Modelling $\delta$ Scuti stars using asteroseismic space data

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Received 30 May 2005, accepted - Published online later

Key words stars: $\delta$ Sct – stars: rotation – stars: oscillations – stars: fundamental parameters – stars: interiors

In the last years, space missions such as COROT, Kepler or MOST have provided very accurate photometric observational data. In the particular case of $\delta$ Scuti stars, the observed frequency spectra have hundreds (if not thousands) of modes and a clear amplitude distribution. In this work we present new techniques for modelling these observations and the results obtained. We searched for regular patterns in the observational data, which yields something resembling the large separation. This allows to reduce the possible positions of the star in the HR diagram, yielding a value of the mean density with an accuracy never reached before for isolated stars of this type. Finally, we answer whether a $\delta$ Scuti star is stable despite all of the observed frequencies are simultaneously excited.

1 Introduction

The $\delta$ Scuti stars are intermediate-mass pulsating variables with spectral types ranging from A2 to F0. They are located on and just off the main sequence in the lower part of the Cepheid instability strip (luminosity classes V & IV). Nowadays, the $\delta$ Scuti stars are considered as particularly suitable for asteroseismic studies of poorly known hydrodynamical processes occurring in stellar interiors such as convective overshoot, mixing of chemical elements and redistribution of angular momentum (Zahn 1992), etc. Due to the complexity of the oscillation spectra, their pulsating behaviour is not fully understood, in particular in what regards the rotation-pulsation interaction (see a complete review on such effects in Goupil et al. 2005). In the last decade, numerous interpretation works have taken the effects of rotation into account (Foz Machado et al. 2006; Suárez et al. 2007a; Suárez et al. 2007b; Bruntt et al. 2007).

The very precise space photometry supplied by the CoRoT mission give us the possibility to deal with a range and an amount of frequencies not reached by usual ground based observations. In this work we focus on the star HD174936. This is a field $\delta$ Scuti star observed during the first short run SRc01 for which we have a frequency resolution corresponding to 27 days of observation, namely 0.45 $\mu$Hz.

The evolutionary code CESAM (Morel 1997; Morel & Lebreton 2008) and the pulsation codes GraCo (Moya et al. 2004; Moya & Garrido 2008) have been used as numerical codes to calculate frequencies, growth rates and other physical quantities. GraCo provides, in particular, non-adiabatic variables and growth rates. Comparing the theoretical predictions given by these numerical codes with the observed range of excited frequencies and studying the periodic spacing in the oscillation frequency distribution, we have performed a seismic study in order to constrain the physical parameters of the star.

Finally, we have used a representative model of HD-174936 to study if the star can excite, at the same time, the huge number of pulsational modes observed in $\delta$ Scuti stars from space (Poretti et al. 2009; Moya & Rodríguez-López 2010).

2 Analysis of the data

The star was observed during the first short run of CoRoT. Around 27 days of very precise photometry at a sampling time of 32 s is the data base used for the frequency analysis presented here. The spectral window of the satellite observations is almost perfect (less than 5% of side lobes). A detailed explanation of the analysis of this star can be found in García Hernández (2009).

The time series was analysed using the prescriptions given in Reegen (2007) and Lenz & Breger (2005). If we adopt the rather conservative criteria to stop the search for frequencies when the significance level is 10 (see Reegen 2007), then 422 frequencies are found. The obtained power spectrum is shown in Fig. 1. More peaks could be extracted because of the high significance of the corresponding fitting, but the prewhitening procedure becomes exponential.

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and we can not be sure whether we are filtering real frequencies from the object or any other artifact due to the instrument or intrinsic to the mathematical technique (Poretti et al. 2009).

Recently, Kallinger & Matthews (2010) have suggested that the lowest amplitude modes observed in δ Scuti stars from space can be due to surface granulation, and as a consequence only some tenths of modes with the highest amplitude would be real pulsation modes.

Mode identification, mainly for δ Scuti stars, is one of the bottle necks for the progress in asteroseismology. Individual mode identification using white light, as supplied by the CoRoT photometer, is not possible. However, statistical properties of the full stellar oscillation spectrum provide us with information related with global properties of the stellar model. In particular, the classical large ($\Delta \nu = \nu_{n+1,\ell} - \nu_{n,\ell}$) and small ($\delta \nu = \nu_{n,\ell} - \nu_{n-1,\ell+2}$) separations, frequently used in the solar context, could also be applied to this star. However, some caution has to be taken, because for δ Scuti main sequence stars, the excited oscillation modes are not expected to be in the asymptotic regime.

