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Asteroseismology of δ Scuti Stars: Problems and Prospects

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Abstract. We briefly outline the state-of-the-art seismology of δ Scuti stars from a theoretical point of view: why is it so difficult a task? The recent theoretical advances in the field that these difficulties have influenced are also discussed.

Key words. Oscillations—δ Scuti stars—stars: main and pre-main sequence stars.

1. Introduction

This review is intended for students and readers who are unfamiliar with δ Scuti stars. For more detailed and specific reviews on this topic, we refer to Dziembowski (1990); Goupil & Talon (2002); Pamyatnykh (2003); Kurtz (2003); Poretti *et al*. (2003); Breger *et al*. (2004).

Section 2 defines what is meant here by a δ Scuti star. Section 3 explains the main problems which are responsible for the fact that the seismology of δ Scuti stars has not yet held its promises. Section 4 presents some theoretical advances which can help to overcome some of the above difficulties. Section 5 introduces a field which is rapidly developing: seismology of oscillating pre-main sequence (PMS) stars which are located roughly at the same location in the HR diagram but are moving on their way towards the main sequence instead of evolving on or off the main sequence (reviews Catala 2003; Marconi & Palla 2004).

2. What is a δ Scuti star?

δ Scuti stars are intrinsically pulsating stars of spectral type A–F, with masses ranging roughly between 1.5 and 2.5 $M_\odot$. They evolve on or near the main sequence in the HR diagram and cross the so-called classical (or Cepheid) instability strip.

2.1 *Structure and evolution*

The classical δ Scuti stars lie on the main sequence where they burn their central hydrogen. These stars have a convective core which recedes with time leaving behind a chemical gradient. The temperature gradient is so large that the nuclear burning core is convective. Above the convective radius, the medium is convectively stable and the fluid elements crossing this radius are braked by buoyancy but still have some momentum and they overshoot in the radiative region. The overshoot region undergoes chemical mixing with the underlying H depleted convective layers and this lengthens the MS lifetime of the star. The amount of overshoot (extension of convective motions penetrating into the convectively stable region above) is not known and this is one piece of information which we expect to obtain from the study of such stars as it influences the evolution, the age of such a star, affects the mass-luminosity relation for postMS and evolved stars, etc. In the outer region, because of the large opacity, a very thin convective region exists. There the excitation of the oscillations takes place. For the coolest stars, this is also the region for the main damping process: the interaction turbulent convection–pulsation which can thereby be studied. In-between the energy is transported by radiation.

When the star evolves on the MS, its effective temperature decreases. The outer convective region extends deeper inside the star. On the other hand, as the amount of burning material decreases, the convective core gets smaller and smaller.

Some figures for a typical case can fix ideas: for a $1.7\,M_\odot$ MS star with 86% central hydrogen left, the inner convective core has a radius $r_c = 0.12R_* = 136.5$ Mm for a stellar radius $R_* = 1.63R_\odot$. The convective core can be more or less extended depending on the assumed amount of overshoot. The bottom of the upper convective region is found at the radius $r_b = 0.991R_* = 1124$ Mm.

For an older (*i.e.*, cooler) star (14% central hydrogen left, $R_* = 2.84R_\odot$), the convective core has receded ($r_c = 0.05R_* = 99$ Mm) while the upper convective region has extended downward ($r_b = 0.915R_* = 1878$ Mm).

We also encounter δ Scuti stars when they have exhausted their hydrogen and have just moved off the main sequence. Then they have an inert isothermal He core, above which hydrogen burns in a shell.

As a third possibility, stars crossing the instability strip in the δ Scuti domain can be very young stars approaching the Zero Main Sequence (ZAMS). The inner structure of a PMS star crossing the instability strip on its way to the ZAMS, differs from that of an MS star as it does not yet burn hydrogen. The central regions then are radiative. The star lives on its gravitational energy. The outer layers remain very similar to that of an MS δ Scuti star at the same location in the HR diagram, that is, with the same effective temperature and luminosity.

