The solitary g-mode frequencies in early B-type stars

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We present possible explanations of pulsations in early B-type main sequence stars which arise purely from the excitation of gravity modes. There are three stars with this type of oscillations detected from the BRITE light curves: κ Cen, a Car, and κ Vel. We show that by changing metallicity or the opacity profile it is possible in some models to dump pressure modes keeping gravity modes unstable. Other possible scenario involves pulsations of a lower mass companion.

1 Introduction

For many years, it seemed that B-type main sequence (MS) pulsators can be divided into two groups: β Cephei stars with low-order pressure (p) and/or gravity (g) mode pulsations (e.g., Moskalik & Dziembowski, 1992; Stankov & Handler, 2005) and Slowly Pulsating B-type stars (SPB) with high-order g-mode pulsations (Waelkens, 1991; Dziembowski et al., 1993). This simple dichotomy was spoiled by the continuous increase in accuracy of the time-series photometry obtained from multi-site campaigns and, mainly, from space missions (CoRoT, Kepler, BRITE). Thereby, many pulsators with so far unknown oscillation spectra were identified. The first example are hybrid pulsators with low order p/g-modes and high-order g-modes excited simultaneously. Then, even more unexpected by theoretical models oscillation spectra were obtained from the CoRoT and Kepler space data: late B-type stars with only high frequencies and early B-type stars with only low frequencies (Degroote et al., 2009; Balona et al., 2011, 2015). All these three groups pose a challenge for theoretical modelling of stellar pulsations.

Recently, early B-type stars with solitary g-mode frequencies were also identified from the BRITE photometry. Here, we present interpretation of this case, exemplified by the three stars observed by the BRITE satellites: κ Cen, a Car, and κ Vel.

In Sect. 2, we give basic information about the stars. In Sect. 3 we search for pulsational models of early B-type stars which can account for the observed frequencies in these three stars. Section 4 contains other possible explanations. We end with Summary and prospects for further works.

2 The objects of interest

According to the spectral classification, all three stars are main sequence objects of early B spectral type. Their basic parameters are given in Table 1. The subsequent

Table 1: Basic data for the studied stars.

Star	SpT	m_V [mag]	T_{eff} [K]	$\log L/L_\odot$	$V_{\text{rot}} \sin i$ [km s^{-1}]	N	freq. range [d^{-1}]
κ Cen	B2 IV	3.1	19800 ± 900	3.4 ± 0.2	11 ± 7[1]	12	(0.33, 1.37)
a Car	B2 IV-V	3.4	18000 ± 600	3.5 ± 0.1	40 ± 7[2]	5	(0.37, 1.71)
κ Vel	B2 IV-V	2.5	19400 ± 600	4.2 ± 0.1	~ 49[3]	8	(0.17, 0.66)

(1) Hubrig et al. (2009); (2) Bernacca & Perinotto (1970); (3) Leone & Lanzafame (1997)

columns include: spectral type, brightness in the Johnson V passband, effective temperature and luminosity derived from the mean photometric indices and Hipparcos parallaxes, and the value of $V_{\text{rot}} \sin i$ from the literature. Moreover, the last two columns contain the information about the number of frequency peaks identified in the BRITE light curves and the range of these frequencies.

None of these stars is single. κ Cen is most probably a physical triple system (Kouwenhoven et al., 2007). Visually, the bright star, κ Cen A is paired with the faint component κ Cen B (11th magnitude) which is a dwarf of the spectral class K2. Then, κ Cen A is a spectroscopic binary and splits into Aa (the B2 IV-type star) and Ab (probably a class A0 V). The primary Aa was a candidate β Cephei variable that showed line-profile variations (Schrijvers et al., 2002).

The next object, a Car, is a single-lined spectroscopic binary (SB1) with the orbital period $P_{\text{orb}} = 6.74483(9)$ d, the radial-velocity amplitude $K = 18.2(2.0)$ km s^{-1} and the eccentricity of the orbit $e = 0.34(14)$ (Monet, 1980). κ Vel is also a binary of the SB1 type. The orbital period $P_{\text{orb}} = 116.65$ d, the radial velocity amplitude $K = 46.5$ km s^{-1} and eccentricity $e = 0.19$ were derived by Curtis (1907).

