First detection of period doubling in a BL Herculis type star. Observations and theoretical models

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Abstract We report on the discovery of the first BL Herculis star displaying period-doubling behaviour as predicted by the hydrodynamic models of Buchler & Moskalik [1]. The star, with $P_0 = 2.4\,\text{d}$, is located in the Galactic bulge and was discovered with OGLE-III photometry. We present new nonlinear convective models, which, together with recent evolutionary tracks, put constraints on the stellar parameters. In particular, we estimate the mass and metallicity of the object.

1 Introduction

BL Herculis stars are a subgroup of type II (or Population II) Cepheids, pulsating with periods between 1 and 4 days (see [8] for a recent review). They show a singly-periodic large-amplitude light variation. Such behaviour was qualitatively reproduced with early nonlinear radiative models, e.g. Buchler & Moskalik [1, 3]. In several of their models with periods between 2 and 2.6 days, Buchler & Moskalik [1] found period-doubling behaviour – oscillations with periodic alternations of deep and shallow minima – a phenomenon not observed in any BL Her star at that time. Here we report on the discovery of the first BL Her star clearly showing period-doubling behaviour. We summarize the observations and new pulsation models for this star. A more detailed analysis, as well as discussion of another BL Her star in...
Fig. 1 Pre-whitening sequence for BLG184.7 133264. Upper panel: power spectrum of the original data. The spectrum is dominated by a pulsation frequency $f_0$ and its daily aliases. Middle panel: power spectrum after removing $f_0$ and its harmonics. The highest peak corresponds to a subharmonic frequency $\frac{1}{2} f_0$. The daily aliases are also prominent. Lower panel: power spectrum after removing $f_0$, its harmonics and its subharmonics.

Fig. 2 Light curve of BLG184.7 133264 phased with twice the pulsation period, $2f_0$.

which period-doubling behaviour is strongly suspected can be found in Smolec et al. [6].

2 Observations

The star of interest, BLG184.7 133264 is in the Galactic bulge and was discovered in data collected during the third phase of the Optical Gravitational Lensing Experiment [7]. It pulsates in the fundamental mode with a period of $P_0 = 2.4$ d. The $I$-band data for the star were analysed using standard consecutive pre-whitening technique. Results are presented in Fig. 1. After removing the fundamental mode frequency, $f_0$, and its harmonics, additional signals are visible (middle panel of Fig. 1). The dominant peak is located at $\frac{1}{2} f_0$, which is a subharmonic of the primary frequency. Other subharmonics ($\frac{5}{2} f_0$, $\frac{7}{2} f_0$, and $\frac{9}{2} f_0$) are also present. The presence of these frequencies in the power spectrum is a characteristic signature of period doubling. In the time domain it means that the light curve repeats itself after two pulsation periods, instead of one. This gives rise to strictly periodic alternations (Fig. 2).
Period doubling in BL Herulcis type star

Fig. 3 The theoretical BL Her instability strip in the HR diagram for $M = 0.50M_\odot$ and $Z = 0.01$ (left panel). Nonlinear models are computed along a line of constant period, $P_0 = 2.4$ d. The thick segment along this line indicates the period-doubling domain. Light curves for four selected models (marked with crosses) are displayed in the right panel (arbitrarily shifted in the vertical direction). These are to be compared with the observed light curve (represented by a Fourier fit to the data) plotted at the top.

3 Theoretical models

Using our nonlinear convective pulsation codes [5], we have computed several model sequences in order to model the period doubling in BLG184.7133264 and to constrain its parameters. Computational details are presented in [6]. Here we focus on presenting our best-fitting models and the resulting constraints on the parameters of BLG184.7133264.

We have considered a grid of model masses ($M = 0.50M_\odot$, 0.55$M_\odot$, 0.60$M_\odot$ and 0.65$M_\odot$) and model metallicities ($Z = 0.01$, 0.001 and 0.0001). For each ($M$, $Z$) combination, an extensive grid of linear models was computed which covers the full BL Her instability strip in the HR diagram (Fig. 3). Next, a sequence of nonlinear models was computed along a line of constant period, $P_0 = 2.4$ d (right panel of Fig. 3). Period-doubling behaviour was found over a range of luminosities. In Fig. 3 these are shown by the thick line for a particular ($M$, $Z$) combination. This domain correlates with the loci of the 3:2 half-integer resonance between the fundamental and first overtone modes, shown by the dashed line in Fig. 3. As shown by Moskalik & Buchler [2], half-integer resonances are responsible for the period-doubling behaviour. Our detailed analysis [6] confirms that the 3:2 resonance indeed causes the period doubling behaviour in the BL Her models, as Buchler & Moskalik have already shown [1].

The model light curves were compared with the observations. Our best-fitting models closely match the pulsation amplitude and also match the amplitude of the alternations (i.e., the amplitude of the subharmonic peak in the frequency spectrum) of BLG184.7133264. A good match is possible only for models with the highest metallicity, $Z = 0.01$. For lower metallicities, the pulsation amplitudes are lower than observed and, in addition, the amplitudes of the alternations are much larger than observed. This result is independent of the adopted values of the convective...
Fig. 4 The BaSTI [4] horizontal branch evolutionary tracks for $Z = 0.01$. Evolutionary tracks start at the Zero-Age Horizontal Branch (solid, horizontally running line). Each track is labeled with the corresponding model mass. Over-plotted are the edges of the instability strip, with the shaded area indicating the BL Her domain with fundamental mode periods between 1 d and 4 d. Pulsation models are plotted with different symbols.

parameters, as analysed in detail in [6]. The three best-fitting models, all with $Z = 0.01$, have different masses: $M = 0.50M_\odot$, $0.55M_\odot$, and $0.60M_\odot$. Based on pulsation computations alone, we cannot decide on the best model. However, since all these models fall roughly in the same place in the HR diagram (see Fig. [4]), evolutionary tracks may provide further constraints.

In Fig. 4 we plot horizontal branch evolutionary tracks from the BaSTI database corresponding to $Z = 0.01$ [4]. It is clear that only our least massive model ($M = 0.50M_\odot$) fits the evolutionary scenario. The tracks for larger masses run well beyond the instability strip. The light curve of the best model is shown in Fig. 3 (second model light curve from top, plotted with a thick line).

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