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Asteroseismic modeling of the pulsating B star HD 163830

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Abstract

In this paper, we report our preliminary results regarding the asteroseismic modeling of the slow pulsating B star HD 163830, based on eighteen of the twenty detected frequencies of this star. The powerful method of matching stellar models both to oscillation data and effective temperature and gravity of HD 163830 is applied to identify a best-fit model. These eighteen frequencies correspond to low-order, high-degree g-modes of an stellar model of $1.016 \times 10^8\mathrm{yr}$, of a $4.4M_\odot$ star with chemical composition $X = 0.71$, $Z = 0.02$.

Individual Object: HD 163830

Introduction

The Slowly Pulsating B stars (SPBs) were first introduced by Waelkens (1991) as a distinct group of variables B2 to B9 stars. The SPBs are situated in the main sequence, just below the β Cep stars in the H-R diagram, with masses ranging from 3 to 7$M_\odot$ and typical periods from 0.5 to 3 days. The variability is interpreted in terms of non-radial pulsations of high-order g-modes (Dziembowski 1993). As is well known, the g-modes are driven mainly by κ mechanism in the deep layers of the star. Indeed, the deep interior of these stars can be probed. Unfortunately, their frequency spectrum is very dense, which makes asteroseismic modeling very difficult.

Only 12 SPBs were known before Hipparcos mission, since oscillation periods of the order of 1 day are hard to detect from the ground. The Hipparcos mission greatly increased the number of known SPB stars. Currently, about 40 stars are considered as bona fide SPBs (Waelkens et al. 1998).

Recently, Aerts et al. (2006) reported the discovery of a new SPB, HD 163830 (V=9.3, B5II/III), for which they detected twenty frequencies in the range 0.4 - 12.3 $\mu\mathrm{Hz}$. Two of them ($0.405 \pm 0.009\,\mu\mathrm{Hz}$ and $0.91 \pm 0.02\,\mu\mathrm{Hz}$) are clearly of a different character, being an order of magnitude smaller than the other frequencies.

A possible explanation for these frequencies is that they are associated with star's rotation frequency. Unfortunately, we have no information about the rotation of this star. Consequently, we will not include these frequencies in our analysis. Using the one high-quality archival 7-color Geneva measurement available for HD 163830, they derived the effective temperature of the star, $T_{\rm eff} = 13700 \pm 500\,{\rm K}$ and gravity, $\log g = 3.79 \pm 0.14$ dex, which is compatible with the spectral type and luminosity class of B5II/III assigned by Houk (1982).

Matching stellar models both to oscillation data and known observables

As usual, we quantify the difference between observed and calculated spectrum by the following χ^2 definition:

$$\chi^2 = \frac{1}{N}\sum_{i=1}^{N}\frac{\left(\nu_i^{\rm obs} - \nu_i^{\rm calc}\right)^2}{\sigma_i^2}, \tag{1}$$

where $\nu_i^{\rm obs}$ is the observed frequency for the $i^{\rm th}$ mode, $\nu_i^{\rm calc}$ is the corresponding model frequency for the $i^{\rm th}$ mode, σ_i^2 is the observational uncertainty for the $i^{\rm th}$ mode and N is the total number of matched modes. To match the observed and calculated spectrum, we must minimize χ^2. The stellar model giving the lowest χ^2 (the best-fit model) is that model with maximum probability that, given one measurement, the observed spectrum matches the calculated spectrum. The value of $\chi^2_{\rm min}$ (minimum value of χ^2) gives a measure of how well the two spectra match. As is well known, if the discrepancy between $\nu_i^{\rm obs}$ and $\nu_i^{\rm calc}$ is due only to statistical scatter according to Gaussian distribution, then we would expect the value of $\chi^2_{\rm min}$ to come close to 1. As we will see in the next sections, the value of $\chi^2_{\rm min}$ is much bigger than 1, due to the underestimated values of σ_i.

Our pulsation model (LNAVENR) was calibrated with similar pulsation models in a series of ESTA papers. Because Aerts et al. (2006) do not indicate any uncertainty in the calculated frequencies for such high g-modes of this star, we could not estimate our relative theoretical uncertainty of the calculated frequencies. Consequently, we neglected the corresponding σ_i^2 term.

Additionally, we use

$$\chi^2_{\rm model} = \frac{1}{2}\left[\frac{\left(T_{\rm eff}^{\rm obs} - T_{\rm eff}^{\rm calc}\right)^2}{\sigma_T^2} - \frac{\left(\log g^{\rm obs} - \log g^{\rm calc}\right)^2}{\sigma_g^2}\right], \tag{2}$$

as a measure of discrepancy between the corresponding model's effective temperature and surface gravity and the observed values for HD 163830. $T_{\rm eff}$ and σ_T are the effective temperature and its uncertainty ($\sigma_T = 500\,{\rm K}$), and g and σ_g are the surface gravity and its uncertainty ($\sigma_g = 0.14$).