This global and relatively simple picture of the structure of a δ Scuti star is in reality complicated by the fact that these stars are generally fast rotators. Measurements of the surface projected velocities $v \sin i$ show that it can reach values as large as 200 km/s (thus roughly corresponding to a ratio of the centrifugal acceleration to the gravity up to 30–50%) (Royer *et al.* 2002a, b). At these rotational velocities, the centrifugal force distorts quite significantly the star which is no longer spherically symmetric. Theory tells us that rotation generates instabilities which cause both mixing of the chemical elements and transport of angular momentum in the radiative region which in turn affects the rotation profile. How fast is the convective core rotating? How does the rotation–convective interaction affect the structure of the core? Heavy 3D hydrodynamical calculations have recently simulated a rotating convective core for an A-type star with a typical $2\ M_\odot$ and a rotation equal to the solar rotation which is still rather slow for this type of star (Browning *et al.* 2004). One important result of interest here is that the convective core is prolate, *i.e.*, elongated towards the poles but the overshoot region keeps a spherical symmetry. The amount of overshoot is found to amount to a few tenths of the pressure scale height which is the expected order of magnitude. More importantly, the overshooting extension depends on the rotation rate and therefore must not be expected to be the same for different types of stars and even from one star to another. It is of course important to have some means of testing such numerical results. The best way, theoretically speaking, is seismology as these stars fortunately oscillate. Hence the idea is to obtain precise seismic information about hydrodynamical processes that take place below the emitting surface, even deep inside the star in order to test the modelling of physical processes which have more general applications and can be applied to other types of stars, namely transport processes: overshoot, time dependent convection, rotation interaction with oscillation and with convection.

2.2 *Oscillations*

δ Scuti stars are pulsating with periods of a few hours. The mechanism which excites the observed modes is similar to that of a thermal machine or heat engine in that, energy is stored in some peculiar region of the star at compression. Hence the (PdV) work done is positive and this mechanical energy feeds the oscillation. The mode is linearly unstable if this driving overcomes the (radiative) damping. Energy storage at the proper phase is performed through an opacity mechanism (kappa mechanisms, see Shibahashi, these proc.). For δ Scuti stars, the main driving operates in the second helium ionisation region. The kappa mechanism excites low (photometrically detected) as well as intermediate (detected through line profile variations) degrees of l. Radial and nonradial modes with low radial order n have their periods of the same order as the local thermal time scale in the driving region and therefore are efficiently excited. In this low frequency regime, the nature of the excited modes can be complicated: either pure p-modes (pressure fluctuation propagation), or pure g (buoyancy restoring force) or mixed p- and g-modes (modes in avoided crossing or *nearly kissing* modes, see Shibahashi (these proc.)) These latter modes are p-modes in the outer region and g-modes in the inner region; they are then good candidates for probing very inner stellar regions.

However one must be aware that seismology of stars other than the sun cannot be handled the same way. We know much less about these stars: uncertainties in stellar parameters (mass, age, chemical composition) – which are needed to model the structure of the star in the first step of an iterative process – are in most cases too large. Therefore for stars, one must determine all these unknowns together with extracting the information about the physics of the star. This would still be quite easy if we knew for each detected frequency what the associated mode is: and what the degree l, the radial order n and the azimuthal order m are. It is indeed crucial to know which modes we observe as we have to compare with frequencies of the same modes computed from the to-be-probed stellar models. We also need to know the nature of the oscillation mode which we detect and which frequency we measure. In other words, we need to know the resonant cavity which the mode probes as well as its surface geometrical description. This latter one is usually represented by a spherical harmonic of given l, m as the spherical harmonics can define an orthonormal basis and form a very convenient representation of the stellar oscillation (as long as the star is not rotating too fast and in absence of other processes breaking the axisymmetry). These numbers, n, l, m also have to be determined in the iterative process.

