What Have We Learnt About B-Type Main Sequence Pulsators from the BRITE Data?

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We summarize our seismic studies of the β Cep/SPB pulsators based on the BRITE data. The results of the complex seismic analysis of ν Eri, α Lup, θ Oph and κ Sco are presented. We also show results for 12 Lac and γ Peg, whose analysis is based on ground-based observations and MOST data, respectively. One of the most important lessons from the analysis of the BRITE data seems to be that hybrid B-type pulsators are a rule rather than an exception. Moreover, models calculated with standard opacity tables cannot explain observed oscillation spectra. Interestingly, similar modifications of the mean opacity profile are necessary for all studied stars.

1 Introduction

The discovery of hybrid pulsators of β Cep/SPB type has opened up a possibility of getting more stringent constraints on parameters of model and theory. The simultaneous excitation of pressure (p) and gravity (g) modes offers probing stellar regions sensitive to various physical processes. On the other hand, the presence of high-order g modes in massive main sequence stars is the most challenging fact still awaiting theoretical explanation because these modes are stable in all standard-opacity models (e.g. Pamyatnykh et al., 2004; Daszyńska-Daszkiewicz et al., 2017). Ipso facto, seismic modelling of hybrid pulsators is more demanding, and more sophisticated approach is needed.

This paper encapsulates the main results of our seismic analysis of a few early B-type pulsators observed with BRITE Constellation that exhibit both low-order p/g modes and high-order g modes. We also provide our results for the two B-type hybrid pulsators, whose oscillation data were derived from MOST and ground based observations.

In Sec. 2, we give the basic information on the studied objects. Sec. 3 reports the results of seismic analysis based on standard and non-standard opacity data. The last section is an attempt to summarize and draw some conclusions.

2 The analysed B-type hybrid pulsators

The star ν Eridani was the first hybrid pulsator of spectral type B (Handler et al., 2004; Aerts et al., 2004; Jerzykiewicz et al., 2005). These authors analysed the

Table 1: The basic data for the studied stars. The third column contains the brightness in the Johnson V filter. In the last two columns we put the number of detected frequencies and their ranges. Other columns are self-explanatory.

Name	SpT	m_V [mag]	$\log T_{\rm eff}/{\rm K}$	$\log L/L_{\odot}$	N_{ν}	frequency range [d^{-1}]
ν Eri	B2IV	3.1	4.346(14)	3.886(44)	17	(0.26, 0.69)+(5.6, 7.9)
α Lup	B2IV-V	3.4	4.364(28)	4.180(64)	14	(0.14, 0.74)+(3.3, 4.0)
θ Oph	B2IV-V	2.5	4.360(18)	3.609(64)	16	(0.41, 2.77)+(7.1, 8.0)
κ Sco	B1.5III	2.3	4.365(10)	4.205(32)	12	(0.23, 0.36)+(4.8, 5.7)
γ Peg	B2IV	2.8	4.316(17)	3.710(65)	14	(0.64, 0.91)+(6.0, 9.1)
12 Lac	B2III	5.2	4.375(18)	4.077(111)	11	0.36 +(4.2, 7.4)

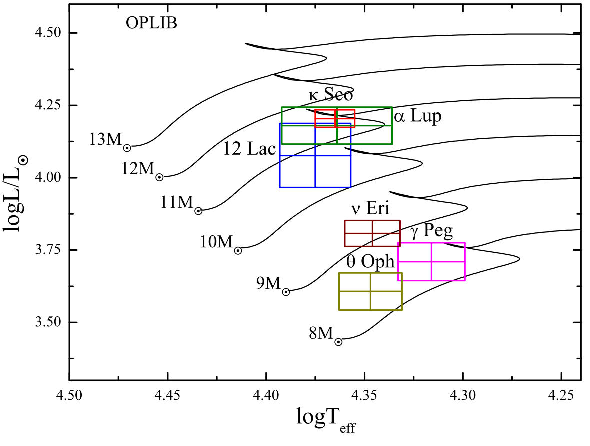

Fig. 1: The HR diagram with the position of six hybrid pulsators of B type discussed in the paper. The evolutionary tracks were computed adopting the initial hydrogen abundance $X_0 = 0.7$, metallicity $Z = 0.015$, solar chemical mixture AGSS09 (Asplund et al., 2009) and the OPLIB opacities (Colgan et al., 2015). No rotation and no core overshooting were assumed.

data collected during multi-site photometric and spectroscopic campaigns and extracted 12 frequencies corresponding to p-mode pulsations and detected two frequencies which could be associated only with higher-order g-mode pulsations. The photometric and spectroscopic data also allowed for unambiguous identification of many pulsational modes. Then, the star was a subject of many asteroseismic modelling (e.g. Pamyatnykh et al., 2004; Ausseloos et al., 2004; Daszyńska-Daszkiewicz & Walczak, 2010). With the BRITE observations the oscillation spectrum was further enriched with a few additional g modes (Handler et al., 2017) and currently their number is 7. Recently, Daszyńska-Daszkiewicz et al. (2017) have shown that simultaneous determination of seismic corrections to both the model and opacity profile is indispensable to account for the observed oscillation spectrum of ν Eri.