In order to search for periodic patterns in the frequency set, we consider them as a set of Dirac’s $\delta$’s of equal amplitude, centred at each frequency value. If the frequencies were equally spaced, then we will have a Dirac comb with Fourier transform being another Dirac comb with periodic inverse values and multiples of the original spacing. That means that if we have a given periodicity in the frequency set of $\delta f$, then we will have a peak in the Fourier Transform of $\delta f$ and its sub-multiples, i.e. $\delta f/n$ with $n = 1, 2, 3, ...$. Although Handler et al. (2000) uses a similar technique, they do not give any details of the method.

We started this analysis assuming the hypothesis that, selecting a subset with the highest peaks of the entire frequency set, we are actually considering mainly the modes of the lowest $\ell$ values. The visibility of the modes decreases approximately as $\ell^{-2.5}$ or $\ell^{-3.5}$, depending whether the $\ell$ degree is odd or even (Dziembowski 1977). Although some authors have identified higher $\ell$ values in the frequency spectrum of a star observed as a whole (Daszyńska-Daszkiewicz et al. 2006), in general, the selection of the highest amplitude modes ensures that most of the modes have $\ell < 4$, enough to obtain general properties with an statistical study.

Therefore, we use the hypothesis that, selecting a subset of frequencies with the highest amplitudes, we select mainly the frequencies of lowest $\ell$ values. To probe that, we have constructed several subsets with an arbitrary number of frequencies taking always the highest peaks and applied the Fourier transform to them. We have applied the method to HD 174936: Fig. 2 (left panel) shows that the greater the number of frequencies in the subset, the lower the peaks. Clearly, when we select 50 frequencies a periodic pattern can be recognised, because of the simultaneous appearance of peaks at 25.8, 13, 8, 6.5 and 4.9 $\mu$Hz. This indicates that we probably have a Dirac comb of 25.8 $\mu$Hz, which is the signature of a large separation of around 52 $\mu$Hz. We adopted a range of values of [45,60] $\mu$Hz to be representative of this large separation. Other peaks surrounding the main one at 25.8 $\mu$Hz (and sub-multiples) may be produced by the quasi-periodic “sampling” exhibited by the frequency set. The rest of shorter periodicities are less clear to explain, because the periodic pattern of small separations and g-modes are of the same order.

3 The modelling

The stellar models were computed with the evolutionary code CESAM following the recommendations of the ESTA group studies (Lebreton et al. 2008; Moya et al. 2008). The physics used is that suitable for this stellar type, and used in numerous studies (Casas et al. 2006; Casas et al. 2009; García Hernández et al. 2009).

Theoretical oscillation spectra were computed for the equilibrium models using the GRAnada oscillation COde provides diagnostics on the instability and non-adiabatic observables. In this code the non-adiabatic pulsation equations are solved following Unno et al. (1989).

4 Constraining the seismic models of HD 174936

HD 174936 has a $T_{\text{eff}} = 8000 \pm 200$ K, a log $g = 4.08 \pm 0.2$ and a $[Fe/H] = -0.32 \pm 0.2$. These values are taken from “CorotSky Database” (Charpinet et al. 2006). The rotational velocity ($v \sin i = 169.7$ km/s) has been determined from high-resolution spectroscopy. It was obtained in the framework of the mission preparation and it is available at the GAUDI archive (Solano et al. 2005). It has been shown that rapid rotation should be considered when calculating the stellar physical parameters from photometry. Following Michel et al. (1998); Suárez et al. (2002), and considering the absence of additional information on the inclination angle of the star, uncertainties in the HR-Diagram box of 200 K in $T_{\text{eff}}$ and ~ 0.2 dex in log $g$ are adopted.

We constructed models in the HR diagram corresponding to the four corners and the center of the uncertainty
Fig. 2  Left panel: Power spectrum for various subsets of frequencies, selected by amplitudes. The solid line represents the power spectrum when the highest 50 frequencies are selected; the dashed line correspond to the highest 100 frequencies; the dotted line to 250; and the dot-dashed line to all of them. It can be seen how the peaks disappear as the number of frequencies increases. The peak corresponding to the large separation (25.8 $\mu$Hz) and its sub-multiples are labelled. Right panel: Power spectrum of the theoretical frequencies calculated for a representative model of HD 174936. Only modes with frequencies in the range [100,700] and with $\ell = 0 - 3$ have been taken into account. The peak at 26.61 $\mu$Hz (and sub-multiples) is the half of the possible large separation obtained using these modes.

Fig. 3  Frequency versus growth rate and amplitude. Growth rate (solid line, left axis) shows the stability range ($< 0$) and one vertical line of the amplitude height for each frequency is represented (right axis).

