NON-ADIABATIC PULSATIONS IN δ SCUTI STARS

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Abstract

For δ Scuti stars, phase differences and amplitude ratios between the relative effective temperature variation and the relative radial displacement can be derived from multicolor photometric observations. The same quantities can be also calculated from theoretical non-adiabatic pulsation models. We present here these theoretical results, which indicate that non-adiabatic quantities depend on the mixing length parameter α used to treat the convection in the standard Mixing Length Theory (MLT). This dependence can be used to test and to constrain, through multicolor observations, the way MLT describes convection in the outermost layers of the star.

We will use the equilibrium models provided by the CESAM evolutionary code. The pulsational observables are calculated by using a non-adiabatic pulsation code developed by R. Garrido and A. Moya. In the evolutionary and pulsation codes, a complete reconstruction of the non-grey atmosphere (Kurucz models) is included. The interaction between pulsation and atmosphere, as described by Dupret et al. (2002), is also included in the code.

Key words: Stars: δ Scuti – Stars: atmosphere – stars: oscillations

1. Introduction

Asteroseismology has been developed in recent years as an efficient tool to investigate stellar interiors and evolution. The main observational inputs of asteroseismology are the pulsation periods. However, for non solar like oscillations (for example in δ Scuti stars) these periods are not sufficient to constrain the theoretical predictions. Without additional information, it is not possible to identify the modes, which is the first step of any seismic analysis. The main origin of this difficulty is that their pulsation modes are not in the asymptotic regime and they may be affected by the "avoided crossing" phenomenon. Rotation and eventually coupling also destroy any regular pattern.

From an observational point of view, one of the ways to obtain more information from photometric observations is to study the multicolor flux variations. The linear approximation to non radial flux variations of a pulsating star was first derived by Dziembowski (1977b), and then reformulated by Balona & Stobie (1979a,b) and by Watson (1988). In the above studies and in Garrido et al. (1990), that formula was used to discriminate between the different spherical orders l of some pulsating stars. Several attempts to fit real observations, FG Vir (Breger et al. 1999a), BI CMi (Breger et al. 2002), 4 CVn (Breger et al. 1999b), V1162 (Arentoft et al. 2001) and some other δ Scuti stars (Garrido 2000) have shown that the method can be useful at least for low rotational velocities (see Daszyńska-Daszkiewicz et al. 2002 for fast rotators).

Most of the theoretical and numerical pulsation models have been developed in the adiabatic approximation (Christensen-Dalsgaard 1982; Tran & Leon 1995). However, the pulsation is always highly non-adiabatic in the surface layers of the star, where the thermal relaxation time is of the same order as, or even lower than the pulsation period. Therefore, the use of a non-adiabatic description including the entire atmosphere is required to determine accurately the eigenfunctions in these layers, and to relate them with multicolor photometric observables. Nevertheless, this description does not change significantly the eigenfrequencies of the system.

Different authors (Dziembowski 1977a; Saio & Cox 1980; Pesnell 1990; Townsend 2002) have developed codes and performed calculations of non-adiabatic stellar pulsations without a complete description of the pulsation-atmosphere interaction. In these approaches the photometric edge is always treated as a boundary condition.

Recently, (Dupret et al. 2002) have derived a non-adiabatic pulsation treatment of the atmosphere. The theoretical predictions in this approach can be directly connected with the photometric observations in a more extended framework than by merely comparing the periods.

More precisely, theoretical and observed amplitude ratios and phase differences, as observed in different color photometric bands, can be compared. Garrido et al. (1990) showed that, for low l values, the wavelength dependence of the limb darkening integrals is very weak. Therefore, combinations of some colors – at least three distributed in as wide as possible a range of wavelengths – give consistent values for the phase lag ϕ^T and R, a parameter which measures departures from adiabatic conditions, as was defined by Watson (1988). Confrontations between non-adiabatic predictions and multicolor photometric observations were also performed by Cugier et al. (1994) for

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β Cephei stars, Balona & Evers (1999) for δ Scuti stars and Townsend (2002) for Slowly Pulsating B (SPB) stars, but without a detailed non-adiabatic pulsation treatment in the atmosphere. Dupret et al. (2003) have reformulated the photometric magnitude variations, permitting a dependence on quantities directly obtained from theoretical non-adiabatic calculations, including the entire atmosphere, and applied it to the study of β Cephei and SPB stars.