BRITE photometry of all stars was corrected for instrumental effects which included outlier rejection and decorrelations with centroid positions and CCD temperature. Finally, offsets between individual setups were accounted for and such data were subject to the subsequent time-series analysis. The oscillation spectra of the three stars derived from the combined blue and red BRITE magnitudes are shown in Fig. 1. In total, twelve, five and eight terms with amplitudes above the detection threshold were found in the photometry of κ Cen, a Car, and κ Vel, respectively. The frequency $\nu_4 = 0.59294$ d^{-1} of a Car is equal to $4\nu_{\text{orb}}$ with an accuracy better than 1σ. Thus, ν_4 could be a tidally excited mode given rather high eccentricity $e = 0.34$ and not very long orbital period $P_{\text{orb}} \approx 6.7$ d.

3 Pulsational models

3.1 Models with standard opacities

In the first step, we computed pulsational models with standard opacity data commonly used in pulsational computations, i.e., OPAL and OP. To this end, we used the Warsaw-New Jersey evolutionary code and nonadiabatic pulsational code of Dziembowski (1977).

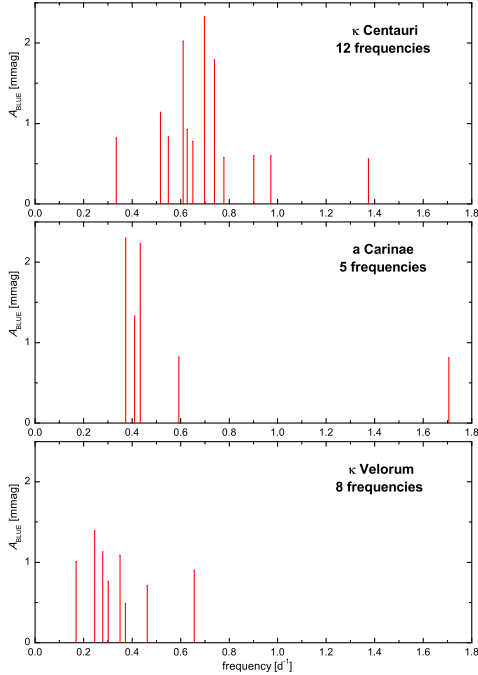In Fig. 2, we plot the normalized instability parameter, η, as a function of the

Fig. 1: The oscillation spectra of κ Cen, a Car, and κ Vel obtained from the BRITE photometry.
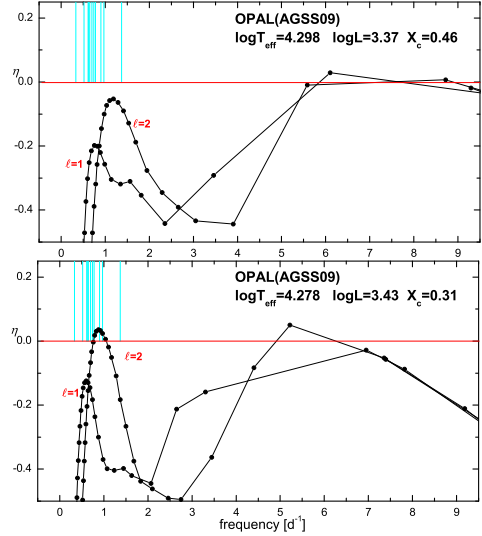

Fig. 2: The normalized instability parameter, η, as a function of the mode frequency for two OPAL models with a mass of $M = 7\ M_\odot$ suitable for κ Cen. The model in the bottom panel is more evolved. Pulsational modes with the degree $\ell = 1, 2$ are shown. The observed frequency peaks are plotted with the vertical lines.

mode frequency for two main sequence models with $M = 7\ M_\odot$ computed with the OPAL data for the initial hydrogen abundance $X_0 = 0.7$, metallicity $Z = 0.015$ and the solar element mixture of Asplund et al. (2009). The positive values of η are for unstable modes. The two models differ in the effective temperature and have stellar parameters suitable for κ Cen. The frequency peaks of κ Cen are marked as the vertical lines.

