A single, complete, and coherent seismic solution for five delta Scuti stars belonging to the Praesepe cluster.

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Abstract. The present paper discusses the seismic modelling of five δ Scuti stars belonging to the Praesepe cluster. Linear analysis is confronted with observations, using refined descriptions for the effects of rotation on the determination of the global stellar parameters and on the adiabatic oscillation frequency computations. A single, complete, and coherent solution for all the selected stars is found, which implies important constraints to the convection description for a certain range of effective temperatures. Furthermore, an estimate of the global parameters of the selected stars is given which allows us to constrain the cluster global characteristics.

Certain characteristics of stars belonging to the same cluster are generally assumed to be similar, viz the metallicity, distance, and age. We consider the following stars belonging to the Praesepe cluster: BW Cnc, BS Cnc, BU Cnc and BN Cnc (already included in the sample considered by M99), which were observed by several campaigns of the STEPHI network [1], and a fifth star, BV Cnc, which was observed by [2]. One can wonder if these five selected δ Scuti stars can show common, or at least similar, seismic solutions, that is, one particular solution that explains the whole set of observations. Up to now, only sets of individual solutions for each star (methodology followed by [3], hereafter M99) have been taken into account. In the present work, we adopt the solutions reported by M99 as the reference domain of possible solutions to search for one single, complete, and coherent solution. To do so, we use refined techniques for modelling intermediate mass stars, in particular those taking different effects of rotation into account. The modern seismic techniques used largely improve those adopted in M99 and other precedent works. One of the major improvements is the use the complete second-order formalism (including near degeneracy effects) developed by [4] based on the works by [5] and [6], which, in addition, takes the effect of the star deformation due to rotation into account.

1. Modelling
In order to individually model each selected star we first calculate the their corresponding fundamental parameters. To do so, the photometric observed parameters are used after being
properly corrected (using the method by [7]) for the effects of rotation. In [8], such a correction is applied to δ Scuti stars belonging to several open clusters. The method developed by [7] is model-dependent, therefore solutions depend on some typically free parameters. In particular, for the present set of δ Scuti stars in the Praesepe cluster, the best common solution given by the correction for the effect of rotation was obtained for $\alpha_{\text{MLT}} = 1.614$ and $d_{\text{ov}} = 0.2$, which correspond to an age of the cluster of 650 Myr ($\pm 20 - 40$ Myr). The age uncertainty of 20–40 Myr can be neglected in terms of global characteristics of the non-rotating co-partners [see the influence of age on photometric corrections for rotation in different open clusters in [8]].

We then computed seismic models based on the the fundamental parameters obtained for each star. Such models consist of pseudo-rotating equilibrium models and their corresponding adiabatic oscillation spectra. Theoretical adiabatic oscillation spectra are computed with the oscillation code FILOU ([9],[10]) which uses the complete treatment of second-order effects of rotation by [4], based on the formalisms by [5] and [6].

With the asteroseismic models so obtained we determine the observed radial orders which are then compared with mode instability predictions obtained from a linear stability analysis (which is based on linear stability computations carried out in the manner of [11]). We adopt the nomenclature of M99, i.e. $\alpha_{\text{NL}} = l/H_p$ is the mixing-length parameter of the non-local convection model used in the stability computations. The non-local mixing-length parameter $\alpha_{\text{NL}}$ is calibrated to the same depth of the outer convection zone as suggested by the evolutionary computations which use the standard mixing-length formulation by [12] and a local mixing-length parameter $\alpha_{\text{MLT}} = 1.614$, for which the equivalent calibrated value of $\alpha_{\text{NL}} = 1.89$ is obtained. Moreover, in order to analyse the impact of varying the mixing-length on mode stability, we calculate an additional series of stellar models with $\alpha_{\text{NL}} = 1.50$

2. Results & discussion

Ranges of observed and predicted radial orders $n$ of unstable modes are compared for two values of the two values of $\alpha_{\text{NL}}$ used in this work: 1.89 and 1.50, in the manner depicted in Fig. 1. The use of radial modes is justified because driving and damping in δ Scuti stars takes place predominantly in the HeII ionisation zone, which is rather close to the stellar surface, where the vertical scale is much less than the horizontal scale of the oscillations and when $\ell$ is low the modal inertia is quite insensitive to degree $\ell$. In order to consider all the most relevant error sources (see [13] for more details) an uncertainty of $\pm 1 n$ in the determination of the range of radial orders is considered. For each star, we have two representative models corresponding to considering $\pm 10\%$ of the observed $V_{\text{sini}}$ value, so we calculate four radial order ranges are calculated per object.