This requires very high quality data, long observation runs, and if possible using different techniques in order to collect as much information as possible – seismic and nonseismic. Far much less ambitious than for the sun, what is now currently being attempted is building a *seismic model* by means of a *best model fitting* method, an optimized procedure which aims at building a model which fulfills all the collected observational constraints including the best fit to the observed oscillation frequencies (in the χ^2 sense). Of course, this model may not be unique but at least it bears some improvement compared to what was known before. In addition, masses, ages for all stars except for the sun, are not known with a high precision. Building seismic models can help to determine these parameters with some accuracy for a large number of stars, in view of statistical studies which are needed for instance, in chemical evolution of galaxies.

3. Seismology of δ Scuti stars: Not an easy task

Seismology of δ Scuti stars, although very promising, has not yet been very fruitful as it faces serious difficulties which will have to be overcome first. If one measures the frequencies, ν_{nlm}, with a high enough precision and if one identifies the associated n, l, m values, even if the stellar parameters are not well known (unlike the sun), the excited modes of δ Scuti stars are discriminant enough that their frequencies enable to determine these stellar parameters. The difficult part, however, is identification of the modes.

3.1 *Mode identification*

Oscillations of δ Scuti stars are not fully understood: all modes (at least the lowest l degrees) are theoretically expected to be (linearly) excited in a given frequency range but not all modes in this range are detected (see for instance, for the optimal case FG Vir (Breger *et al.* 2005)). Hence the question is: which ones are detected? As an illustration of the diversity of power spectra for δ Scuti and difficulties to interpret them, we can mention 3 stars:

- FG Vir which oscillates with a large number of modes; at least 19 frequencies a few modes seem to have been firmly identified (Breger *et al.* 2004). The star is a moderately fast rotator with $v \sin i = 80$ km/s.

  Based on this mode identification, the model fitting method shows that no stellar model can provide frequencies which match simultaneously all the observed frequencies (Breger *et al.* 1999; Daszynska-Daskiewicz *et al.* 2005).
- 1 Mon shows no more than 3 well determined frequencies; two have tentatively been identified (Balona *et al.* 2001).
- HR 6534 (friendly baptised Orianita) illustrates a case of a real rapidly rotating δ Scuti star. In such a case, perturbation theory in order to include the effect of rotation, even at 3rd order, to compute the frequencies can no longer apply (Suarez *et al.* 2005).

Mode identification usually proceeds in determining the degree l of the mode either by using near equidistance in the power spectra (large and small separation), using multicolour photometry (l degree) and line profile variations (m azimuthal order) and comparing observed and computed frequencies (radial order n). in the case of δ Scuti none of these methods are really easy to use. Indeed, the existence of nearly kissing modes in the observed frequency range, although most interesting for probing the inner structure, destroys the near equidistances as their frequencies do not follow the pure p-mode 'rules'. Modes are also missing and this also perturbs a possible near equidistant distribution. Direct comparison between theoretical and observed frequencies is difficult as several choices of stellar models are possible within the uncertainties in the stellar parameters (mass, effective temperature, luminosity, chemical composition, etc.). Hence the stellar model to be used is not unique.

As the outer layers of δ Scuti stars are convective, identification of the l degree through multicolor photometry has been found very dependent on the adopted convection treatment (for instance on the value of the mixing length in a classical mixing length description) (Balona & Evers 1999) and a reliable time dependent convection description is necessary.

For δ Scuti stars, fast rotation is also a serious problem in the mode identification framework as it not only destroys the equidistant rotational splitting between $m \neq 0$ modes but for the fastest cases, the description with one single spherical harmonic is no longer valid, hence attempting to identify one mode with one single (n, l, m) set of numbers no longer makes real sense.

3.2 *Linear excitation and damping: Time dependent convection*

The linear time dependence of the oscillation in a given mode, either displacement or temperature changes for instance, is expressed as $ae^{i(\omega t+\kappa t)}$ where ω is the pulsation frequency, κ the linear growth rate and a is a complex number representing the complex amplitude of the oscillation which is undertermined (or arbitrary) in a linear description.