This figure recalls the important features of gravity modes in massive main sequence models. Firstly, the instability of gravity modes increases with evolution on the main sequence and the maximum of $\eta(\nu)$ for a given degree ℓ shifts to lower frequencies. Secondly, the instability increases with ℓ and is shifted towards the higher frequencies with ℓ. One can also see that the oscillation spectrum of κ Cen cannot be explained by such models because the g-modes, especially with the lowest frequencies, are quite far from the instability. Moreover, the p-modes, which are not observed, remain unstable.

Computations with the OP opacities yield higher instability of g-modes, because the metal bump is located deeper than in the OPAL opacities, but still p-modes are unstable. To stabilize the p-modes, we lowered metallicity to $Z = 0.012$. This does not affect so much the g-modes because their instability is more resistant to the metallicity reduction (e.g., Pamyatnykh, 1999). The result is shown in Fig. 3, where we plot η of the OP model computed with the metallicity $Z = 0.012$.

Similarly to κ Cen, a Car has a mass of about $7\ M_\odot$ but is slightly more evolved. As mentioned above, the instability of gravity modes increases with evolution on the MS. It appeared that even with the OPAL opacities it is possible to find pulsational
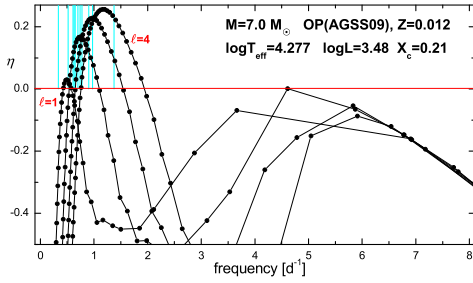
Fig. 3: The same as in Fig. 2 but for the model computed with the OP data and metallicity $Z = 0.012$. Pulsational modes with the degree up to $\ell = 4$ are shown.
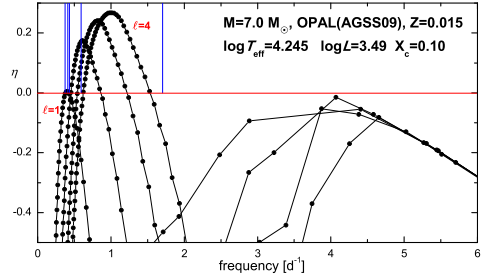

Fig. 4: A comparison of the oscillation frequencies of a Car with the pulsational model computed with the OPAL data and metallicity $Z = 0.015$. Modes with the degree up to $\ell = 4$ are shown. The model has a mass of $M = 7\,M_\odot$ and is more evolved than the models of κ Cen in Fig. 2.

models which can account for the observed frequency range of a Car. Figure 4 shows a comparison of the a Car oscillation spectrum with $\eta(\nu)$ of a $M = 7\,M_\odot$ model computed with the OPAL opacities and metallicity $Z = 0.015$. The highest frequency mode can be explained by rotational splitting.

κ Vel is quite a problematic object as the observed parameters do not locate it on the main sequence. One would need much higher rotation, or unreliable overshooting and/or metallicty to put this star on the MS. The estimated mass of κ Vel is about $10\,M_\odot$. If the star were a post-MS object then the observed oscillations could not be explained as well because pulsational modes with such low frequencies would be stable in the post-MS models in the considered range of masses.

3.2 Models with modified opacities

Because of the still existing uncertainties in the opacity data, we computed models with a modified profile of the mean opacity at the depths that can affect the pulsational driving of early B-type star models. Our modification consists in an artificial changing of the opacity profile at certain depths inside the star, i.e., at certain $\log T$.

The pulsations of B-type main sequence stars are excited by the κ-mechanism operating in the Z-bump around $\log T = 5.3$. The most important contributions to the Z-bump opacity come from Fe, Ni, Mn and Cr. The maximum opacity of these elements occurs at various depths expressed usually by $\log T$, e.g., the maximum contribution of Ni to the Z-bump is at $\log T = 5.46$. In Figs. 5 and 6, we plot the instability parameter η for a model computed with the modified opacities which were reduced by 20% at $\log T = 5.3$ and increased by 50% at $\log T = 5.46$.