Best-fit model

To compare the detected oscillations frequencies of HD 163830 with those predicted by theory in the approximation of a non-rotating B-type star (the SPBs are considered to be slow rotators, i.e., $v \sin i \leq 100\,\mathrm{kms}^{-1}$), we identify a best-fit model from a grid of evolutionary stellar models starting at the PMS until a late phase of isothermal helium core contraction and expanding envelope (a total number of ≈ 2250 stellar models were processed).

We computed evolutionary models using CESAM2K for stellar masses 4.4$M_\odot$, 4.5$M_\odot$, and 4.6$M_\odot$ for chemical composition $X = 0.71$, $Z = 0.01$, $Z = 0.015$ and $Z = 0.02$, a mixing-length parameter of 1.75 times the pressure scale height and with core overshooting 0.2 (see Figure 1). Subsequently, we computed the frequencies of modes having $l = 1, 2$ of all the models, using ROMOSC non-adiabatic code. As is well known, a necessary condition for a model frequency to be detected in the real star is that the model frequency be unstable. We tested the stability of the model's oscillations using the usual condition $\eta > 0$, where $\eta = W / \int_0^1 |dW/dx| dx \propto \mathrm{Im}(\omega)/\mathrm{Re}(\omega)$, W is the total mechanical work done by pulsation, ω is the dimensionless frequency and $\mathrm{Im}(\omega)$ and $\mathrm{Re}(\omega)$ are the imaginary and real part of ω, respectively.

To identify the best-fit model, we recall that χ^2 is a measure of how well the corresponding model's oscillation spectrum matches the observed spectrum, independent of the effective temperature and surface gravity of the model, and χ^2_{model} is a measure of how well the corresponding model's effective temperature and surface gravity match the observed values of HD 163830.

If the observed oscillation spectrum is valid, then we expect that models that best match the spectrum should also fall within the observed constraints on T_{eff} and g (see Guenther & Brown 2004). In the case of HD 163830, we clearly have consistent results in the region of $1.016 \times 10^8\,\mathrm{yr}$ for stellar mass 4.4$M_\odot$ with $Z = 0.02$ (see Figure 2).

Seismic interpretation and conclusions

We identify the model of $1.016 \times 10^8\,\mathrm{yr}$, stellar mass 4.4$M_\odot$, and chemical composition $X = 0.71$, $Z = 0.02$ as the best-fit model for HD 163830. The effective temperature (13469 K) and the surface gravity ($\log g = 3.8521$) of the best-fit model match very well the observed values of HD 163830. The location in the H-R diagram (see Figure 3) is consistent with the SPBs region (see Favata et al. 2000). The value of χ^2 (7.9668), which is much bigger than 1, is due to the underestimated values of σ_i (Aerts et al. 2006). The detected and calculated frequencies are listed in Table 1. We remark that only five modes are stable: f_6, f_{11}, f_{13}, f_{15} and f_{17}.

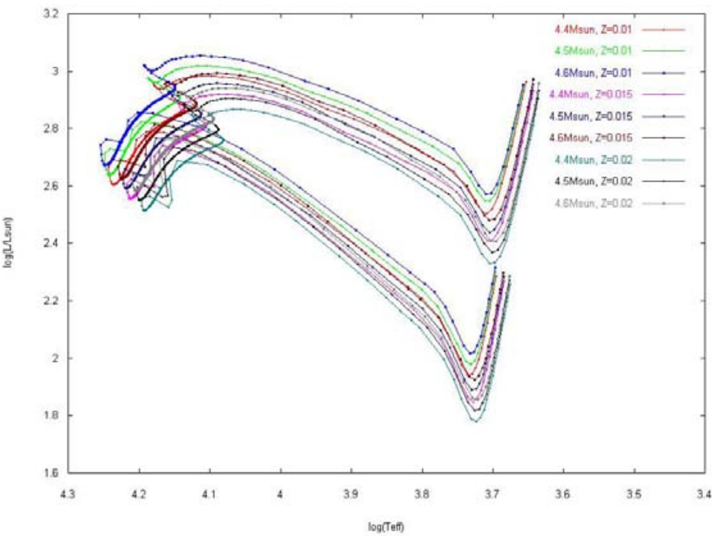

Figure 1: The grid of stellar models used to identify a best-fit model for the star HD 163830.

