Asteroseismic study of $\gamma$ Doradus members of the cluster NGC 2506

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The present work performs an asteroseismic study of a $\gamma$ Doradus star member of the open cluster NGC 2506. This works conjugates the observational information of the star and the strong constraints imposed by the cluster membership, with the latest developed theoretical asteroseismic tools for the modelling of this type of objects, in particular the Frequency Ratio Method (FRM) and Time-Dependent Convection (TDC), to study the $\gamma$ Dor stars found in the NGC 2506 stellar cluster. The use of both techniques gives us the opportunity of constructing a self-consistent procedure, allowing the mode identification and improving the modelling of the $\gamma$ Dor members of the cluster. In this work we present the result of the analysis of the first target of our project, showing the advantage of modelling cluster member’s $\gamma$ Dor stars. This is the first step in a more ambitious project. In the near future, we plan to expand the study to other variable members of the NGC 2506 cluster. This will improve our knowledge of $\gamma$ Dor pulsators and probe the self-consistency of our procedures.

1 Introduction

The $\gamma$ Doradus (Dor) stars are suitable objects for asteroseismic study. They are high-order gravity ($g$) mode pulsators, which permits the probing of their stellar core and the use of the asymptotic approximation, for which analytical solutions of the oscillation equations exist (Smeyers & Moya 2007). The Frequency Ratio Method (FRM; Moya et al. 2005, Suárez et al. 2005), based on this property, is particularly adapted for obtaining asteroseismic information on $\gamma$ Dor pulsating stars that show, at least, three pulsation frequencies. The method provides an estimate of the identification of the radial order $n$ and the spherical degree $\ell$ of observed frequencies and of the integral of the buoyancy frequency (Brunt-Väisälä) weighted over the stellar radius along the radiative zone ($I_{\text{obs}}$).

The excitation mechanism of $\gamma$ Dor stars was an outstanding problem until the works of Guzik et al. (2000) and Dupret et al. (2005) who used respectively, frozen and Time-Dependent Convection (TDC) theories showed that the position of the base of the convective envelope is the key for driving $\gamma$ Dor $g$ modes. Moreover, TDC is formulated in the framework of mixing length theory and therefore the $\gamma$ Dor instability strip is predicted to be sensitive to the mixing-length parameter $\alpha_{\text{MLT}}$.

The asteroseismic modelling of $\gamma$ Dor, even armed with these techniques, still needs the global parameters of the observed stars. One of the ways to obtain a significant enhancement is to use the strong constraints imposed by the cluster membership for example, the age, metallicity and distance (Creevey et al. 2009; Suárez et al. 2002, 2007).

At the beginning of the recognition of the $\gamma$ Dor stars as a new class of variable stars, a great effort has been devoted to their detection in clusters. At that time the main aim of the community was to check whether this type of pulsations was linked or not to age and obviously, stellar clusters were the most suitable targets for this purpose (Martín & Rodríguez 2002).

One of the richest cluster in $\gamma$ Dor members is the old open cluster NGC 2506, for which photometric observations provide a considerable number of variable stars (Arentoft et al. 2007). Among them, 15 have been identified as $\gamma$ Dor stars candidates (labeled as V$_{11}$ – V$_{25}$ in that paper).

This work attempts to investigate the impact of using a procedure which includes FRM and TDC on the modelling of $\gamma$ Dor stars, taking advantage of their membership in clusters. In particular, we here provide preliminary results for the $\gamma$ Dor star V$_{11}$, belonging to the open cluster NGC 2506.

2 Observational Data

The old open cluster NGC 2506 ($\alpha$, $d)_{2000} = (08h \ 00^m \ 01^s, -10^\circ \ 46' \ 12''$) has been reported to hold around 20 oscillating stars of different types, 15 of them being $\gamma$ Dor candidates. The physical properties of the cluster are: distance = 3460
Fig. 1 HR Diagram position of γ Dor variables. Crosses represent the stars parameters given by Henry et al. (2007). The NGC 2506 γ Dor members (Arentoft et al. 2007) are displayed by filled circles, among which V11 (labelled with ‘11’). Dashed lines show the theoretical γ Dor instability strip for αMLT=2 as calculated by Dupret et al. (2005).

Table 1 Minimum and maximum values of the physical parameters of NGC 2506 V11 matching its observational parameters, with ages larger than 1800 Myr

| M (M_☉) | T eff (K) | [Fe/H] (dex) | L (L_☉) | Age (Gyr) | αMLT | αov |
|---------|-----------|--------------|---------|-----------|-------|------|
| 1.25    | 6930      | -0.52        | 6.03    | 1.80      | 0.5   | 0.1  |
| 1.45    | 7229      | -0.12        | 6.92    | 3.12      | 1.5   | 0.3  |

In Fig. 1 we show these γ Dor candidates of NGC 2506 (filled circles) together with known bonafide (crosses) γ Dor stars in the HR diagram. We also show the theoretical instability strip for αMLT=2 as calculated by Dupret et al. (2005).

In this study we concentrate on NGC 2506 V11 (V = 15.454) which is labelled ‘11’ in Fig. 1. Its global parameters are given by T eff = 7080 ± 150 K and Log (L/L_☉) = 0.81 ± 0.03. It has been chosen as a first target because it shows the highest frequencies: 1.165, 1.270 and 1.400 (d⁻¹), respectively.

3 Modelling of NGC 2506 V11 using global parameters

The first step in the modelling of V11 was the selection of those models matching the global parameters of the star. Obviously, stellar models could differ considering the specific values chosen for these global parameters (T eff, Metallicity, Log g, etc.) or for the values of the stellar modelling such as the Mixing-Length parameter αMLT or overshooting αov, etc.