While we understand the excitation mechanism for δ Scuti stars (kappa mechanism), and are able to predict roughly the blue side of the instability strip ($\kappa > 0$), the return to stability on the red edge ($\kappa < 0$) is attributed to an efficient interaction between convection and pulsation and has been quantified with some confidence only recently (see section 4.1).

3.3 *Finite amplitude oscillations*

When a mode is linearly unstable (excited), its amplitude $|a|$ can grow with time (roughly on a thermal time scale) from an infinitesimal perturbation to a finite value which, when larger than the detection threshold value, is the observed value. It would help the mode identification if one was able to estimate theoretically the amplitude of each mode and to determine whether each mode is detectable or not. Unfortunately, the saturation mechanism which stops the mode amplitude increase is not definitely identified in the case of δ Scuti stars.

The amplitude growth can be limited by a self saturation mechanism (energy of the mode is pumping back to the stellar thermal reservoir of the star) or by nonlinear resonant coupling with stable modes (energy transfer from unstable modes to stable ones). The self saturation mechanism seems to lead to too large amplitudes compared with the observations. Several types of resonant coupling are possible. The most probable resonant cases involve two mode or three resonant mode couplings but for a given unstable mode, many stable modes can be resonantly coupled to a given unstable mode and the estimation of its amplitude is of a statistical nature, *i.e.*, hardly predictable for individual modes (Dziembowski *et al.* 1988).

To proceed further in the understanding and modelling of the finite amplitude behavior, we need some observational hints and we must await the detection – from future (ground based and space) observations – of a much larger number of modes for each individual star as in the case of FG Vir (Breger *et al.* 2005).

4. Advances in theoretical modelling

4.1 *Time dependent convection*

As already mentioned earlier, the basic mechanism which makes the modes linearly unstable is the kappa mechanism. On the red side of the instability strip however, the growth rates are not properly computed when the convection is assumed frozen in. Indeed, the frozen-in approximation, which assumes that the convective flux does not vary over a pulsation period ($\delta F_c = 0$), is no longer valid because the eddy turn-over time scale is no longer much larger than the pulsation period. Frozen convection models do not predict the stabilization of the modes (growth rates κ negative) at the red edge of the instability strip. This stabilization (required because a red edge is observed) can only be obtained by time dependent convection. Modelling over the whole extension of the instability strip thus requires to include a time dependent convection (TDC) in the theoretical description.

Several approaches have been developed in order to provide a 1D description of 3D time dependent convection and its interaction with pulsation. They differ in their assumptions and simplifications (Houdek *et al.* 1999; Houdek 2000; Xiong *et al.* 1997; Xiong & Deng 2001; Dupret *et al.* 2004). As a consequence, the temperature for the red edge of the fundamental radial mode for instance is not quite exactly the same depending on the adopted description, one obtains for instance T_{RE} (Xiong & Deng 2001) $<$ T_{RE} (Dupret *et al.* 2004) $<$ T_{RE} (Houdek 2000).

Nevertheless, these approaches agree on some issues such as the following:

- Main driving and damping always occur around the second ionization zone of H_e, because the periods are of the same order as the thermal time-scale in this region. Therefore, the bottom of the convective region in the outer layers must reach down the H_e^{++} region for damping by convection to be efficient in δ Scuti stars ($|\delta F_c| > |\delta F_{\rm rad}|$). This implies a strong dependence of the red edge location on the effective temperature and on the mixing-length parameter α (related to the convective zone size).
- On the cool side of the instability strip and at the bottom of the convective envelope $\delta F_{\rm rad}$ drops outward rapidly. In the frozen convection description, this implies that energy is blocked at the hot phase of pulsation, which produces a positive PdV work (see in Fig. 1 the increase of the work for the FC case near the convection zone bottom). In the TDC case, δF_c is sufficient to produce a negative work that counterbalances this effect, leading to the stabilization of the modes (see in Fig. 1 the work due to δF_c (W_{Fc})) .
- Several mechanisms contribute to the driving and damping. The work integral can be split into $W_{\rm tot} = W_{FR} + W_{Fc} + W_{pt} + W_{Ect} + W_{\rm visc}$ where W_{FR} is the contribution to the work due to the radiative flux variations, W_{Fc} comes from the convective