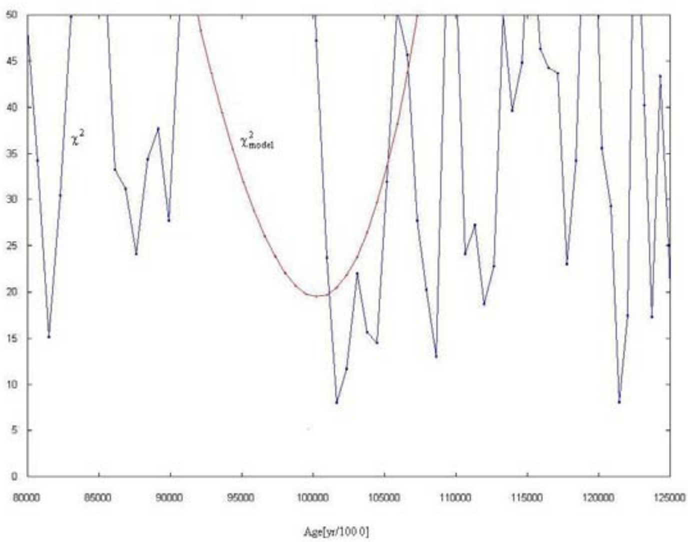

Figure 2: The region where the 4.4$M_\odot$ models that best match the spectrum also fall within the observed constraints on $T_{\rm eff}$ and g.

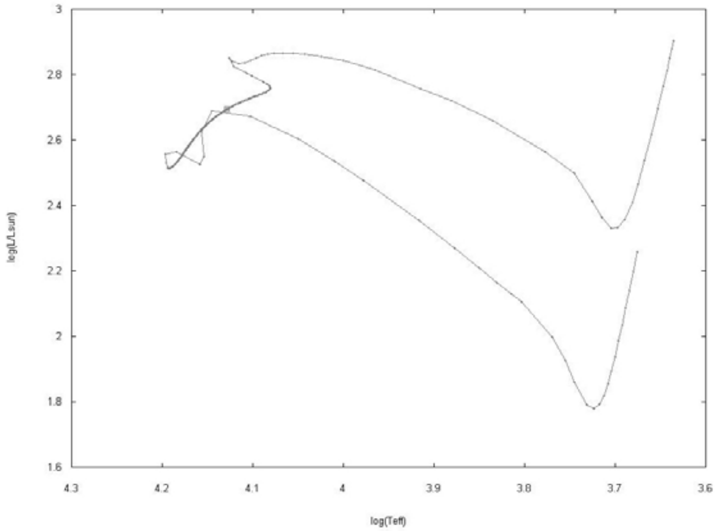

Figure 3: The evolutive track in the H-R diagram and the location (rectangle symbol) of the best-fit model for HD 163830 (mass 4.4$M_\odot$ and age $1.016 \times 10^8\,\mathrm{yr}$; see the text).

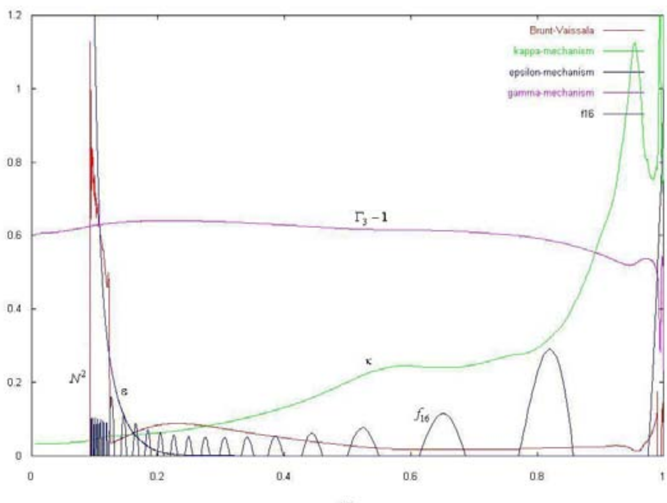

Figure 4: The high-order g-mode f_{16} and the region (μ - gradient zone) where it is trapped.

