Six β Cephei stars as seen with BRITE and from the ground

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We present an overview of BRITE-Constellation observations of β Cephei stars that have been assigned to the first author as contact PI. We discuss the objects individually, show the synergies with ground-based observations, possible problems in the analysis and confront the quality of the results between the two types of observing method. In comparison to ground-based photometry, BRITE measurements result in lower noise levels in the periodogram. We note that due to longer integration times possible for some satellites, BRITE can now obtain much better results for fainter stars than previously. In addition, thanks to its better low-frequency stability, BRITE provides evidence that gravity mode pulsation is more common among β Cephei stars than previously thought.

1 Introduction

The β Cephei stars are a group of massive pulsating stars that have variability periods between $2 - 7$ hr, and masses between $9 - 17$ $M_\odot$ (Stankov & Handler, 2005). They have been shown to be accessible to asteroseismic methods many years ago, and initial results on the amount of convective core overshooting, differential rotation, etc. have been obtained (e.g., Pamyatnykh et al. 2004; Dupret et al. 2004). One of the prerequisites for success is that methods to identify the oscillation modes of these stars with their spherical degree and azimuthal order are reliable — which is the case for these stars.

Asteroseismology has recently undergone a revolution because high-precision photometric space data have become available through the MOST, CoRoT, Kepler, and K2 missions. The noise level in the periodograms of the target stars was pushed down by two to three orders of magnitude in comparison to ground-based data. However, the impact of these missions on seismology of β Cephei stars was rather modest, because few of these stars were observed, and because single-colour space photometry alone allows mode identification only through recognition of eventual patterns in the stellar pulsation spectra.

Therefore, much hope has been put into BRITE-Constellation. This mission is predestined for asteroseismic studies of β Cephei stars because its primary target are fields with bright stars in the Galactic plane, and because of the possibility to obtain two-colour photometry from space (Weiss et al., 2014). Both enables pulsational mode identification, firstly through the two-colour photometry itself (Daszyńska-Daszkiewicz, 2008), but also because of the ease of high-resolution spectroscopic studies of bright stars. Such projects are even feasible for amateur astronomers with modest-sized telescopes.

In the following, initial results on six β Cephei stars observed with BRITE are reported. For all of these, ground-based support observations are available, either photometry including an important ultraviolet passband, or time-resolved high-resolution spectroscopy.

2 The individual stars

2.1 ν Eri

This star has been the subject of detailed observational and asteroseismic studies before (Handler et al., 2004; Aerts et al., 2004; De Ridder et al., 2004; Pamyatnykh et al., 2004; Ausseloos et al., 2004; Jerzykiewicz et al., 2005; Dziembowski & Pamyatnykh, 2008; Daszyńska-Daszkiewicz & Walczak, 2010). It is therefore an ideal test case for the capabilities of BRITE, and was observed in the Orion II field by BAb, BLb, BTr and BHr. Indeed, the results from previous observational projects were largely confirmed and even superseded. In particular, the known pressure (p) mode pulsation frequencies of the star were recovered (give or take some amplitude variability). Additionally, six new gravity (g) modes, firmly establishing ν Eri as a hybrid pulsator, were detected thanks to the better low-frequency stability and lower overall noise level in the BRITE data compared to ground-based measurements. On the other hand, a problem with the mode identifications derived from the BRITE two-colour data was noticed, in the sense that the measured amplitude ratios were lower than theoretically predicted. However, since the same effect is present in the ground-based optical photometry, this is not a problem related to the BRITE observations. Due to lack of space, we refer to Handler et al. (2017) for detailed discussions and note that a theoretical paper based on the new BRITE results has also been written (Daszyńska-Daszkiewicz et al., 2017).

2.2 PT Pup

The pulsations of this β Cephei star have been studied photometrically by Heynderickx (1992) and Heynderickx et al. (1994), who reported two modes of pulsation with closely-spaced frequencies and identified them as $\ell = 2$ and $\ell = 0$, respectively. A spectroscopic study by Maisonneuve (2011) resulted in two similar, but slightly different frequencies. The mode identifications derived were $\ell = 1, m = +1$ or $\ell = 2, m = 0$ for the first mode, and $\ell = 1, m = +1$ or $\ell = 0$ for the second.

We already had two seasons of time-resolved ground-based photometry in the Strömgren *uvby* filters available for PT Pup before BRITE observed the star. We are using the T6 automated photometric telescope (APT) at Fairborn Observatory, Arizona (Strassmeier et al., 1997) for such purposes. Therefore we knew that the two closely-spaced pulsation modes reported in the earlier literature were in fact three, with spherical degrees of $\ell = 2, 2$ and 0, in order of increasing frequency; a fourth oscillation was also detected. The disagreement between the initial studies was therefore simply due to the real pulsational content being unresolved.

