Might intermediate-order g modes observed in the CoRoT hybrid γ Doradus/δ Scuti star HD 49434 be stochastically excited?

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1 Introduction

Hybrid γ Dor/δ Scuti stars are of great interest because they offer additional constraints on stellar structure and may be used to test theoretical models. γ Dor stars pulsate in high-order g modes with periods of the order of 1 day, driven by convective flux blocking at the base of their convective envelopes. In turn, δ Scuti stars pulsate in low-order p and g modes with periods of the order of 2 hours, driven by the \( \kappa \)-mechanism operating in the He\( \text{II} \) ionization zone. Most of the already confirmed hybrid stars clearly display separate frequency domains. However, some of these objects are known to exhibit a range of excited intermediate modes. Such a feature has been detected for the first time in the frequency power spectrum of the Am star HD 8801 by Handler (2009). That work also shows that the amplitudes of these intermediate oscillation modes are of the same order of magnitude as of those detected in the classical δ Scuti domain. The presence of intermediate-order modes opens new questions concerning the possible mechanism responsible for their excitation.

In this regard, the present work aims at providing insight into the possible excitation mechanism of such intermediate-order modes, through the analysis of the frequency power spectrum of the hybrid star HD 49434, which has been selected for the asteroseismic core programme of the CoRoT satellite (Baglin et al. 2006). HD 49434 (spectral type F1V) is a bright (\( V = 5.75 \)) and multiperiodic pulsator located near the blue edge of the γ Dor instability strip (IS) and inside the δ Scuti IS. Photometric data recently made available by CoRoT (Chapellier et al. 2009) allowed confirming the hybrid nature of HD 49434. This star had been referenced as a candidate hybrid γ Dor/δ Scuti by Uytterhoeven et al. (2008), following an extensive photometric and spectroscopic ground-based campaign. A compelling feature of its frequency power spectrum is the presence of excited intermediate-order g modes.

From a theoretical point of view, different approaches are currently being adopted in order to explain such spectral features. Theoretical studies based on model computations of cool δ Scuti stars (Houdek et al. 1999; Samadi et al. 2002) predict the presence of solar-like oscillations with amplitudes large enough to be detectable with ground-based instruments, although so far not confirmed. It should be stressed here that these models lie exactly on or near the γ Dor IS determined afterwards by Dupret et al. (2005). Therefore, it is plausible considering that solar-like, γ Dor-like and δ Scuti-like oscillations might be simultaneously excited in such intermediate-mass, main-sequence stars.

Rotational splitting has already been invoked as a possible explanation for these observed frequencies (Bouabid et al. 2009; Uytterhoeven et al. 2008). More recently, Kallinger and Matthews (2010) suggested that most of the peaks in the rich frequency spectra of the δ Scuti stars already analysed using data from CoRoT (see e.g., García Hernández et al. 2009) could be the signature of non-white granulation background noise, meaning that only a few tens of those frequencies should be interpreted as stellar p modes.

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On the other hand, based on the Time-Dependent Convection (TDC) of Grigahcène et al. (2005), Dupret et al. (2005) showed that TDC models predict the likely existence of hybrid stars with both δ Sct p-mode and γ Dor g-mode oscillations. Furthermore, TDC models predict the existence of a frequency gap that is stable to pulsations in the range 5–15 d$^{-1}$ for low-degree modes. Therefore, according to these models, neither the classical κ-mechanism nor the convective flux blocking at the bottom of the convective envelope can explain the excitation of observed intermediate-order g modes.

In the present work, we address the possibility that such intermediate-order g modes are excited by a stochastic mechanism. In order to do so, a first approach to the problem can be easily implemented by considering the characteristics of this type of excitation, in particular those concerning the statistical behaviour of the mode amplitudes. A simple diagnostic method has been established by Pereira and Lopes (2005) that probes the stellar pulsations’ excitation mechanism by analysing the temporal variation in the amplitude of oscillation modes. Numerical simulations and the application to the γ Dor star HD 22702 (Pereira et al. 2007) serve as a test of the method. In this work we employ this statistical method to investigate the nature of the intermediate-order g modes visible in the spectrum of HD 49434.

2 Observations vs. TDC models

Recent data from CoRoT allowed confirming the hybrid nature of HD 49434, previously referenced as a candidate. In Fig. 1 we simultaneously display partial (i.e., exclusively within the gap) ground-based and CoRoT frequency spectra of HD 49434 (middle and bottom panels, respectively). The top panel displays the frequency spectrum of HD 8801.

Making use of the fundamental parameters of HD 49434 ($T_{\text{eff}} = 7300 \pm 200$ K, log $g = 4.1 \pm 0.2$, [Fe/H] = $-0.1 \pm 0.2$, and $v \sin i = 84 \pm 5$ km s$^{-1}$) taken from Uytterhoeven et al. (2008), we are able to show in Fig. 2 the theoretical excited frequency spectrum for spherical degree $\ell$ ranging from 0 to 10 and corresponding to a representative model ($M = 1.55$ M$\odot$ and $T_{\text{eff}} = 7300$ K). We note that the stability of modes within the gap decreases as degree $\ell$ increases. This is due to the fact that the Lamb frequency ($S_{\ell}$) behaves according to $S_{\ell}^2 \propto \ell(\ell + 1)$, so that the size of the propagation cavity for g modes increases with $\ell$ for a given frequency (Grigahcène et al. 2010). The gap extent gets clearly reduced for higher values of $\ell$ without however becoming completely filled.

