 1430353 the peak at $\nu_1 = 0.9824 \text{d}^{-1}$ could be the rotational frequency since a small peak is present at 2$\nu_1$. The doublet at $\nu_2 = 1.8107$, $\nu_3 = 1.82230$ and $\nu_4 = 0.2533 \text{d}^{-1}$ as well as three weak doublets at 0.144, 0.832, 1.564 with separations 0.0114 d$^{-1}$ (which is the same as $\nu_2 - \nu_3$) have no obvious explanation. All peaks in KIC 3865742 have $\nu < 2.7 \text{d}^{-1}$. The harmonic of the highest peak at $\nu = 0.2432 \text{d}^{-1}$ is present, so perhaps one may regard this as an SPB/ROT variable. In Balona et al. (2011) the star is not recognized as SPB but as one of those stars belonging to a frequency grouping.
Figure 6. Periodograms of some stars classified as SPB variables.

The periodogram of KIC 4931738 is quite extraordinary. There are three main peak groups at 0.45, 0.75 and 1.05 d\(^{-1}\). Each of these groups is comprised of a set of several equally-spaced peaks with \(\delta \nu = 0.037\) d\(^{-1}\). Perhaps this is a proximity effect in a binary where \(\delta \nu\) is the orbital frequency. In KIC 4936089 the periodogram consists of a series of peaks in the range 0.8 < \(\nu\) < 1.6 d\(^{-1}\) with amplitudes diminishing with increasing frequency. The light curve shows strong beating with a period of about 31 d. KIC 8177087 is a sharp-lined B7 III He-strong star (Lehmann et al. 2011). There are several peaks with \(\nu < 0.46\) d\(^{-1}\).

KIC 9715425 has a very peculiar light curve showing large excursions or flare-like outbursts typically lasting 10 d and amplitudes of about 20–80 ppt. There is a continuous underlying variation with a period of around 1 d with beating and changes in amplitude. After JD 2455500 the behaviour changes. The outbursts stop and the short-period amplitude becomes larger at about 15 ppt gradually decreasing to 10 ppt at the end of the observing run. The periodogram of the whole data string is dominated by a group of frequencies below 2 d\(^{-1}\). The largest peak is at \(\nu_1 = 0.9638\) d\(^{-1}\) with a very weak harmonic. Harmonics of

Figure 7. Top panel: periodograms of the Be star KIC 6954726. Middle panel: the complete PDC light curve showing moderate outbursts. Bottom panel: part of the light curve showing regular variations with variable amplitude.

Figure 8. Periodogram of the Be star KIC 8057661.
two small peaks at 0.7440 and 0.7747 d\(^{-1}\) can also be seen. In addition, a small group of peaks around \(\nu_2 = 1.6081\) d\(^{-1}\) is visible.

In KIC 10118750 the periodogram is dominated by six close peaks with the strongest at \(\nu_1 = 3.6302\) d\(^{-1}\). The first harmonic of \(\nu_1\) is strong, suggesting that this may be the rotation frequency. The periodogram of KIC 10658302 is remarkable. There is a group of 6 peaks starting at \(\nu_1 = 0.1931\) d\(^{-1}\) and equally spaced with \(\delta \nu = 0.0161\) d\(^{-1}\). The remaining peaks all lie in the range 0.8–1.8 d\(^{-1}\) and show an interesting pattern with the same value of \(\delta \nu\). This may be a proximity effect on an SPB binary.

11 BE STARS

Be stars are B stars in which emission or partial emission is present in some Balmer lines (strongest in the H\(\alpha\) and the H\(\beta\) lines). The emission is due to a disk of gas surrounding the star. The disk is created through outbursts which occur from time to time. The reason for the outbursts is not known. The most popular view is that the stars are close to critical rotation and that pulsations are somehow responsible for triggering the mass loss (Rivinius 2013). An alternative view is that the outbursts are a result of stellar activity (Balona 2013b).

In KIC 6954726 (StHA166) two close, sharp peaks at \(\nu_1 = 1.0279\) and \(\nu_2 = 1.0479\) d\(^{-1}\) are slightly displaced from a broad peak at 0.94 d\(^{-1}\). Two other broad features at about 0.12 and 1.75 d\(^{-1}\) seem to be symmetrically placed. The harmonics \(2\nu_1, 2\nu_2\) are present with small amplitudes. Fig. 7 shows the periodogram of the whole data set. The full light curve shows what appears to be semi-regular outbursts which may be responsible for the broad peak at about 0.12 d\(^{-1}\). Semi-regular light variations with a period of about 1.0 d are visible in the light curve (bottom panel of the figure).

