Stars and their variability observed from space
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KIC 11971405 - THE SPB STAR WITH THE FOUR ASYMPTOTIC SEQUENCES OF G MODES

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Abstract. We re-analsed all *Kepler* photometric data of the fast rotating B-type pulsator KIC 11971405; we extracted pulsation frequencies, and found five period spacing patterns, i.e. sequences of frequencies quasi-equally spaced in period.

Our modelling shows that four sequences could be associated with prograde sectoral modes with the degrees $\ell = 1, 2, 3, 4$; the fifth sequence is most probably accidental. Fitting the four g-mode sequences simultaneously offers a unique opportunity to obtain constraints on the internal processes described by the free parameters, e.g., convective overshoot and other types of mixing. We found that at least moderate overshoot from a convective core is reqired, but a high amount of mixing in the radiative zone is not supported.

In addition we confirmed a need to revise the opacity data. In order to obtain unstable theoretical counterparts of the observed modes, a significant increase in the opacity coefficient in the driving zone appeared necessary.

Keywords: stars: early-type, individual: KIC 11971405, oscillations, rotation, atomic data: opacities

1 Introduction

KIC 11971405 is a B5 IV-Ve star observed by *Kepler* during its nominal mission. Pápics et al. (2017) analysed *Kepler* spectroscopic observations and photometric data. The values they derived for the effective temperature and gravity are $T_{\rm eff} = 15\,100 \pm 200$ and logg= 3.94 ± 0.06, respectively, thus placing the star in the middle of the Slowly Pulsating B-type (SPB) instability strip (see e. g., Walczak et al. 2015; Szewczuk & Daszyńska-Daszkiewicz 2017). Pápics et al. (2017) also concluded that the star is a fast rotator with $V_{\rm rot} \sin i = 242 \pm 14\,{\rm km\,s^{-1}}$.

The *Kepler* light-curve of the star shows high complexity. The analysis by Pápics et al. (2017) revealed several photometric outbursts, and a rich oscillation spectrum. They found three period spacing patterns which, according to asymptotic theory (see e.g. Tassoul 1980; Bouabid et al. 2013), can be interpreted as high radial-order gravity (g) modes with consecutive radial orders.

Our re-analysis of *Kepler* data is described in Section 2, and the results of seismic modelling in Section 3. Conclusions end the paper.

2 Frequency analysis

Observations of KIC 11971405 spanning the whole duration of the nominal mission of *Kepler* (i.e., Q0–17) are available in the public domain. To extract the light-curve from target pixel files we proceeded in a similar manner as in the case of KIC 3240411 (Szewczuk & Daszyńska-Daszkiewicz 2018). As before, we used *PyKE* package (Vinícius et al. 2017; Still & Barclay 2012).

We ended up with 60874 data points, and followed a standard pre-whitening procedure until the S/N ratio of the highest peak in the periodogram was above four. We found 188 frequencies, and noticed that in some parts of the residues the variance was much higher than the average for the whole data set, especially at time when outbursts occurred. We decided to remove those parts, leaving 36009 data points spanning 867 days. We then repeated the pre-whitening procedure on that data set and found 1131 frequencies, among which 1096 seemed to be independent.

We looked for patterns in period, and found five such structures, three already found by Pápics et al. (2017) and two additional ones. Fig. 1 shows four of patterns which we were able to associate with high radial-order g modes with consecutive degrees $\ell = 1$, 2, 3 and 4 (see the next Section). The one not shown in the figure was most probably accidental.

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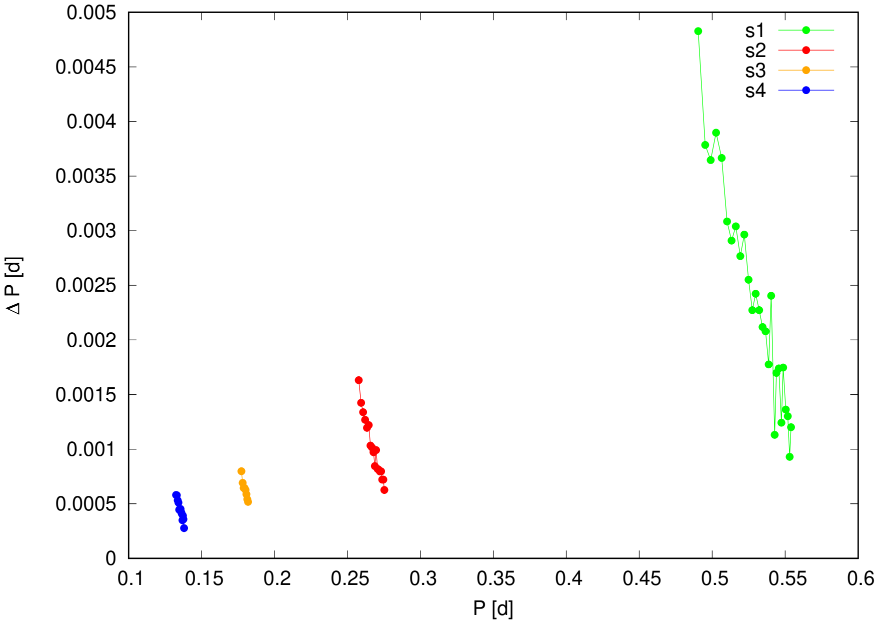

Fig. 1. 4 out of 5 period spacing patterns we found are shown in this plot of P vs ΔP. The two sequences with periods less than 0.2 d are new ones.