In this paper, the approach of Dupret et al. (2002, 2003) is applied to δ Scuti stars. The non-adiabatic observables can be directly related with the characteristics of the thin convective envelope, described by the Mixing Length Theory (MLT) and parameterized by α (the mean path of a convective element being α times the local pressure scale height). Therefore, this parameter can be constrained by searching for the best fit between the theoretical and observed photometric amplitude ratios and phase differences between different color photometric bands. We study here this dependence with α.

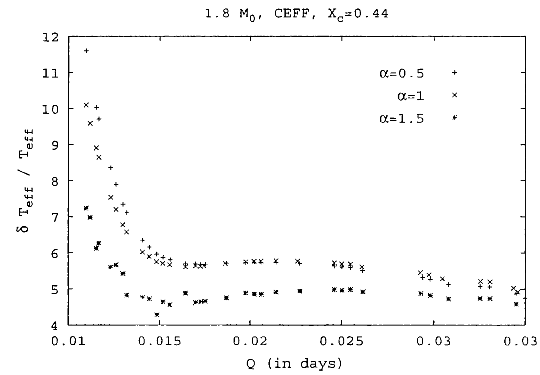

Figure 1. The non-adiabatic quantity $|\delta T_{\rm eff}/T_{\rm eff}|$ as a function of the pulsation constant Q (in days) for different modes with spherical degrees $l = 0, 1, 2, 3$ for models with 1.8 $M_\odot$, $X_c = 0.44$, and different values for the MLT parameter: $\alpha = 0.5, 1, 1.5$.

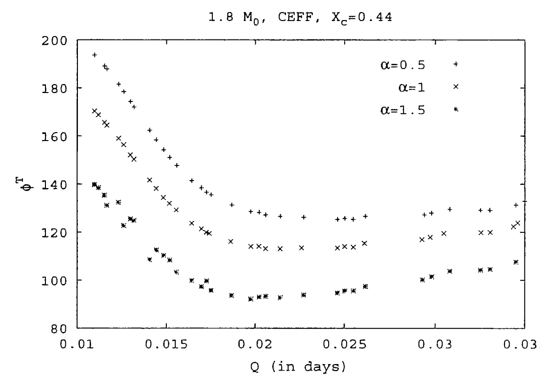

Figure 2. The non-adiabatic quantity ϕ^T (phase lag) as a function of the pulsation constant Q (in days) for different modes with spherical degrees $l = 0, 1, 2, 3$ for models with 1.8 $M_\odot$, $X_c = 0.44$, and different values for the MLT parameter: $\alpha = 0.5, 1, 1.5$. Note the sensitivity of this non-adiabatic results with respect to α.

2. Theoretical models and resolution algorithm

To solve the non-adiabatic oscillations of a δ Scuti star including the atmosphere, the total structure of the star is divided in two parts, interior and atmosphere.

Our equilibrium stellar models are computed using the CESAM code (Morel 1997). In this code, the stellar atmosphere is reconstructed from a given Rosseland optical depth (the connecting layer) until the end of the star, using the Kurucz equilibrium models (Kurucz 1993).

The non-adiabatic pulsational equations in the stellar interior have been derived following closely Unno et al. (1989). Two variables have been changed as compared to those used by Unno et al. (1989), in such a way that the interior and atmosphere pulsation equations link in a simple way (Moya et al. 2003).

The pulsation equations in the complete atmosphere are solved following the approach described in Dupret et al. (2002).

In order to solve the complete set of equations, our code begins by computing, for given n and l values, the adiabatic solution, and then use it as initial value for the non-adiabatic computations. The non-adiabatic calculations allow us to derive ϕ^T, $|\delta T_{\rm eff}/T_{\rm eff}|$ and $|\delta g_e/g_e|$ which are directly related to the photometric color variations.

3. Results

In Figs. 1 and 2, non-adiabatic results obtained for models with 1.8 $M_\odot$ and $X_c = 0.44$ and with different values for the MLT parameter $\alpha = 0.5, 1, 1.5$ are compared. The non-adiabatic quantities $|\delta T_{\rm eff}/T_{\rm eff}|$ and ϕ^T are significantly affected by the value of α, especially the phase lag ϕ^T.

To explain the sensitivity of the non-adiabatic results to α, it is convenient to introduce the convective efficiency. In the MLT, the convective efficiency is defined as (Cox 1980):

$$\Gamma = \left[\frac{4}{9}\left(\frac{c_p \kappa p \rho c_s \alpha^2}{9\sigma_{\rm steff} T^3 g \sqrt{2\Gamma_1}}\right)^2 (\nabla_{rad} - \nabla)\right]^{\frac{1}{3}} \quad (1)$$

The dependency of Γ is illustrated in Fig. (3).