PT Pup was a target of BRITE's CMa/Pup campaign in late 2015/early 2016. It was observed by BLb and BTr, and at $V = 5.7$ is a rather faint target for BRITE. However, instead of the usual 1-s integrations, BTr integrated for 5 or 7.5 s depending on the setup, which made this data set of excellent quality, and enabled the detection of two more oscillation frequencies. A schematic pulsation spectrum of PT Pup is

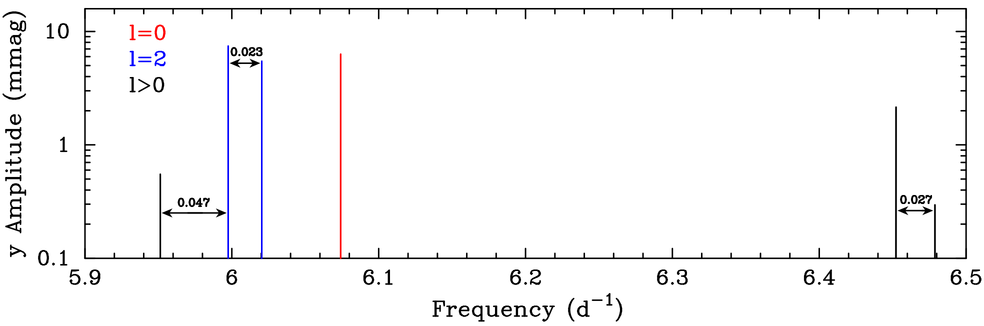

Fig. 1: A schematic amplitude spectrum of PT Pup. Note the logarithmic ordinate scale. The four oscillation modes with amplitudes above 1 mmag had already been detected from the APT measurements, and three of them identified with their spherical degree. The two lowest-amplitude modes are newly detected with BRITE. Their frequency spacing from known nonradial modes implies they are components of rotationally split multiplets.

shown in Fig. 1.

This is a very good example of how BRITE and ground-based measurements can help to understand a star better. The APT photometry provided identifications of the three dominant pulsation modes; the BLb data for PT Pup were not precise and numerous enough to accomplish this. However, the BTr measurements were of such high quality that two more oscillation frequencies hidden in the noise of the ground-based data were detected. These two frequencies may give sufficient information for asteroseismic modelling. Furthermore, one frequency in the g-mode domain was also detected thanks to the BTr measurements, with indications for more (cf. below). Unfortunately, their low amplitudes (< 0.4 mmag) preclude a certain detection.

In the light of these results, it is worthwhile to return to the spectroscopy by Maisonneuve (2011) and attempt a mode identification using the newly derived constraints on ℓ. Additional spectroscopy by the Poznań group is also available (Niemczura, priv. comm.).

2.3 ξ^1 CMa

This star is known as a pure radial pulsator (e.g., Heynderickx et al., 1994). That does however not mean it is one of the more boring β Cephei stars! For instance, it is a known magnetic star (Hubrig et al., 2006), its radial velocity amplitude is larger than the local sound speed (Saesen et al., 2006), and its pulsations have been detected in X-rays (Oskinova et al., 2014). Furthermore, there are two conflicting determinations for its rotation period, both from spectropolarimetry: longer than 40 yr (Shultz et al., 2015), or 2.1795 d (Fossati et al., 2015).

Just as for PT Pup, BLb and BTr observations are available. We have additionally monitored ξ^1 CMa with the APT coinciding with BRITE. Both data sets confirm the radial mode identification. Besides the single mode frequency, we detected its first and second (BTr data only) harmonics. Particularly worth noting is the low noise level in the BTr data: it is below 40 ppm in the periodogram! A search for a possible rotational signal in the BRITE light curves yielded a null result.

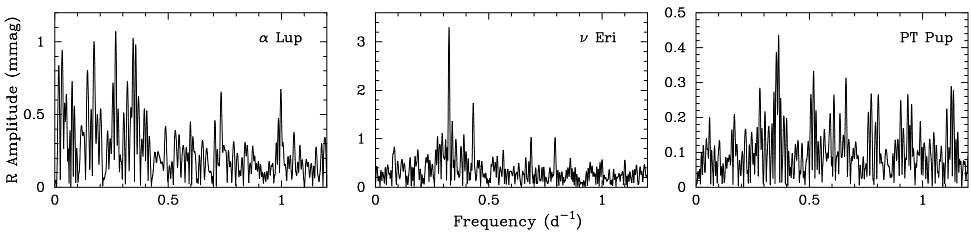

Fig. 2: Amplitude spectra in the low-frequency (g mode) domain of three of the six stars investigated here. There are significant signals for all of these stars, with evidence for more.