For the objects with the largest mass, BU Cnc and BN Cnc, the predicted unstable ranges are compatible with the observed results ($\pm 1 n$), for both $\alpha_{\text{NL}} = 1.50$ and $\alpha_{\text{NL}} = 1.89$. The results for both objects are thus not sensitive to the value of $\alpha_{\text{NL}}$. This is to be expected because these more massive stars have shallower outer convection zones and thus their structures are less sensitive to the assumed value of the mixing-length parameter.

For BW Cnc and BS Cnc (less massive), which present a corrected temperature range of $\log T_{\text{eff}} = 3.87 - 3.88$, the observed ranges are in good agreement with the theoretical predictions using $\alpha_{\text{NL}} = 1.50$, whereas with $\alpha_{\text{NL}} = 1.89$ the predicted ranges are in grave disagreement with the observations. For these stars a smaller mixing-length parameter $\alpha_{\text{NL}}$ is then required than suggested from a calibrated solar model. The need of a smaller value for $\alpha_{\text{NL}}$ than that from a calibrated solar model was also reported by [14] for the δ Scuti star FG Vir.

Finally, for the less massive object, BV Cnc, the values for $\alpha_{\text{NL}}$ cannot be distinguished. Nevertheless, the observed ranges agree with the theoretical predictions within $\pm 1 n$. Therefore, in general, these results constitute a consistent solution in terms of physics and cluster membership, and the observed and theoretical ranges of radial orders are in reasonable agreement.
Figure 1. Observed and predicted (using linear stability analysis) ranges of unstable radial modes for the selected δ Scuti stars ($n_1$ is the lowest value, and $n_2$ the largest value of the radial order of the unstable modes) displayed for the selected δ Scuti stars. Filled circles represent the observed ranges. Rhombus and squares correspond to predicted radial order ranges for $\alpha_{NL} = 1.89$ and $\alpha_{NL} = 1.50$, respectively. Each diagonal-dashed line represents the width (in radial orders) of the represented ranges. Taken from [13].
for all the stars considered in this work.

Details of the procedure, model characteristics, as well as the detailed comparison between the present results with those of M99 are given in [13] which includes, in addition, an estimate (crude) of the effect of rotation on mode stability, assuming that instability depends predominantly on the effective temperature of the model [15]. As well, in that work, more details on the procedure, the characteristics of models, and a detailed comparison between the present results with those of M99 are provided.

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References

[1] Michel E, Chevreton M, Belmonte J A, Li Z P, Alvarez M and The Stephi Team 1995 Helioseismology, ESA SP 376, Proceedings of the 4th Soho Workshop, held Pacific Grove, California, USA, 2-6 April 1995, Paris: European Space Agency (ESA), —c1995, Poster Session, p.533 ed Hoeksema J, Domingo V, Fleck B and Battrick B pp 533P—

[2] Frandsen S, Pigulski A, Nuspl J, Breger M, Belmonte J A, Dall T H, Arentoft T, Sterken C, Medupe T, Gupta S K, Pinheiro F J G, Monteiro M J P F G, Barban C, Chevreton M, Michel E, Benko J M, Barcza S, Szabó R, Kolaczkowski Z, Kopacki G and Udovichenko S N 2001 A&A 376 175–187

[3] Michel E, Hernández M M, Houdek G, Goupil M J, Lebreton Y, Hernández F P, Baglin A, Belmonte J A and Soufi F 1999 A&A 342 153–166

[4] Suárez J C, Goupil M J and Morel P 2006 A&A 449 673–685

[5] Dziembowski W A and Goode P R 1992 ApJ 394 670–687

[6] Soufi F, Goupil M J and Dziembowski W A 1998 A&A 334 911–924

[7] Pérez Hernández F, Claret A, Hernández M M and Michel E 1999 A&A 346 586–598

[8] Suárez J C, Michel E, Pérez Hernández F, Lebreton Y, Li Z P and Fox Machado L 2002 A&A 390 523–531

[9] Tran Minh F and Lon L 1995 Roxburg, I. W., Maxnou, J. L., eds., Physical Processes in Astrophysics. Springer Verlag, Berlin. p 219

[10] Suárez J C 2002 Ph.D. Thesis, ISBN 84-689-3851-3, ID 02/PA07/7178

[11] Balmforth N J 1992 MNRAS 255 603–649

[12] Böhm-Vitense E 1958 Zeitschrift für Astrophysics 46 108

[13] Suárez J C, Michel E, Houdek G, Pérez Hernández F and Lebreton Y 2007 MNRAS 379 201–208 (Preprint arXiv:0705.3626)

[14] Daszyńska-Daszkiewicz J, Dziembowski W A, Pamyatnykh A A, Breger M, Zima W and Houdek G 2005 A&A 438 653–660 (Preprint astro-ph/0504177)

[15] Pamyatnykh A A 1975 IAU Symp. 67: Variable Stars and Stellar Evolution pp 247–250