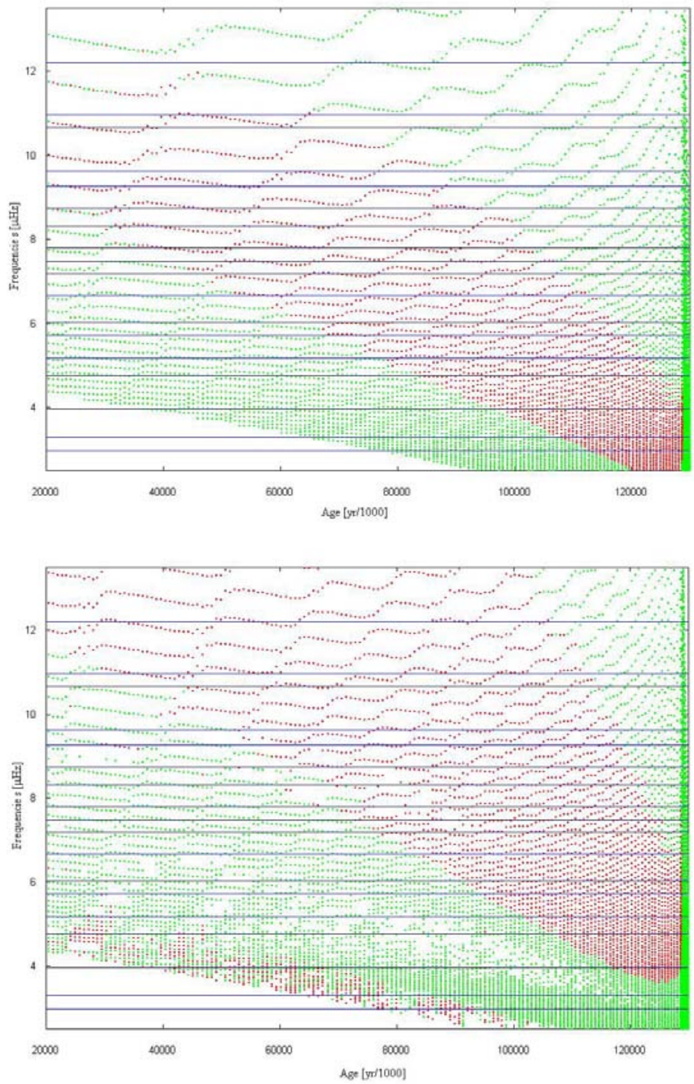

Figure 5: The evolutive frequency spectrum predicted for $l = 1$ (top) and $l = 2$ (bottom) modes for stellar models with parameters $4.4M_{\odot}$, $X = 0.71$, $Z = 0.02$, a mixing-length of 1.75 times the pressure scale height and core overshooting 0.2. Unstable modes are indicated with red symbols and stable modes with green symbols. The eighteen of the twenty observed frequencies of HD 163830 are indicated as full horizontal lines. HD 163830 is located at $1.016 \times 10^{8}\,\mathrm{yr}$.

Table 1: The eighteen of the twenty detected frequencies used in the asteroseismic modeling of the star HD 163830 and the corresponding calculated frequencies of the best-fit model. The quoted formal errors in the observed frequencies underestimate the true variance.

	f_j (μHz)	ν_i (μHz)	$\frac{\mathrm{Im}(\omega)}{\mathrm{Re}(\omega)}$	order (l)
f_1	7.806 ± 0.005	7.8085	-2.55×10^{-5}	2
f_2	7.19 ± 0.02	7.1438	-5.61×10^{-3}	2
f_3	7.48 ± 0.04	7.5994	-5.36×10^{-5}	2
f_4	8.75 ± 0.01	8.8082	-2.21×10^{-5}	2
f_5	9.27 ± 0.01	9.1915	-1.98×10^{-5}	2
f_6	4.77 ± 0.02	4.7445	2.22×10^{-4}	2
f_7	10.980 ± 0.007	11.005	-3.52×10^{-6}	2
f_8	6.67 ± 0.03	6.67	-5.62×10^{-6}	1
f_9	12.206 ± 0.009	12.206	-9.35×10^{-7}	2
f_{10}	6.03 ± 0.02	6.0037	-6.40×10^{-5}	2
f_{11}	5.18 ± 0.03	5.1446	3.09×10^{-4}	2
f_{12}	8.31 ± 0.05	8.3217	-3.43×10^{-5}	2
f_{13}	2.98 ± 0.03	2.9722	1.73×10^{-3}	1
f_{14}	9.63 ± 0.03	9.544	-8.52×10^{-6}	2
f_{15}	3.30 ± 0.03	3.2963	1.58×10^{-4}	1
f_{16}	5.72 ± 0.03	5.7051	-6.13×10^{-5}	2
f_{17}	3.97 ± 0.02	3.9738	2.05×10^{-5}	2
f_{18}	10.66 ± 0.02	10.71	-4.03×10^{-6}	2

Using our automatic program, we calculated and plotted the evolutive frequency spectrum corresponding to modes of $l = 1$ and $l = 2$ (Figure 5). The evolutive frequency spectrum shows numerous $l = 1, 2$ stable modes in the region of SPBs. Clearly, the eighteen of the twenty detected frequencies correspond to low-order, high-degree g-modes, as expected in SPBs.

References

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