2.4 15 CMa

This is a photometrically well-studied rather massive ($M \approx 14\,\mathrm{M}_\odot$) β Cephei pulsator (e.g., Shobbrook et al., 2006), whose initial seismic modelling suggests effective overshooting from the convective core (Walczak & Handler, 2015). After the study by Shobbrook et al. (2006), we have collected APT photometry of 15 CMa in six different seasons spanning nine years. We have also obtained 14 consecutive nights of high-resolution time-series spectroscopy of the star in Jan/Feb 2013, unwittingly coinciding with the same type of observation by a Belgian group (Saesen & Briquet, priv. comm.). The joint spectroscopic data set is under analysis by them.

Returning to BRITE, BLb, BTr and BHr observations are available. A first analysis of this data set confirms the presence of the signals already detected by Shobbrook et al. (2006), plus one new oscillation frequency. The same result is obtained from the APT photometry. The mode identifications from both data sets are the same and the noise levels in the periodogram similar. However, this comparison is based on one BRITE run vs. six seasons of ground-based measurements.

2.5 α Lup

The pulsations of this star have mostly been studied spectroscopically in the past (see Mathias et al., 1994, for a summary and a detailed study), and it has been considered singly periodic with the exception of the photometric analysis by Heynderickx (1992).

We have acquired spectroscopy of the star in 2014, and BRITE has observed it during the Centaurus run. Most data were obtained by UBr and BAb, but some short runs of BTr and BLb just after their commissioning had finished are also available. The analysis of the BRITE data reveals α Lup as a fairly rich hybrid pulsator. There are four modes in the p-mode domain, the strongest of which identified as radial. Remarkable are their low frequencies between $3.3 - 4.0\,\mathrm{d}^{-1}$, suggesting that α Lup soon evolves off the main sequence. None of the new frequencies corresponds to the secondary frequency reported by Heynderickx (1992), or an alias thereof.

Even more remarkable, however, is the apparent presence of several signals in the g-mode domain for the star. We show the low-frequency part of the UBr amplitude spectrum of α Lup in Fig. 2, and compare it with those of ν Eri and PT Pup. Experience with ν Eri (Handler et al., 2017), for which it was shown that spurious low-frequency signals occur, if at all, below $0.15\,\mathrm{d}^{-1}$ in properly reduced BRITE data, suggests that these peaks are unlikely to be spurious. The unescapable conclusion then is that all three stars have g-modes excited.

2.6 β CMa

This star has also photometrically been studied (e.g., by Shobbrook et al., 2006), who detected three oscillation modes, the strongest of them being $\ell = 2$. Mazumdar et al. (2006) spectroscopically detected the same three modes, with identifications of $\ell = 2, m = 2$ for the strongest and $\ell = 0$ for the second, and also performed a theoretical study of its pulsations.

BTr and BLb acquired observations of β CMa; we measured it at the same time with the APT. Unfortunately, the star is saturated on the BTr frames, which leaves only the BLb data for analysis. In those, only the two stronger modes are detectable. It may seem that BRITE did not do well on this star, but truth is also that it happened to fall close to the edge of the CMa/Pup field, which means that BHr which would likely have obtained better data could not observe it due to its smaller field of view. It is desirable that β CMa be re-observed with BRITE-Constellation.

3 Conclusions

BRITE and ground-based observations clearly have many synergies to offer, in particular in context of the β Cephei stars. Ground-based photometry can provide data in the ultraviolet necessary for mode identification. The different time distribution of such measurements also virtually eliminates the aliasing problem in both data sets, if combined (Handler et al., 2017). Supplemented by time-resolved spectroscopy, the mode identifications can be completed; in some cases modes not present in photometry can be detected in spectroscopy.

If we compare the quality of ground-based results with that of BRITE photometry for the six stars we have investigated, we can state that:

- BRITE was doing *much better* than ground-based studies for α Lup, PT Pup and ξ^1 CMa.
- BRITE was doing *somewhat* better for ν Eri (Handler et al., 2017) and 15 CMa. This comparison is however somewhat unfair to BRITE as several seasons of single- and multisite monitoring are compared with only one BRITE run.
- BRITE was doing *worse* for β CMa. In that case however BRITE may be called a victim of circumstance (Sect. 2.6).

One new, encouraging result is that with the longer integrations BTr can perform, fainter target stars have become within reach, as demonstrated for PT Pup and ξ^1 CMa. For the $V = 5.7$ mag star PT Pup the noise level in the β Cephei frequency domain is about 75 ppm.

To conclude, thanks to the accuracy of BRITE observations we can obtain more complete pulsational mode spectra because more oscillation modes can be detected. From the scientific point of view, particularly thanks to BRITE we have growing evidence that g-mode pulsation among β Cephei stars is much more common than previously thought.

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Fig. 3: Peter de Cat, Greg Stachowski, Gerald Handler, Ewa Kosturkiewicz, Milena Ratajczak and Andrzej Pigulski.