We have constructed a grid of models, using the CE-SAM equilibrium code (Morel & Lebreton 2008), varying the mass (in the range [1.25, 2.10] M_☉) with steps of 0.01 M_☉), the metallicity (with values [M/H]=0.08, -0.12, -0.32 and -0.52), the mixing-Length parameter (values αMLT= 0.5, 1.0 and 1.5) and overshooting (values αov= 0.1, 0.2 and 0.3). Standard physical inputs for γ Dor and δ Scuti stars are used (see Casas et al. 2006, 2009 for details). The pulsational observables have been calculated using the GraCo pulsational code (Moya, Garrido & Dupret 2004, Moya & Garrido 2005). Both codes (CESAM and GraCo) have been part of the ESTA group for comparison of codes (Lebreton et al. 2008, Moya et al. 2008).

The number of models lying in the error box and fulfilling the cluster membership (sub-solar metallicity and age > 1800 Myr), is huge (1210 in our grid). The minimum and maximum values obtained are displayed in Table 1. The sub-solar metallicity constraint is automatically fulfilled when the age restriction is imposed, that is, there are no models of solar metallicity with an age larger that 1800 Myr and the global parameters of NGC 2506 V11. This agrees with the global determination for the cluster.

4 Theoretical Results - FRM

The next step in our study was the inclusion of the asteroseismic constraints. To do so, we followed a self-consistent procedure presented by Moya et al. (2008) used in different asteroseismic studies of γ Doradus stars (Rodríguez et al. 2006a, b; Uytterhoeven et al. 2008) and recently applied to the determination of the physical characteristics of the first planetary system observed by direct imaging, HR 8799 (Moya et al. 2010a, b).

We first applied the FRM. This method provides sets of possible mode identifications (n, ℓ) for the three observed frequencies and the corresponding value for the Brunt-Väisälä integral (Iobs). Adding this new constraint, the number of accepted models is reduced by 70%. Then, we searched for those models matching the observed frequencies with the predicted mode identification and Iobs. The model selection was done using χ² statistics. The total number of modes selected is 50, for which the standard deviation of the frequency fit is lower than 0.5 μHz. Table 2 shows the models with the best χ² and the mode identification predicted.

5 Theoretical Results - TDC

The second step of our procedure is the study of the energy balance of the theoretical modes using TDC. We have
Table 2  Best models fitting the observed frequencies, with the mode identification and $I_{\text{obs}}$ predicted by the FRM.

| M/M$_\odot$ | Model | [Fe/H] | $\alpha_{\text{MLT}}$ | $\alpha_{\text{ov}}$ | $n_1$ | $n_2$ | $n_3$ | $\ell_1$ | $\ell_2$ | $\ell_3$ | $\chi^2$ |
|------------|-------|--------|----------------|----------------|-------|-------|-------|--------|-------|-------|-------|
| 1.38       | -0.32 | 1.5    | 0.1            | -50            | 2     | -46   | -24   | 1      | 1.598E-06 |
| 1.36       | -0.32 | 1.5    | 0.1            | -49            | 2     | -45   | -41   | 2      | 2.563E-06 |
| 1.27       | -0.52 | 1.5    | 0.2            | -30            | 1     | -48   | -25   | 1      | 6.073E-06 |
| 1.36       | -0.32 | 1.5    | 0.2            | -48            | 2     | -44   | -23   | 1      | 6.861E-06 |
| 1.28       | -0.52 | 1.5    | 0.1            | -56            | 2     | -30   | -47   | 2      | 8.374E-06 |
| 1.33       | -0.32 | 1.5    | 0.2            | -48            | 2     | -44   | -40   | 2      | 9.794E-06 |

Fig. 2  Age - Mass diagram of the models fulfilling all the observational constraints. The metallicity of each model is also shown.

An accepted those models selected in the previous step that predict over-stable observed frequencies. The models fulfilling all the asteroseismic constraints are drastically reduced to those displayed in Fig. 2. In this figure we show the Age - Mass values of these models together with their metallicity. The minimum and maximum values obtained are displayed in Table 3.

A first consequence of this study is that models with an age around 1800 - 2000 Myr have an internal metallicity similar to that observed for the cluster ([Fe/H]=-0.32), masses in the range [1.33,1.38] M$_\odot$ and radius around 1.77 R$_\odot$. Lower metallicity models can also fulfill all the observational constraints but with ages larger than expected for the stars of NGC 2506.

6 Conclusions

With this prospective study we showed that the application of FRM and TDC to the cluster member $\gamma$ Dor candidate NGC 2506 V$_{11}$ enhances significantly our determination of the mass, radius and age. Specifically, its metallicity is confirmed to be sub-solar. The energy transport efficiency of the outer convective zone is high ($\alpha_{\text{MLT}} = 1.5$). These results must be confirmed with the extension of this study to other $\gamma$ Dor stars of this cluster.

This is a first step of a more ambitious project. In the near future, we plan to expand the study to other variable members of the NGC 2506 cluster. A better knowledge of variable membership and their global parameters will improve our knowledge on $\gamma$ Dor pulsators and probe the self-consistency of our procedures.

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Table 3  Minimum and maximum values of the physical parameters of NGC 2506 V₁₁ fulfilling all the constraints

| Mass       | $T_{\text{eff}} (K)$ | [Fe/H] | L/L$_\odot$ | R/R$_\odot$ | Age (Myr) | $\alpha_{MLT}$ | $\alpha_{ov}$ |
|------------|----------------------|--------|-------------|-------------|-----------|----------------|--------------|
| 1.25 – 1.29| 6997                 | -0.52  | 6.07        | 1.6         | 1832      | 1.5           | 0.1          |
| 1.33 – 1.38| 7223                 | -0.32  | 6.83        | 1.774       | 2585      | 1.5           | 0.3          |

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