3 Seismic modelling

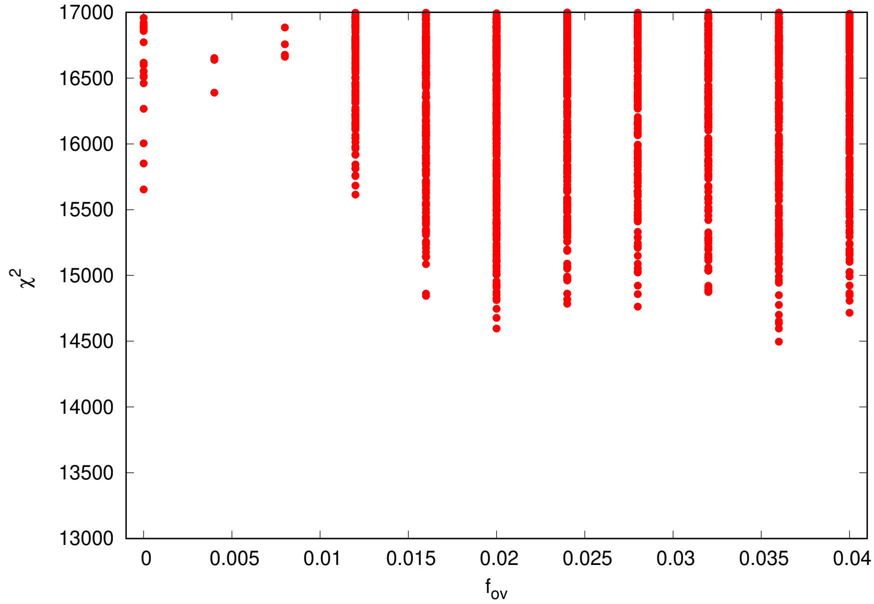

Fig. 2. The discriminant χ^2 as a function of overshoot parameter, $f_{\rm ov}$, in the set of models calculated with the standard OPLIB opacity data.

The main goal of our seismic analysis was to estimate the amount of internal mixing in the KIC 11971405. We therefore constructed a grid of stellar and oscillation models and compared them with observations using the χ^2 discriminant (see e.g., Szewczuk & Daszyńska-Daszkiewicz 2018).

Evolutionary calculations were carried out with the MESA package (see e.g., Paxton et al. 2011, 2013, 2015, 2018). We calculated models inside 3σ error box in effective temperature and gravity, with a step in mass of $\Delta M = 0.05 \mathrm{M}_{\odot}$, rotation velocity $\Delta V_{\rm rot} = 10 \mathrm{km\,s^{-1}}$ (in the range 220 - 400 $\mathrm{km\,s^{-1}}$) and an overshoot parameter from convective core in its exponential description $\Delta f_{\rm ov} = 0.004$ (in the range $0 - 0.04$). In these

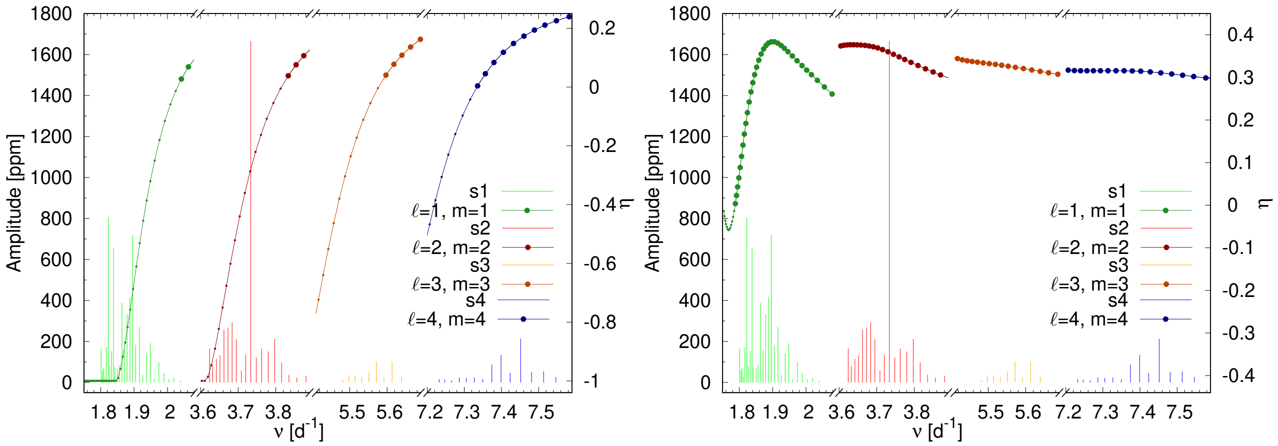

Fig. 3. Left: Comparison of the observed and theoretical frequencies in the best model. Observed frequencies with their amplitudes are marked by continuous vertical lines (left y-axis). Theoretical frequencies with their instability parameter, η, in the best model calculated with the standard OPLIB opacity data are marked by dots (right y-axis). Bigger symbols denote unstable modes, i.e with $\eta > 0$. Smaller symbols are stable modes. **Right:** The same as in the left panel but for the best model calculated with the modified opacity data.