Later on, more hybrid pulsators of this type began to be discovered: 12 Lacertae (Handler et al., 2006), γ Pegasi (Handler et al., 2009), α Lupi (Handler et al., in preparation), θ Ophiuchi and κ Scorpi (Walczak et al., in preparation.). One can find also many examples from CoRoT and Kepler photometry (e.g. Degroote et al., 2009; Balona et al., 2011, 2015).

Tab. 1 contains the basic information on the analysed stars. The number of detected frequency peaks derived from the BRITE light curves is marked by N_{ν}.

The position of these stars on the HR diagram is shown in Fig. 1.

3 Seismic modelling: the need for opacity modifications

The primary asteroseismic data are the pulsational frequencies, provided that the associated modes are unambiguously identified. In certain cases, it is also possible to derive the empirical values of the nonadiabatic parameter f associated with each frequency. The parameter f is the relative amplitude of the bolometric flux variations and in the case of B type stars it is very sensitive to the opacity data (Daszyńska-Daszkiewicz et al., 2005). Moreover, a condition for mode instability should be fulfilled. The approach which uses all these seismic constraints is called complex seismic modelling (Daszyńska-Daszkiewicz & Walczak, 2009).

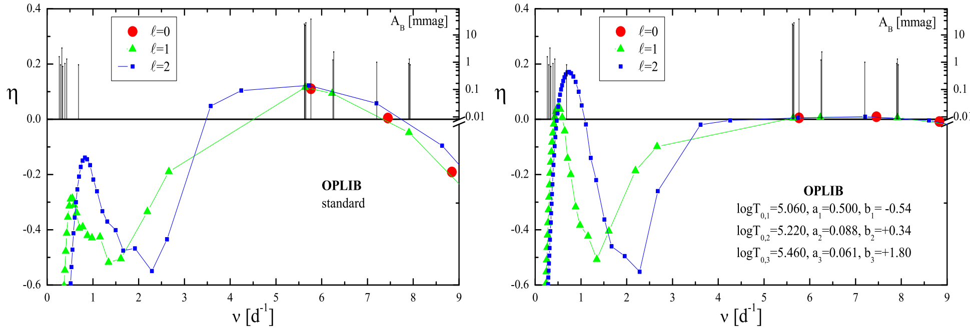

Fig. 2: The instability parameter, η, as a function of the frequency for the standard-opacity model of ν Eri (the left panel) and for the modified-opacity model (the right panel). Pulsational modes with the degrees $\ell = 0 - 2$ are shown. The parameters of modification of the mean OPLIB opacity profile are given in the legend and in Tab. 2. The vertical lines indicate the observed frequencies.

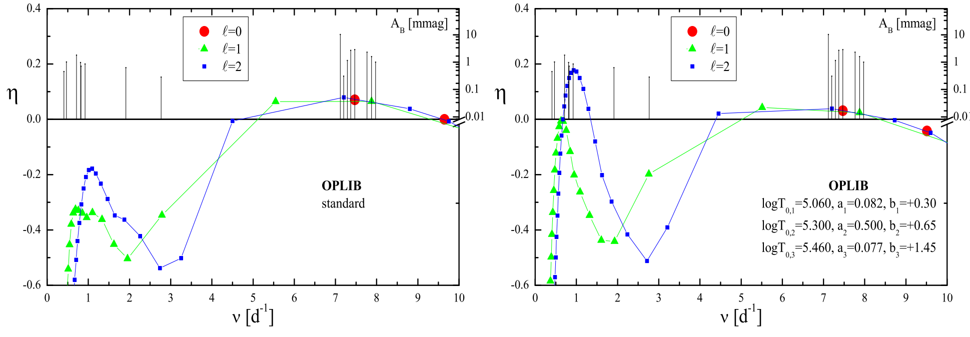

Fig. 3: The same as in Fig. 2 but for θ Oph.

