Theoretical study of $\gamma$ Doradus pulsations in pre-main sequence stars

M.-P. Bouabid$^{1,2}$, J. Montalbán$^2$, A. Miglio$^3$, M.-A. Dupret$^2$, A. Grigahcène$^3$, and A. Noels$^2$

1 UMR 6525 H. Fizeau, UNS, CNRS, OCA, Campus Valrose, F-06108 Nice Cedex 2, France
e-mail: bouabid@oca.eu
2 Institut d’Astrophysique et de Géophysique de l’Université de Liège, Allée du 6 Août, 17 B-4000 Liège, Belgium
3 Centro de Astrofisica da Universidade do Porto, Rua das Estrelas, 4150-762 Porto, Portugal

Received 30 May 2005, accepted 11 Nov 2005
Published online later

Key words stars: variables: gamma Doradus stars - stars: oscillations - stars: pre-main sequence

The question of the existence of pre-main sequence (PMS) $\gamma$ Doradus ($\gamma$ Dor) has been raised by the observations of young clusters such as NGC 884 hosting $\gamma$ Dor members. We have explored the properties of $\gamma$ Dor type pulsations in a grid of PMS models covering the mass range $1.2 M_\odot < M_* < 2.5 M_\odot$ and we derive the theoretical instability strip (IS) for the PMS $\gamma$ Dor pulsators. We explore the possibility of distinguishing between PMS and MS $\gamma$ Dor by the behaviour of the period spacing of their high order gravity-modes ($g$-modes).

1 Introduction

The variability of $\gamma$ Dor stars was identified as due to pulsations by Balona, Krisbinas & Cousins (1994), and the features of the stars belonging to this new class of pulsators were defined by Kaye et al. (1999). They are late A and F-type stars covering a part of the Hertzsprung-Russel diagram (HRD) between $7200 - 7700 \, K$ on the zero-age main sequence (ZAMS) and $6900 - 7500 \, K$ above it (Handler 1999), between the solar-like stars and the $\delta$ Scuti ($\delta$ Set) IS. They are located between stars with a deep convective envelope (CE) and stars with a radiative envelope, in the region of the HRD where the depth of the CE changes rapidly with the effective temperature of the star. $\gamma$ Dor pulse with high order $g$-modes in a range of periods between 0.3-3 days. The excitation mechanism proposed by Guzik et al. (2000) using the frozen-convection assumption is a modulation of the radiative flux at the base of the CE. This mechanism was revisited by Dupret et al. (2005) using a time-dependant convection (TDC) treatment.

From an observational point of view, the limits of the $\gamma$ Doradus IS have been lastly established by Handler & Shobbrook (2002) (HS02 hereafter) and in the rest of the paper these limits will be adopted to define the $\gamma$ Dor IS. Since the depth of the CE plays a major role in the driving mechanism of $\gamma$ Dor pulsations, the theoretical predictions of stability are very sensitive to the parameter $\alpha_{\text{MLT}}$ defining the travel length of convective elements in the classical mixing-length treatment (MLT) of convection (Böhm-Vitense 1958).

Number of observational efforts have been devoted to the search of PMS $\gamma$ Dor pulsators. Saesen et al. (2010) found 6 multiperiodic A and F-type stars with a mean frequency between 0.2 d$^{-1}$ and 3 d$^{-1}$ during their multisite observation campaign on the young open cluster NGC 884 (age $\sim 12.8$ Myr - Slesnick et al. 2002). Zwintz et al. (2009) searched for PMS pulsators in a young open cluster (NGC 2264, age $\sim 3-10$ Myr - Sung et al. 2004; Sagar et al. 1986) but did not find any $\gamma$ Dor which were confirmed cluster members.

The above mentioned theoretical works on $\gamma$ Dor stars systematically studied MS models stability. However, as shown...
in Fig. 1, MS and PMS evolutionary tracks cross the observational γ Dor IS. The presence of stars at different evolutionary phases in this region of the HRD raises some questions: since the internal structure of PMS stars is different, can we expect γ Dor pulsations in such stars? Could these pulsations be used to distinguish between PMS and MS γ Dor?