KIC 8057661 is another Be star. Peaks are visible all the way to about 20 d\(^{-1}\) (Fig. 8). However, the peaks of highest amplitude are all below 5 d\(^{-1}\). The system of peaks below 1.7 d\(^{-1}\) seem to be roughly equally spaced with \(\delta \nu \approx 0.17\) d\(^{-1}\). This may be a \(\beta\) Cep star which is also a Be star. Several such Be/\(\beta\) Cep variables are known of which HD 49330 (Huat et al. 2009) is a good example. A full analysis of these light curves is beyond the scope of this paper.

12 LOCATION OF \(\beta\) CEP AND SPB STARS IN THE INSTABILITY STRIP

There are a few stars with reliable (spectroscopic) parameters. Among these are five SPB/\(\beta\) Cep hybrids (including the Be/BCEP star KIC 8057661), six Maia variables and seven SPB stars. Their location in the H-R diagram is shown in Fig. 9. Apart from the problematic Maia variables, there are three SPB stars within the \(\beta\) Cep instability strip which show no signs of high-frequency modes. In addition, there are several stars with well-determined parameters which show no clear signs of \(\beta\) Cep or SPB pulsations, but lie within the instability strips.

Another strange aspect of these \(\beta\) Cep stars is that all of them have rich low-frequency spectra. In fact, the low frequencies are dominant even in the hottest stars. Current models of \(\beta\) Cep stars have difficulty in accounting for these hot stars with low frequencies (see below).

13 THE K2-0 DATA

Spacecraft drift is the main component leading to increased photometric scatter compared to the original Kepler field. Using simple aperture photometry (SAP), the brightness of a target changes slowly as the star moves from its original location on the CCD until the thrusters are applied to bring the star back to its original location. The periodogram therefore shows strong peaks at about 4.08 d\(^{-1}\) and its harmonics which corresponds to the frequency at which the thrusters are applied. It is possible to obtain a greatly improved light curve simply by locating these peaks in the periodogram and fitting and removing a truncated Fourier series. Extraction of the light curve from the FITS files using SAP, fitting and removing the truncated Fourier series was done using the KEPIC software.

A more sophisticated approach to correcting the light curve has been proposed by Vanderburg & Johnson (2014). In this technique the nonuniform pixel response function of the Kepler detectors are determined by correlating flux measurements with the spacecraft’s pointing and removing the dependence. This leads to an improvement over raw SAP photometry by factors of 2–5, with noise properties qualitatively similar to Kepler targets at the same magnitudes. There is evidence that the improvement in photometric precision depends on each target’s position in the Kepler field of view, with worst precision near the edges of the field. Overall, this technique restores the median-attainable photometric precision within a factor of two of the original Kepler photometric precision for targets ranging from 10–15 magnitude in the Kepler bandpass. This technique is im-

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B-type stars in the K2-0 field were selected according to their spectral types in the *Catalogue of Stellar Spectral Classifications* (Skiff 2014). As a first task, we examined the light curves and periodograms of these B stars extracted by the two methods described above. Our aim was to detect interesting stars, particularly β Cep and SPB variables. The distinction between main sequence and compact B stars is problematic. In the absence of appropriate spectral classification, we assume that bright stars are more likely to be main sequence objects, whereas stars with high proper motions are compact objects. Using these criteria, we have classified 300 B stars in the K2-0 field.

Unlike the *Kepler* field where ground-based photometry is available for all stars, very few ground-based observations are available for stars in the K2-0 field. We searched for UBV photometry in the K2-0 field using the SIMBAD database. Unfortunately, U-band photometry is a vital requirement in order to determine the reddening and hence the intrinsic colour of the star. Lack of U-band photometry means that even basic information such as the effective temperature is lacking for most stars. Since almost no spectroscopy or Strömgren photometry is available for these stars, there is no possibility of estimating their luminosities.

Unlike the *Kepler* field, for which 4 yr of superb photometry is available for all objects, the data for the K2-0 field spans only about 80 d, but only the last 38 d are truly useful. The thruster corrections severely affect the low-frequency range. As a result, we cannot determine whether a star is an ellipsoidal variable unless the amplitude is very large. It is also very difficult to know whether a star is an SPB variable because of the low-frequency peaks cannot be entirely trusted to be intrinsic to the star. High frequencies are relatively unaffected, and the identification of a star as a β Cep variable is quite easy as long as the amplitude is sufficiently large.