This interestingly opens a new question both on the validity of the data analysis treatment used in frequency detection and on the nature of the excitation mechanism once the stellar origin of these frequencies is assured.

3 Search for evidence of stochastic excitation

A search for the signature of stochastic excitation in a number of modes within the gap was carried out according to the statistical method described in Pereira and Lopes (2005). It has been shown that for oscillations that are excited and damped by a physical process in stochastic equilibrium, the ratio of the standard deviation of the amplitude, $\sigma(A)$, over the amplitude mean value, $\langle A \rangle$, is approximately 0.52. This theoretical relation still holds true in the presence of a time series crowded with closely-spaced periods, a relevant issue when applying the method to γ Dor stars. Furthermore, the region for which $\sigma(A) < 0.52 \langle A \rangle$ corresponds to oscillations excited by thermal overstability, this being the region where one expects to find most of the modes excited by the κ-mechanism. On the other hand, the region with $\sigma(A) > 0.52 \langle A \rangle$ corresponds to non-equilibrium stochastic oscillations (yet to be observed).

In order to investigate the nature of the observed intermediate-order g modes we have analysed the 136.9-day time series available for this star which was collected by CoRoT during the long run LRa01 (2007 October–2008 March). We started by dividing the original time series in 41 subseries, each with the approximate duration of 3.33 d. We then selected 4 previously detected modes within the gap, having performed 41 amplitude measurements for each, i.e., one

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Fig. 1  Top Panel: Frequency spectrum of HD 8801 where $\nu$-filter amplitudes are given (Handler 2009). Middle Panel: Vertical lines represent ground-based observed frequencies for HD 49434 (Uytterhoeven et al. 2008). Bottom Panel: Partial CoRoT frequency spectrum of HD 49434. The 4 oscillation modes selected in (3) for the purpose of conducting the statistical test are indicated.
to perform the amplitude measurements.

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Table 1 displays the so-called excitation diagram.

Subseries for 4 selected modes within the interval is given by measurement per subseries. This allowed us to compute the statistic \( \sigma(A)/\langle A \rangle \) (see Table 1).

We went further and performed Monte Carlo simulations in order to compute the probability density function (pdf) for the observed \( \sigma(A)/\langle A \rangle \) statistic assuming stochastic excitation. The modal bin of this distribution turns out to be approximately 0.407 and the \( \sigma(A)/\langle A \rangle \) (pdf) for the observed statistic \( \sigma(A)/\langle A \rangle \) computed along the 41 subseries, thus increasing the significance of the statistic \( \sigma(A)/\langle A \rangle \).

2. The fact that the observational results lie outside the confidence interval (for the two strongest modes) or just on the lower 1σ bound (for the two faintest modes) might tempt us to conclude that these modes are not stochastically excited. However, we need to be cautious and a new analysis should definitely be carried out where we increase the number of amplitude measurements (with the corresponding loss in frequency resolution of each of the subseries), thus increasing the significance of the statistic \( \sigma(A)/\langle A \rangle \).

Fig. 2 Theoretical excited frequency spectrum for spherical degree \( \ell \in [0, 10] \). The theoretical stable frequency gap is clearly seen even for high-degree modes.

Fig. 3 Excitation diagram: The thick solid line represents the theoretical relation \( \sigma(A) = 0.52(A) \), whereas the thin solid line represents the outcome of the simulations that gave \( \sigma(A) \approx 0.41(A) \). The dashed lines represent the 1σ bounds for \( \sigma(A)/\langle A \rangle \) taken from the pdf. Observational results for the selected modes are plotted with accompanying error bars.

(linear with separation 1, in other words, sampling from contiguous subseries), does not allow for a good estimate of \( \sigma(A)/\langle A \rangle \) if we assume stochastic excitation.

Two remarks should be made after inspection of the excitation diagram (Fig. 3):

1. The way the sampling has been performed, i.e., the number of amplitude measurements and the type of sampling (linear with separation 1, in other words, sampling from contiguous subseries), does not allow for a good estimate of \( \sigma(A)/\langle A \rangle \) if we assume stochastic excitation.

2. The fact that the observational results lie outside the confidence interval (for the two strongest modes) or just on the lower 1σ bound (for the two faintest modes) might tempt us to conclude that these modes are not stochastically excited. However, we need to be cautious and a new analysis should definitely be carried out where we increase the number of amplitude measurements (with the corresponding loss in frequency resolution of each of the subseries), thus increasing the significance of the statistic \( \sigma(A)/\langle A \rangle \).

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