flux variations, W_{pt} comes from the turbulent pressure variations, W_{Ect} comes from turbulent kinetic energy dissipation variations and $W_{\rm visc}$ from turbulent viscous stress variations.

Hence the red edge is strongly dependent on the mixing length α, on the metallicity, Z, and the model atmosphere used in the computation. In turn, these quantities can be thereby determined or constrained by the observations.

Using the description of Dupret *et al.* (2004) for instance, a stellar model with a 1.8 –2 $M_\odot$ mass with a temperature of about 6500 K sees its modes between g_3 up to p_7 – and beyond – unstable in the frozen convection approximation whereas in the TDC approximation all these modes are stable and such a star is no longer a pulsating star. Figure 1 shows the impact of including the interaction between convection and oscillation on the sign of the work integral.

A consensus is yet to be obtained. For instance Houdek (2000) finds that the perturbation of the turbulent pressure δ_{pt} is the main stabilizing agent; Xu *et al.* (2002) find instead that δ_{pt} rather contributes to excitation; Dupret *et al.* (2004, 2005a) find that W_{Ect} balances W_{pt} hence $W_{\rm tot} \simeq W_{Fc} + W_{FR}$.

4.2 *Mode identification*

We only consider here photometric methods for the identification of the degree l (see also Handler, these proc.). Photometric variations in a non-radial pulsator depend on various contributions. One comes from the effect of effective temperature variations on the flux variations; a gravity term describes the effective gravity variations (including the acceleration of the comoving frame) on the flux variations; and finally a geometrical term measuring the variation of the visible surface of the star. This last term is very important, as it is proportional to $(1 - l)(l + 2)$. It thus allows the identification

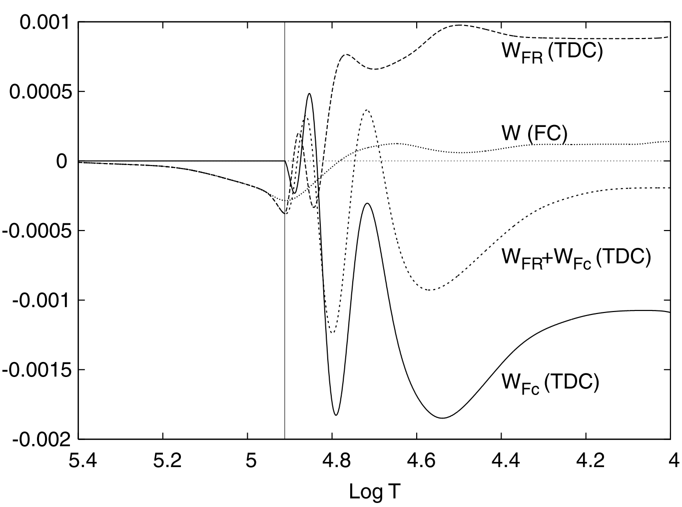

Figure 1. Different physical components of the work integral as a function of $\log T$, obtained with FC and TDC treatment for the radial p_3 mode of a model with 1.8 $M_\odot$ and $T_{\rm eff} = 6680$ K. W_{FR} (resp. W_{Fc}) is the contribution to the work due to the radiative flux (resp. convective flux variations). The vertical line is the base of the convective envelope. On the instability strip red side, the time variation of the convective flux plays a significant role in all the convective envelopes.