To answer these questions, we performed an adiabatic and a non-adiabatic asteroseismic analysis on a grid of PMS and MS models between 1.2 and 2.5M⊙ computed with the stellar evolution code CLES (Scuflaire et al. 2008a). The adiabatic and non-adiabatic computations have been done respectively with the LOSC (Scuflaire et al. 2008b) and MAD (Dupret 2001) codes.

Fig. 2  Top panel: Evolution of a 1.8M⊙ star in the HRD (PMS phase in full black and MS phase in dashed grey). Middle panel: Variation of its CC mass from the PMS phase to the early MS phase (Xc = 0.68). Bottom panel: Evolution of the ℓ = 1 modes period spacing as a function of the effective temperature of the star from the PMS to the Terminal Age Main Sequence (TAMS).

A star approaching the MS from the Hayashi track has already a radiative core that continues to contract. The increase of density due to this contraction leads to the increase of the central temperature (Tc). This phenomenon continues until Tc is high enough (∼1.7×10^7 K) to start the nuclear reactions of the CN subcycle. Because of the high dependence on temperature of the 12C(p, γ)13N(β+)ν13C(p, γ)14N nuclear reaction rate (∝ T^{19}) a convective core (CC) appears. The fraction of mass of this CC changes as the star evolves toward the ZAMS (Fig. 2 - middle panel) and for typical γ Dor stellar masses, the CC remains during the MS. The onset of the CN subcycle appears in the PMS evolutionary track as a kind of loop with a minimum of luminosity after a first maximum (Fig. 2 - top panel).

As shown in Fig. 1, the phase at which the star crosses the IS during the PMS changes with the stellar mass. While low mass models have already developed a CC, more massive models are still contracting with a fully radiative core.

The properties of the g-modes spectrum is determined by the matter stratification in the star, which is described by the Brunt-Väisälä frequency N:

\[ N^2 = g \left( \frac{1}{\Gamma_1} \frac{d \ln P}{dr} - \frac{d \ln \rho}{dr} \right) \tag{1} \]

with g the local gravity, ρ the local density, P the local pressure, r the local radius and \( \Gamma_1 \) the first adiabatic exponent.

1 we consider as PMS models those before the onset of the stationary central H-burning.
From the first order asymptotic theory (Tassoul 1980), the period of a $g$-mode with a radial order $k$ and a degree $\ell$ in a star with a CC and a CE is given by:

$$P_k = \frac{\pi^2}{\sqrt{\ell(\ell+1)}} \int_{r_1}^{r_2} \frac{N}{r} \, dr (2k + 1)$$

with $r_1$ and $r_2$ the limits of the $g$-mode cavity defined by $\sigma_g^2 < N^2 S_\ell^2$, where $\sigma_g$ is the $g$-mode frequency and $S_\ell$ the Lamb frequency for modes of degree $\ell$ (Fig. 3). The dependence of $g$-mode periods on the behaviour of $N$ in the central region of the star allows us to expect a clear difference between the seismic properties of PMS and MS $\gamma$ Dor.

### 2.1 Comparison of the models internal structures

The PMS evolutionary track of a $1.8M_\odot$ star crosses at different points the corresponding MS track. In particular, both tracks cross in the middle of the $\gamma$ Dor IS (Fig. 3 - left panel). By comparing these two models at the same location in the HRD we eliminate undesirable effects on the stellar structure coming from different effective temperatures or luminosities. The internal structures of these PMS and MS models are shown in Fig. 3 where we plotted their $N$ and $S_\ell=1$ frequencies as a function of the radial distance.