Table 2 lists those stars which we believe may be β Cep and SPB variables. Fig. 10 shows periodograms of the β Cep variables and Fig. 11 those of the SPB variables. It should be noted that peaks as high as 20 d\(^{-1}\) can be seen in some of these stars. Such high frequencies are not expected in β Cep stars unless they are close to the zero-age main sequence. It is clearly imperative to obtain ground-based data to determine the nature of these stars.

The lack of multicolour photometry and spectroscopy for K2-0 stars means that it is not possible to place most of the stars in the H-R diagram. For those few stars where UBV photometry is available, we calculated the reddening and estimated the effective temperature from the unreddened \((B-V)\)_0 colour index. There is insufficient information to estimate the luminosities of these stars. In Fig. 12 we have simply placed each star near the center line of the instability strip.

For stars with high frequencies where UBV photometry is not available, we cannot tell whether they are β Cep or Maia variables. We therefore used the available spectral types to decide between the two. All stars with high frequencies and known effective temperatures are cooler than the red edge of the β Cep instability strip and we have classified them provisionally as MAIA variables. Further ground-based spectroscopy or multi-colour photometry is required to exploit the full potential of the K2-0 data.

![Figure 12](image.png) Figure 12. The location of K2-0 SPB (red open circles), presumed Maia stars (black squares) and β Cep variable (black filled circle) in the theoretical H-R diagram. The luminosities are unknown and the stars have been placed near the midpoint of the instability region. The region enclosed by the solid line is the theoretical instability strip for β Cep variables. The dashed region is the theoretical instability strip for SPB variables.

### 14 TWO CHALLENGING PROBLEMS

If we assume that the effective temperatures and luminosities derived from spectroscopy or Strömgren photometry are reasonably accurate, we are faced with two problems which challenge our current understanding of pulsation in hot stars. These are: (i) stars in the β Cep instability strip which exhibit low-frequency peaks and no high frequency peaks, and (ii) stars in the SPB instability strip with high frequencies typical of β Cep stars (what we refer to as MAIA variables in this paper).

It is possible that a low metallicity, \(Z\), may be responsible for (i). It is well known (e.g., Pamyatnykh 1999) that in B-type main sequence models, g modes of high radial order can remain unstable at much lower values of \(Z\) than p-modes. Moreover, reducing the metallicity will shift the location of the star in the H-R diagram to the position occupied by a star with solar abundance and lower mass. Also, an increasing number of low-frequency g modes become unstable with decreasing mass.

In Fig. 13 we show the instability parameter, \(\eta\), as a function of frequency for two models corresponding approximately to the two open circle in the β Cep instability strip in Fig. k2hrs. These models were computed with OP opacities, \(Z = 0.01\) and the initial hydrogen abundance \(X_0 = 0.7\). Modes with harmonic degree \(l = 0–4\) are considered. The model with \(M = 8 M_\odot\) is close to the end of core hydrogen burning, while the model with \(M = 7 M_\odot\) is more or less in the middle of the main sequence evolutionary stage. As can be seen, the low-frequency modes in these models have values of \(\eta\) comparable or higher than the high-frequency modes. In other words, the low-frequency modes are unstable, while the high-frequency modes remain stable (though on the point of instability). Furthermore, the
larger the spherical harmonic, \( l \), the greater the instability of low-frequency modes.

For these models, the low frequencies can be easily understood, but high frequencies cannot be driven. In fact, it is very difficult to drive high-frequency, \( \beta \) Cep-like modes in stars with masses \( M < 6 M_\odot \). With our current understanding of pulsation in B-type main sequence stars, the only explanation seems to be a shift of low-frequency modes to higher frequencies due to rotation. In Fig. 14 we show the instability parameter, \( \eta \), as a function of frequency for a model with \( 6 M_\odot \) and an equatorial rotational velocity \( v = 200 \text{ km s}^{-1} \). Modes with \((l,m)\) up to \((10,+10)\) were considered. In the pulsational computations, the effects of the Coriolis force were taken into account in the frame-
Figure 11. Periodograms of candidate SPB stars in the K2-0 field.

Figure 13. The pulsational instability parameter, \( \eta \), for modes of low degree, \( l \), as a function of frequency (in the observer’s frame) for a model with mass \( M = 8 M_\odot \), \( \log T_{\text{eff}} = 4.2974 \), \( \log L/L_\odot = 3.744 \) (top panel) and \( M = 7 M_\odot \), \( \log T_{\text{eff}} = 4.3018 \), \( \log L/L_\odot = 3.459 \) (bottom panel). OP opacities and a metallicity \( Z = 0.01 \) are used.