of l. The usual method for this identification is based on observations in multicolour photometry. We can write: $m_\lambda = A_\lambda \cos(\omega t + \varphi_\lambda)$ where λ represents the wavelength or more practically the observed wavelength passband. The weights of the different physical terms (see above) depend on the wavelength passbands. Therefore, comparison between the theoretical and observed amplitude ratios $A_{\lambda_1}/A_{\lambda_2}$ and phase differences $\phi_{\lambda_2} - \phi_{\lambda_1}$ makes the identification of l possible (for a review see Garrido 2000). However, a careful, physical and numerical, description of the atmosphere (monochromatic flux and limb-darkening derivatives with respect to temperature and gravity) is required (Garrido 2000; Dupret *et al.* 2003; Barban *et al.* 2003). Also, the theoretical predictions are very sensitive to the amplitude and phase of effective temperature variations, hence a proper description of the oscillation energetics in the superficial layers is required (Dupret *et al.* 2003). For δ Scuti stars, time-dependent convection models are necessary (Dupret *et al.* 2005b). In turn, this enables to probe inefficient convection treatments in subphotospheric layers as oscillating quantities which are strongly dependent on convection can be directly determined from observations (Moya *et al.* 2004; Daszynska-Daskiewicz *et al.* 2005).

Rotation can also perturb on a significant level the mode identification as was pointed out by Soufi *et al.* (1998) and shown quantitatively by Daszynska-Daskiewicz *et al.* (2002).

4.3 *Rotation*

Fast rotation by distorting the structure of the star affects its oscillations in various ways. These effects are no longer negligible whenever the rotational velocity v reaches $\sim$ 100 km/s–200 km/s for the excited δ Scuti-like oscillation modes. Interaction between rotation and pulsation has therefore been included to compute the oscillation frequencies corrected for rotation effets (Dziembowski & Goode 1992; Soufi *et al.* 1998; Goupil *et al.* 2000; Suarez *et al.* 2005; Karami *et al.* 2005) and linear growth rates (Lee & Baraffe 1995) using perturbation theory and/or simplifying approximations. These developments enable quantitative studies and are included in best model fitting methods. For the fastest stars, however, one will have to turn to nonperturbative treatments of the pulsation–rotation interaction which are being currently developed (Rieutord & Valderatto 1997; Lignières *et al.* 2001).

5. Pre-main sequence δ Scuti stars

Pre-main sequence A–F pulsating stars should be precursors of δ Scuti stars or roAp stars. It is of great interest to determine the nature of their oscillations and their internal properties, particularly their rotation profiles as we could then obtain constraints about the evolution of the internal rotation from well before arrival on the main sequence.

Because of their relatively simple inner structure, no nearly kissing modes are expected in the frequency range where observed modes are detected. Hence one expects simple patterns (near equidistance) in the power spectra of these stars at least for the $m = 0$ modes. However, their usually fast rotation certainly complicates the structure of the frequency distribution in their power spectra.

Observationally, although the first claim of the observation of a variable PMS δ Scuti star goes back to 1972 (Breger 1972), it was not until 1995 after the detection of the variability of HR 5999 (Kurtz & Marang 1995) that the field really developed.

More than a dozen such stars are now known (see for a review Catala 2003; Marconi & Palla 2004).

We illustrate this topic with two interesting cases:

5.1 *An eclipsing double line spectroscopic binary PMS system: RS Cha*

The eclipsing double line spectroscopic binary system RS Cha is known as a PMS system since 2000 (Mamajek *et al.* 2000). As the orbit is known, masses, radii for both components are known with high precision. The two stars are of similar masses slightly larger than $1.8\,M_\odot$. Inclination angle and $v \sin i$ are well determined. In addition, photometric determinations provide the effective temperatures ($T_{\rm eff}$) and luminosities (L) of both stars (A, B). Spectroscopic data at SAAO have been analysed and yield the metallicity $Z = 0.028 \pm 0.004$ (Alecian *et al.* 2005).