Because of the same radius and mass, PMS and MS models show similar behaviour of $N$ in the outer layers and the bases of the CE are located at the same depth (Fig. 4 - left panel). Both $N$ profiles present also a bump in the inner layers, due to the density distribution. However, the central layers of the two models are very different. The PMS model has only a small CC ($N^2 < 0$) due to the onset of the CN subcycle while the CC of the MS model is larger. The main difference between the two $N$ profiles lies in the sharp feature located at the limit of the MS convective core. This peak is due to the presence of an important mean molecular weight gradient ($\nabla \mu$) at the limit of a recceding CC.

As mentioned above, more massive PMS models cross the $\gamma$ Dor IS during an earlier phase than lower mass ones. We considered models with CC overshooting in order to have MS models with high enough luminosity and low enough effective temperature crossing a more massive PMS track (Fig. 4 - right panel). A $2.1M_\odot$ quasi chemically homogeneous PMS model that still has a radiative core has the same HRD location as a $1.9M_\odot$ evolved MS model. The different masses but same radius of the two models lead to differences in their density profiles that determines the behaviour of $N$ in the envelope, and therefore the different depth of their CE (Fig. 4 - right panel).

### 2.2 Adiabatic study - Period spacing

From Eq. 2, the period spacing between two $g$-modes with consecutive radial orders and same degree can be written as:

$$\Delta P = P_{k+1} - P_k = \frac{2\pi^2}{\sqrt{\ell(\ell+1)}} \int_{r_1}^{r_2} \frac{N}{r} \, dr$$

With $r_1$ and $r_2$ the limits of the $g$-mode cavity defined by $\sigma_g^2 < N^2 S_\ell^2$, where $\sigma_g$ is the $g$-mode frequency and $S_\ell$ the Lamb frequency for modes of degree $\ell$ (Fig. 3). The dependence of $g$-mode periods on the behaviour of $N$ in the central region of the star allows us to expect a clear difference between the seismic properties of PMS and MS $\gamma$ Dor.

Fig. 4 (bottom panel) represents the evolution of the period spacing from the PMS to the TAMS for a $1.8M_\odot$ star. The period spacing presents a clear variation which is strongly dependant on the evolution of the CC.

For models with the same effective temperature, the maximum difference between PMS and MS period spacing is around 2000 seconds and corresponds to the maximum mass fraction of the CC (Fig. 3 - point B). The period spacing value could be, in principle, used as a first discriminant between PMS and MS $\gamma$ Dor. However the period spacing of PMS stars can be of the same order as the MS $\gamma$ Dor one (Fig. 3 - bottom panel - points A & C) and we cannot always use this value to determine if a $\gamma$ Dor star is in its PMS or its MS evolutionary state.

Nevertheless, a sharp variation of $N$ such as the one due to the $\nabla \mu$ at the border of the CC let a clear asteroseismic signature: the oscillation of the period spacing around its mean value (Miglio et al. 2008 and references therein). While MS models can present that $\nabla \mu$, PMS ones are almost chemically homogeneous, i.e. their $N$ profile is quite smooth. Therefore the PMS period spacing does not clearly change with the radial order (Fig. 5).

### 3 Non-adiabatic study - Stability analysis

Because the adiabatic study does not take into account the excitation and damping of modes, we performed a non-adiabatic analysis. The theoretical IS were calculated for $\ell = 1$ and $\ell = 2$ modes with the non-adiabatic code MAD including TDC treatment (Grigahcène et al. 2005) on a grid of 1.2 – $2.5M_\odot$ stellar models computed with the following physical inputs:

- OPAL2001 equation of state (Rogers & Nayfonov 2002)
- OP opacity tables (Badnell et al. 2005) completed
Our first results are presented in Fig. 5 showing the theoretical IS of high order \( g \)-mode pulsators for MS and PMS models. The location of PMS \( \gamma \) Dor theoretical IS matches up with the MS one.

4 Conclusion

We carried out an adiabatic and a non-adiabatic studies on a grid of PMS and MS models in the mass range \( 1.2M_\odot < M_* < 2.5M_\odot \) to differentiate the asteroseismic behaviour of PMS \( \gamma \) Dor from that of MS ones.