15 DISCUSSION

In Balona et al. (2011) stars were grouped into different classes depending on the appearance of the periodogram. We did not find such a classification scheme useful, preferring instead to search for physical causes of the variation (tidal distortion, rotational modulation, high- and low-frequency pulsations). Without intensive ground-based observations, particularly high-resolution spectroscopy, it is not possible to confirm whether our classifications are correct, but they at least provide a useful starting point.

Of the 115 stars in the Kepler field that we examined, 32 (or 28 percent) appear to be ellipsoidal variables. On the other hand, there is only one eclipsing binary in the sample.

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The pulsational instability parameter, $\eta$, as a function of frequency for models with mass $M = 6M_\odot$, $\log T_{\text{eff}} = 4.1939$, $\log L/L_\odot = 3.299$ and equatorial rotational velocity of 200 km s$^{-1}$.

Ellipsoidal variables must be seen at low inclinations for no eclipses to occur. If the orbital axes are randomly orientated the probability of finding a low inclination, $i$, is proportional to $\sin i$. Because these stars have short periods and therefore close to each other, one expects to see many more eclipsing systems than ellipsoidal variables. The probability of observing 28 percent ellipsoidal variables but less than one percent eclipsing binaries in a random group of stars must therefore be very small. Perhaps the most plausible explanation is that the variations are not orbital in nature but a result of magnetic fields and activity in B star atmospheres has been underestimated in the past. Perhaps star spots may be a result of a magnetic field generated by the Tayler instability in a differentially rotating star (Spruit 2002; Mullan & MacDonald 2005).

Another puzzle, already mentioned in Balona et al. (2011), is the incidence of high-frequency pulsations in stars which are cooler than the red edge of the $\beta$ Cep instability strip. It has been assumed that these may be binaries in which a $\delta$ Sct secondary companion is in orbit around a more luminous B-type primary. This would be an acceptable explanation if the numbers of such stars were few. The fact more than half of the sample needs to be explained in this way makes this explanation very unlikely. The fact that similar stars have been observed by CoRoT (Degroote et al. 2009) and also in the K2-0 field as well as from ground-based observations of stars in a young open cluster (Mowlavi et al. 2013), suggests that another explanation is required. We have therefore provisionally assumed that these are examples of the so-called Maia variables. There are pulsating stars situated between the red edge of the $\beta$ Cep instability strip and the blue edge of the $\delta$ Sct instability strip.

This does not necessarily mean that a new driving mechanism needs to be found for Maia variables. It is perhaps possible that the high frequencies are low-frequency g modes generally associated with SPB stars shifted to high frequencies by rotation. In fact, it has long been a puzzle why nearly all SPB stars observed from the ground are slow rotators. The resolution to this problem may be just the Maia variables discussed here. In other words, the SPB stars have the same rotational velocity distribution as normal B stars, but it is only the low frequencies which attain sufficient amplitudes to be easily detected. However, frequencies higher than about 10 d$^{-1}$, as found in some Maia stars, cannot be easily understood in this way.

We find nine examples (8 percent) of the strange ROT-d pattern (Fig. 3) which is so common among A stars (Balona 2013a, 2013). Most are late B stars, but one of them, KIC 5458880, is classified as B0 III. A satisfactory explanation for the periodogram structure has not been found, but it is probably related to rotation. A careful study of rotational modulation using high-dispersion spectroscopy would surely lead to a further understanding of the atmospheres of B stars.

These surprising conclusions open up a new perspective on B star atmospheres. The fact that so many B stars appear to show rotational modulation suggests that the role of magnetic fields and activity in B star atmospheres has been underestimated in the past. Perhaps star spots may be a result of a magnetic field generated by the Tayler instability in a differentially rotating star (Spruit 2002; Mullan & MacDonald 2005).

A particularly puzzling aspect, which was already mentioned in Balona et al. (2011), is that $\beta$ Cep pulsations are always accompanied by a rich spectrum of low-frequency modes. One possibility is that these might be stars of low metallicity where low-frequency g modes tend to be more unstable, relative to the high-frequency modes, than in stars with higher metallicity. For the moment, however, the problem is unresolved.
ACKNOWLEDGMENTS

This paper includes data collected by the Kepler mission. Funding for the Kepler mission is provided by the NASA Science Mission directorate. The authors wish to thank the Kepler team for their generosity in allowing the data to be released and for their outstanding efforts which have made these results possible.

Much 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.

LAB wishes to thank the South African Astronomical Observatory and the National Research Foundation for financial support.

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