Decreasing the opacity at $\log T = 5.3$ is needed to stabilize higher frequency modes whereas to maintain and increase the instability of low frequency modes one needs to increase the opacity at the deeper layer with temperature $\log T = 5.46$.

4 Other possible scenarios

There is one more possible scenario. κ Cen is a triple system and if the Ab component, which is possibly the A0 main sequence star, has a mass of about $3.0\,M_\odot$ then
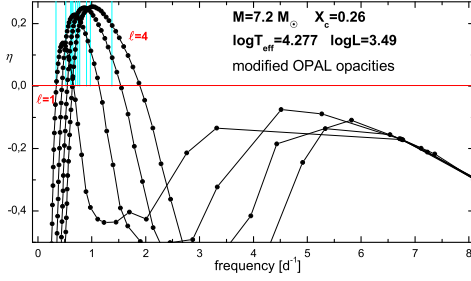
Fig. 5: The parameter η as a function of the mode frequency for a $M = 7.2\ M_\odot$ model computed with the modified OPAL opacities and metallicity $Z = 0.015$. The opacities were increased by 50% at $\log T = 5.46$ and reduced by 20% at $\log T = 5.3$.
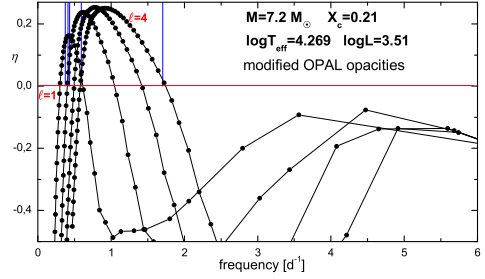

Fig. 6: The same as in Fig. 5 but for a more evolved model suitable for a Car.

the g-mode pulsations may come from this component (e.g., Walczak et al., 2015; Szewczuk & Daszyńska-Daszkiewicz, 2017). Similarly, in the case of a Car pulsation may originate from the companion. In the case of κ Vel, the pulsations of the lower mass companion seem to be the most credible explanation. This component could be invisible because: 1) it rotates very fast or 2) it is too faint. If the component is fainter by ~ 2 mag then there is even no need for fast rotation. From the spectroscopic orbit, we get a lower limit for the mass of the unseen component. Assuming the orbital inclination angle $i = 90°$, we obtain $6.2\ M_\odot$ if the mass of the primary is $M = 8\ M_\odot$ and $7.0\ M_\odot$ if the mass of the primary is $M = 10\ M_\odot$. Solitary g-modes can be easily explained in models with masses $M \in (6 - 7)\ M_\odot$.

5 Summary and further works

We investigated models of early B-type stars in order to explain the oscillation spectra derived from the BRITE data for the three stars: κ Cen, a Car and κ Vel. All of them exhibit only low frequency peaks although, according to the spectral classification, they are in the main sequence stage, so that the p-mode frequencies would be expected.

Our calculations may help explaining the solitary low-frequency modes in the MS stellar models we consider. The well-known facts are: 1) g-modes are more unstable in more evolved models; 2) instability of g-modes increases with the mode degree, ℓ, and is shifted to higher frequencies with ℓ; 3) the instability of g-modes in the OP models is higher than in the OPAL models. The instability of g-modes is more resistant to the metallicity reduction comparing to the p-mode instability, and in the case of a Car this effect is sufficient to account for the oscillation frequencies. Moreover, we examined the effects of increasing the opacities in stellar models representative for the studied stars. We found that by decreasing the opacity at $\log T = 5.3$ and increasing at $\log T = 5.46$ it is possible to "kill" the instability of the p-modes keeping the g-modes unstable. The models with such modification of the mean opacity profile explain the observed frequencies of κ Cen. We confirmed the Salmon et al. (2012) result that increasing opacity at $\log T = 5.46$ is crucial for g-mode instability.