We pointed out the theoretical existence of PMS high order \( g \)-mode pulsators in the region of the observational \( \gamma \) Dor IS. The theoretical PMS IS has the same edges than the MS one and presents a good agreement with the observational \( \gamma \) Dor IS for \( \alpha_{MLT} = 2.00 \). The only difference between MS and PMS IS lies in the fact that even with a CC overshooting no MS evolutionary track can reach the upper region of the HRD, where unevolved massive PMS \( \gamma \) Dor exist.

The measurement of the period spacing allows us to make the distinction between PMS and MS models by two different ways:

- At fixed stellar parameters, the difference between central internal structures may lead to a significant difference between the values of the period spacing. We are aware that we should investigate if we can still distinguish PMS stars once we consider stellar parameters uncertainties but it is not the purpose of the present paper.
- The behaviour of the period spacing is also different between MS and PMS models. While during the MS the important \( \nabla_{\mu} \) and the evolution of the CC leads to an oscillation of the period spacing, the lack of such a \( \nabla_{\mu} \) during the PMS phase leads to a period spacing independent of the mode radial order.

In a forthcoming paper the difference between PMS and MS non-adiabatic \( g \)-modes frequency spectra will be presented.

References

Asplund, M., Grevesse, N., Sauval, A. J.: ASPC 336, 24
Badnell, N. R., Bautista, M. A., Butler, K., Delahaye, F., Mendoza, C., Palmeri, P., Zeippen, C. J., Seaton, M. J.: 2005, MNRAS 360, 458
Balona, L. A., Krisciunas, K., Cousins, A. W. J.: 1999, MNRAS 270, 905
Böhm-Vitense, E.: 1958, ZA 46, 108
Dupret, M.-A.: 2001, A&A 366, 166
Dupret, M.-A., Grigahcène, A., Garrido, R., Gabriel, M., Scuflaire, R.: 2004, A&A 414, 17
Dupret, M.-A., Grigahcène, A., Garrido, R., Gabriel, M., Scuflaire, R.: 2005, A&A 435, 927
Ferguson, J. W., Alexander, D. R., Allard, F., Barman, T., Bodnarik, J. G., Hauschildt, P. H., Heffner-Wong, A., Tamanai, A.: 2005, ApJ 623, 585
Guzik, J. A., Kaye, A. B., Bradley, P. A., Cox, A. N., Neuforge, C.: 2000, ApJ 542, 57
Grigahcène, A., Dupret, M.-A., Gabriel, M., Garrido, R., Scuflaire, R.: 2005, A&A 434, 1055
Handler, G.: 1999, MNRAS 309, 19
Handler, G., Shobbrook, R. R.: 2002, MNRAS 333, 251
Henry, G. W., Fekel, F. C., Henry, S. M.: 2005, AJ 129, 2815
Kaye, A. B., Handler, G., Krisciunas, K., Poretti, E., Zerbi, F. M.: 1999, PASP 111, 840
Miglio, A., Montalbán, J., Noels, A., Eggenberger, P.: 2008, MNRAS 386, 1487
Rogers, F. J., Nayfonov, A.: 2002, ApJ 576, 1064
Sagalar, R., Piskunov, A. E., Miakutin, V. I., Joshi, U. C.: 1986, MNRAS 220, 383
Scuflaire, R., Théado, S., Montalbán, J., et al.: 2008a, Ap&SS 316, 83
Scuflaire, R., Montalbán, J., Théado, S., et al.: 2008b, Ap&SS 316, 149
Slesnick, C. L., Hillenbrand, L. A., Massey, P.: 2002, ApJ 576, 880
Sung, H., Bessel, M. S., Chun, M.-Y.: 2004, AJ 128, 1684
Tassoul, M.: 1980, ApJS 43, 469
Zwintz, K., Hareter, M., Kuschnig, R., et al.: 2009, A&A 502, 239