Fig. 4  HR diagram showing the observational photometric uncertainty box (the large one) for HD 174936. The small box is that obtained when the asteroseismological constraints are used. Filled stars correspond to models representative of the star.

Box, with the observed metallicity and its errors (see Fig. 4). $\alpha_{MLT} = 0.5$ and overshooting 0.2. Then, for each equilibrium model we computed the corresponding adiabatic and non-adiabatic oscillations, and from the whole set of models, we selected those fitting the average large separation defined in Sect. 2. Finally, from the remaining subset of models we selected those predicting unstable the observed frequencies with the largest amplitudes. The properties of the resulting subset of models are then discussed and analysed.

Rapid rotation makes the seismic interpretation of the oscillation spectra of $\delta$ Scuti stars difficult, specially regarding the mode identification. For very fast rotators, it has been shown (Lignieres et al. 2006) that the rotation-pulsation interaction cannot be described using a perturbation theory. The non-perturbative theory for the oscillations computation applied to polytropes predict that both small and large spacings are affected by rotation. Following Reese et al. (2008) we estimate (within the range [250, 450] $\mu$Hz)

such an effect on the large separation is about 6 $\mu$Hz for the models considered in this work. This value remains within the uncertainties in the determination of the large separation given in Sect. 2, allowing us to use non-rotating models to restrict the space of valid models as described in the previous section. This allows us to use non-rotating models to restrict the space of valid models as described in the previous section.

Equilibrium non-rotating models were computed in the manner described in Sect. Only models showing large separations within the range of [45, 60] were considered.

1 Predictions obtained for a $n=3$ polytropic model.
For the δ Scuti stars, the range of the observed frequencies is far from the asymptotic regime and a clear periodicity is not expected. However, as it is demonstrated in Sect. 2, a pattern, identifiable as a large separation, can be indeed found in the data (Fig. 2 left panel).

We thus searched for similar regularities in the models (see Fig. 2 right panel). We found that the peak at 26.61 μHz (and sub-multiples) is the half of the probable large spacing, allowing us to discard the models that have not reached the observed large separation. Note that only modes with frequencies in the range [100,700] and with \( \ell = 0 - 3 \) were taken into account. Additional constraints come from the stability analysis of the modes, as it is illustrated in Fig. 3.

Following an iterative method, the original uncertainty box can be reduced drastically (Fig. 4). The preliminary result obtained is that we have the following ranges in age, mass and radius of HD 174936: age \([788.5, 1705.9]\) Myr, mass \([1.47, 2.05]\) \(M_\odot\) and radius \([1.61, 2.05]\) \(R_\odot\). This implies a drastic decrease of the mass uncertainty from a 54% (without asteroseismology) to a 23% (with asteroseismology). A rough estimate of the rotation effects on these seismic models predicts a variation of 0.03 \(M_\odot\) in mass, which is lower than the accuracy here obtained.

Finally, using a representative model for this star, we have studied if the star can have, from an energetic point of view, all these modes exited at the same time, with the result that all these modes need a very small amount of stellar energy (Moya & Rodríguez-López 2010).

5 Conclusions

We have performed an asteroseismic analysis of the δ Scuti star HD 174936, observed by CoRoT during its first short run, SRe01. The very precise space photometry provides the possibility of dealing with a significantly large number of frequencies (around 400), for which we demonstrated that the star has enough energy to excite. However, Kallinger & Matthews (2010) have recently suggested that most of the lowest amplitude frequencies can be a consequence of surface granulation.

We have combined the classical seismic analysis with the use of statistical properties of the modes. In particular, we have searched for periodic patterns in the frequency spectrum of HD 174936 in order to find new observational constraints. We have found a peak distribution in the frequency spectrum that seems to correspond with a large separation and to predict unstable the observed modes. These restrictions yield a range of models with \([7801, 8192]\) K in temperature and \([4.07, 4.19]\) in \(\log g\), which corresponds to a range of \([1.47, 1.82]\) \(M_\odot\) in mass, \([788.5, 1705.9]\) Myr in age and \([1.61, 2.05]\) \(R_\odot\) in radius.

Acknowledgements. A.G.H. and R.G. acknowledge support from the Spanish “Plan Nacional del Espacio” under project ESP2007-65480-C02-01. A.G.H. acknowledges support from a “FPI” contract of the Spanish Ministry of Science and Innovation. CRL acknowledges an Ángeles Alvarín contract under Xunta de Galicia. JCS acknowledges support from the “Instituto de Astrofísica de Andalucía (CSIC)” by an “Excellence Project post-doctoral fellowship” financed by the Spanish “Conjerania de Innovación, Ciencia y Empresa de la Junta de Andalucía” under project “FQM4156-2008”.

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