Because the stars we studied are spectroscopic binaries, we cannot exclude that the pulsations come from the unseen components. In the case of κ Vel, the pulsations of the lower mass companion seem to be the most plausible explanation of the observed

frequencies.

References

Asplund, M., Grevesse, N., Sauval, A. J., Scott, P., *The Chemical Composition of the Sun*, ARA&A **47**, 481 (2009), `0909.0948`

Balona, L. A., Baran, A. S., Daszyńska-Daszkiewicz, J., De Cat, P., *Analysis of Kepler B stars: rotational modulation and Maia variables*, MNRAS **451**, 1445 (2015), `1504.02041`

Balona, L. A., et al., *Kepler observations of the variability in B-type stars*, MNRAS **413**, 2403 (2011), `1103.0644`

Bernacca, P. L., Perinotto, M., *A catalogue of stellar rotational velocities: I. Main sequence single stars. II. Main sequence spectroscopic binaries and eclipsing systems.*, Contributi dell'Osservatorio Astrofisica dell'Universita di Padova in Asiago **239** (1970)

Curtis, H. D., *The orbits of the spectroscopic binaries alpha Carinae, kappa Velorum, and alpha Pavonis.*, PASP **19**, 259 (1907)

Degroote, P., et al., *CoRoT's view of newly discovered B-star pulsators: results for 358 candidate B pulsators from the initial run's exoplanet field data*, A&A **506**, 471 (2009), `0907.2183`

Dziembowski, W., *Oscillations of giants and supergiants*, Acta Astron. **27**, 95 (1977)

Dziembowski, W. A., Moskalik, P., Pamyatnykh, A. A., *The Opacity Mechanism in B-Type Stars - Part Two - Excitation of High-Order G-Modes in Main Sequence Stars*, MNRAS **265**, 588 (1993)

Hubrig, S., et al., *New magnetic field measurements of β Cephei stars and slowly pulsating B stars*, Astronomische Nachrichten **330**, 317 (2009), `0902.1314`

Kouwenhoven, M. B. N., Brown, A. G. A., Portegies Zwart, S. F., Kaper, L., *The primordial binary population. II.. Recovering the binary population for intermediate mass stars in Scorpius OB2*, A&A **474**, 77 (2007), `0707.2746`

Leone, F., Lanzafame, A. C., *Behaviour of the HeI 587.6, 667.8, 706.5 and 728.1nm lines in B-type stars. On the helium stratification in the atmosphere of magnetic helium peculiar stars.*, A&A **320**, 893 (1997)

Monet, D. G., *A discussion of apsidal motion detected in selected spectroscopic binary systems*, ApJ **237**, 513 (1980)

Moskalik, P., Dziembowski, W. A., *New opacities and the origin of the Beta Cephei pulsation*, A&A **256**, L5 (1992)

Pamyatnykh, A. A., *Pulsational Instability Domains in the Upper Main Sequence*, Acta Astron. **49**, 119 (1999)

Salmon, S., et al., *Testing the effects of opacity and the chemical mixture on the excitation of pulsations in B stars of the Magellanic Clouds*, MNRAS **422**, 3460 (2012), `1203.0527`

Schrijvers, C., Telting, J. H., De Ridder, J., *A Spectroscopic Search for Non-Radial Pulsations in Early B-Type Stars*, in C. Aerts, T. R. Bedding, J. Christensen-Dalsgaard (eds.) IAU Colloq. 185: Radial and Nonradial Pulsationsn as Probes of Stellar Physics, *Astronomical Society of the Pacific Conference Series*, volume 259, 204 (2002)

Stankov, A., Handler, G., *Catalog of Galactic β Cephei Stars*, ApJS **158**, 193 (2005), `astro-ph/0506495`

Szewczuk, W., Daszyńska-Daszkiewicz, J., *Domains of pulsational instability of low-frequency modes in rotating upper main sequence stars*, MNRAS **469**, 13 (2017), `1703.08075`

Waelkens, C., *Slowly pulsating B stars*, A&A **246**, 453 (1991)

Walczak, P., et al., *Wider pulsation instability regions for β Cephei and SPB stars calculated using new Los Alamos opacities*, A&A **580**, L9 (2015)