Here, we present the results of (complex) seismic modelling for the six stars using the available data. In the case of ν Eri, we fitted three centroid frequencies (the radial and two dipole modes) and the parameter f corresponding to the radial mode. For α Lup, we could fit only the radial mode. Three modes (the radial, dipole and quadrupole) were used in modelling of θ Oph together with the parameter f

Table 2: The parameters of the Gaussian functions used to modify the mean opacity profile for a given star model. The seismic models fit best all pulsational properties and were computed with the OPLIB data modified at the three depths expressed in $\log T$.

star	$\log T_{0,1}$	a_1	b_1	$\log T_{0,2}$	a_2	b_2	$\log T_{0,3}$	a_3	b_3
ν Eri	5.06	0.50	-0.5	5.22	0.09	$+0.3$	5.46	0.06	$+1.8$
α Lup	5.06	0.14	1.0	5.30	0.32	1.0	5.46	0.32	$+1.0$
θ Oph	5.06	0.08	$+0.3$	5.30	0.50	$+0.7$	5.46	0.08	$+1.5$
κ Sco	5.06	0.32	$+0.3$	5.22	0.08	$+0.3$	5.46	0.08	$+1.0$
γ Peg	5.06	0.45	-0.6	5.22	0.07	$+0.5$	5.46	0.06	$+2.1$
12 Lac	5.06	0.45	-0.3	5.22	0.08	$+0.5$	5.46	0.08	$+2.0$

for these three modes. In the case of κ Sco our modelling was based on just one non-axisymmetric dipole mode ($\ell = 1,\ m = -1$). The two frequencies were fitted (corresponding to the radial and dipole modes) in the seismic models of γ Peg and 12 Lac. Always, we tried to reproduce the instability of the observed frequency range. For more details of our seismic modelling see: ν Eri – Daszyńska-Daszkiewicz et al. (2017), α Lup – Handler et al. (in preparation), θ Oph and κ Sco – Walczak et al. (in preparation).

As mentioned in the Introduction, all seismic models constructed with the standard opacity data failed to explain the observed frequencies of the hybrid B-type pulsators. In particular, high-order g modes with low degrees were stable in all models. The examples are shown in the left panels of Fig. 2 and Fig. 3, where the run of the instability parameter η is plotted as a function of the mode frequency. Seismic models of ν Eri and θ Oph are shown in Figs. 2 and 3, respectively.

To solve this problem, we constructed models with modified mean opacity profiles $\kappa(T)$. We changed the standard opacities by adding Gaussian functions with the position of the maximum at $\log T_0$, the width a and height b. We considered modification at the three depths expressed in $\log T$. The value of b is the amount of opacity which is added or deducted from the standard value. For example, $b = 1$ means that the opacity was increased by 100% at a given value of $\log T_0$. In the range $\log T \in (5.0,\ 5.5)$, we determined the corrections to $\kappa(T)$ by searching the parameters with the steps: $\Delta \log T_0 = 0.005$, $\Delta a = 0.001$ and $\Delta b = 0.05$. In the considered range of depth (temperature), iron dominates the stellar opacity with some contributions from nickel, chromium and manganese (e.g. Salmon et al., 2012).

The right panels of Figs. 2 and 3 show the best seismic models of ν Eri and θ Oph with the modified OPLIB opacity profiles. These models meet all the requirements mentioned at the beginning of this Section. An important note has to be added here. Including the parameter f in seismic modelling reduces enormously the number of possible modifications of $\kappa(T)$. This is the case for ν Eri and θ Oph.

In Tab. 2, we list the parameters of the modified opacity profile which give the best (complex) seismic models. As one can see, a huge increase of κ is needed at $\log T_0 = 5.46$. This is the temperature at which nickel contributes mostly. This increase of opacity results from a requirement imposed by the instability condition of high–order g modes.

4 Conclusions

By analyzing the six B-type hybrid pulsators, we tried to find clues to missing components in modelling of the interiors of hot main sequence stars. In particular, we have shown that in each case significant modifications of the mean opacity profile in the depth range $\log T \in (5.0 - 5.5)$ are indispensable to explain all pulsational properties. A huge amount of opacity (at least 200%) at the depth $\log T = 5.46$ (at which nickel has a significant contribution) has to be added to account for the observed low frequencies which correspond to high-order g modes. This seems to be a solution that resolves this general problem.

Such a large increase of stellar opacities is difficult to justify. It can result either from non-homogeneity in the chemical composition or/and from the present-day methods of the opacity computations.

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