computations we assumed rigid rotation, a AGSS09 chemical mixture (Asplund et al. 2009), OPLIB opacity data (Colgan et al. 2015, 2016) and an initial amount of hydrogen, $X = 0.71$. We tested a few values of metallicity $Z = 0.013$, 0.014, 0.0148, 0.0149, 0.0150, 0.0151, 0.0152, 0.016 and extra mixing in the radiative zone (described in terms of mixing coefficient min_D_mix = 0, 50, 100, 500, 1000, 5000, 10000 $\mathrm{cm^2\,s^{-1}}$). In order to include the effects of rotation on pulsations we adopted the traditional approximation. We used customized oscillation code of Prof. Dziembowski (see e.g., Dziembowski et al. 2007). At this stage the step in the rotation velocity was reduced to $\Delta V_{\mathrm{rot}} = 0.05\,\mathrm{km\,s^{-1}}$.

Mode identification was carried out simultaneously with seismic modelling, i.e., we compared the values of χ^2 for models from our grid and the given pattern (s1, s2, s3 and s4) for different pairs of (ℓ, m) numbers. The best fitting was reached when the sequence s1 corresponded to the modes ($\ell = 1, m = +1$), s2 to the modes (2, 2), s3 to the modes (3, 3), and s4 to the modes (4, 4). The remaining sequence not depicted in Fig. 1 is most probably composed of modes with various (ℓ, m) numbers and/or a combination of frequencies. Furthermore, we found that the overshoot parameter, f_{ov}, should be approximately higher than 0.016 (see Fig. 2). Moreover, we do not see the need for very efficient mixing in the radiative zone. The best models in the sense of low χ^2 were with min_D_mix = 0, 50 and 100 with the minimum reached for 50. There is also no strong dependence on metallicity.

One of the best models from our grid has the following parameters: $M = 4.65\mathrm{M_\odot}$, $V_{\mathrm{rot}} = 267\,\mathrm{km\,s^{-1}}$ ($54\%\,V_{\mathrm{crit}}$), $X = 0.71$, $Z = 0.014$, $f_{\mathrm{ov}} = 0.02$, min_D_mix = $50\,\mathrm{cm^2\,s^{-1}}$, $\log T_{\mathrm{eff}} = 4.183$, $\log L/\mathrm{L_\odot} = 2.709$ and $\log g = 4.08$. Fig. 3 shows a comparison of the theoretical and observed frequencies. While the frequency values in this model reproduce the observed ones quite well, there was a serious problem with mode excitation.

A common problem with mode excitation in the seismic models of B-type pulsators suggests a need to revise the opacity data (see e.g., Daszyńska-Daszkiewicz et al. 2017b,a). We therefore recalculated our grid of models with modified OPLIB opacity data. As did Szewczuk & Daszyńska-Daszkiewicz (2018), we increased opacity at $\log T = 5.46$ by 200%, at $\log T = 5.22$ by 100%, and decreased it at $\log T = 5.06$ by 50%.

From a grid with modified opacities we identified our best model as having the following parameters: $M = 4.55\mathrm{M_\odot}$, $V_{\mathrm{rot}} = 283\,\mathrm{km\,s^{-1}}$ ($59\%\,V_{\mathrm{crit}}$), $X = 0.71$, $Z = 0.014$, $f_{\mathrm{ov}} = 0.02$, min_D_mix = $50\,\mathrm{cm^2\,s^{-1}}$, $\log T_{\mathrm{eff}} = 4.167$, $\log L/\mathrm{L_\odot} = 2.698$ and $\log g = 4.02$. But this time all observed frequencies from the sequences have unstable theoretical counterparts, or in other words their instability parameters, η, are greater than zero (see the right panel of Fig. 3).

4 Conclusions

As far as we know, this is the first attempt to fit simultaneously the four observed sequences of period spacing. These patterns correspond to prograde sectoral modes of consecutive mode degrees $\ell = 1, 2, 3, 4$. In total we fitted 70 frequencies.

On the one hand, we found a need of at least moderate overshooting from the convective core and relatively low mixing in the radiative envelope, and also a need to modify the opacity data. But on the other hand, there is still room to increase the goodness of the model of fitting. In particular, the effect of the amount of hydrogen and different modifications of the opacity data should be tested. Our assumption of rigid rotation may also be inappropriate, and differential rotation should be tested. Finally, we note that the rotation velocities which we consider here place our models on the border of the validity of the traditional approximation.

Clearly, further studies are necessary. More elaborate descriptions of our seismic modelling along with the extended grid of models of KIC 11971405 will be published elsewhere.

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