With the knowledge of these stellar parameters, it is found that it is possible to model simultaneously both stars at same age. Hence to obtain more stringent constraints on the physical description of this type of stars, a better determination of $T_{\rm eff}$ is necessary on one side and more information about the pulsations of both stars. From residual orbital radial velocities obtained from the SAAO 2004 data, it is definitely confirmed that both stars oscillate (Alecian *et al.* 2005). The data quality unfortunately is not good enough to provide secure periods yet.

5.2 *A binary PMS system HD 104237*

We now turn to another binary PMS star system: HD 104237 (friendly baptised Christianita). The A component appears to be a δ Scuti type pulsator showing multiperiodic pulsations (5 frequencies + 3 possible) (Donati *et al.* 1997; Kurtz & Müller 1999; Böhm *et al.* 2004).

From the orbit, the mass ratio is known with some precision. A photometric determination for the primary gives $T_{\rm eff} \sim 8500\,$K; $\log L/L_\odot \sim 1.55$ although other determinations show that these values are not secure. Nevertheless using these values for the purpose of illustration, Fig. 2 shows a comparison between the observed frequencies in a power spectrum and the computed frequencies for a stellar model satisfying these constraints (see Samadi *et al.*, these proc.). Computed frequencies for all modes with $l = 0$ to $l = 3$ frequencies in the same frequency range as in observations, are included.

When no rotation effect is included, the computed power spectrum displays a simpler pattern than for classical (MS, off MS) δ Scuti stars. The excited modes for that particular case are of rather high radial order, definitely non-radial modes. They display a near equidistant pattern which should provide a determination of the large separation. Not all these computed modes are detected however. Besides the pattern is more complicated when one takes into account the m-splitting due to rotation. Here we have taken a typical rotation $v = 50\,$km/s compatible with the observed $v \sin i = 12 \pm 2\,$km/s.

This example shows that one faces the same problems as for MS δ Scuti stars although less severely. To go further, one nevertheless needs mode identification; a determination of the rotation period would definitely help. The next step is a stability analysis in order to provide additional constraints on the modelling of this PMS δ Scuti like star.

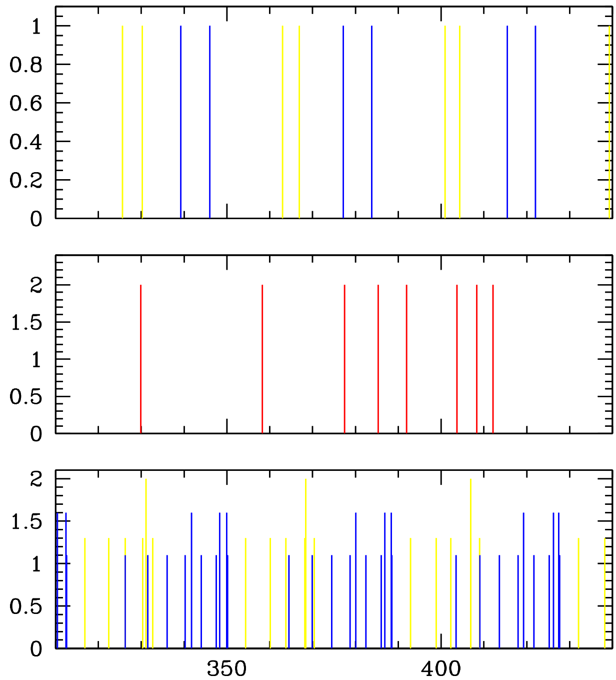

Figure 2. Top: Computed power spectrum with $l = 0 - 3$, $m = 0$ mode frequencies (arbitrary amplitudes); no rotation effect included. Middle: Observed frequencies for HD 104237 (arbitrary amplitudes). Bottom: same as top but with $m \neq 0$ modes included (represented by smaller amplitudes) with a chosen rotation velocity $v = 50$ km/s.

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