Phase-lags originate in the equation of energy conservation through the introduction of explicitly imaginary parts. For a radial mode, and freezing the convective luminosity, this equation has the form:

$$i\sigma T \delta S = \delta\epsilon_N - \frac{d\delta L_R}{dM_r} \quad (2)$$

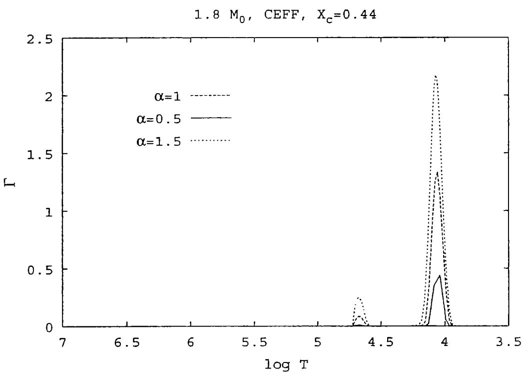

Figure 3. Convective efficiency as a function of the logarithm of temperature, for a $1.8\ M_\odot$ *model with* $X_c = 0.44$*, and three different values of the MLT parameter:* $\alpha = 0.5, 1, 1.5$*. Note the changes in the superficial convection zone when changing* α*.*

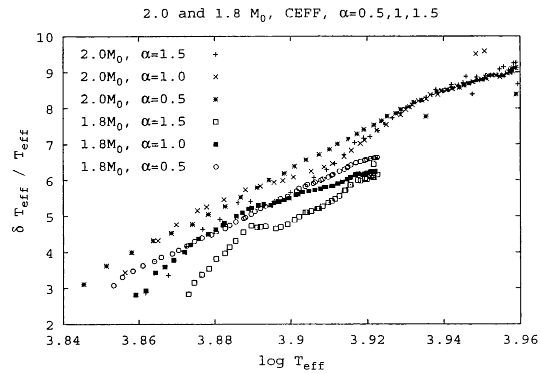

Figure 5. $|\delta \mathrm{T_{eff}}/\mathrm{T_{eff}}|$ *as a function of* $\log T_{eff}$ *for the fundamental radial mode in two complete tracks for* $2.0\ M_\odot$ *and* $1.8\ M_\odot$ *for three different values of the MLT parameter* $\alpha = 1.5, 1.0, 0.5$.

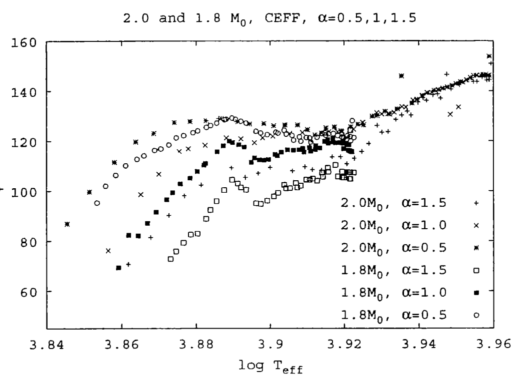

Figure 4. ϕ^T *as a function of* $\log T_{\rm eff}$ *for the fundamental radial mode in two complete tracks for* $2.0\ M_\odot$ *and* $1.8\ M_\odot$*, for three different values of the MLT parameter* $\alpha = 1.5, 1, 0.5$.

where M_r is the mass enclosed in a sphere of radius r, and

$$\frac{\delta L_R}{L_R} = -\frac{\delta\kappa}{\kappa} + 4\frac{\xi_r}{r} + 4\frac{\delta T}{T} + \frac{d\left(\frac{\delta T}{T}\right)/d\ln r}{d\ln T/d\ln r} \quad (3)$$

Phase-lags originate mainly from the interplay between the different terms of Eq. (3), which affect the right hand side of Eq. (2), when the thermal relaxation time is sufficiently small. A first phase-lag is introduced in the partial ionization zone of He II, giving rise to an opacity bump and a considerable decrease of the adiabatic exponents in this zone, which affect significantly the term $\delta\kappa/\kappa$. A second source of phase lag occurs in the surface convective zone (partial ionization zone of H I and He I). In this zone, changes of α affect essentially the gradient of temperature and the size of the convective zone, which in turn affect the phase-lag through the above equations.

If we plot the phase lag versus $\log T_{\rm eff}$ for the fundamental radial mode of two complete tracks of $2.0\ M_\odot$ and $1.8\ M_\odot$ stars for three different values of the MLT parameter $\alpha = 1.5$, 1.0 and 0.5, we obtain Fig. 4, where we can see how, when the stars are hot enough to have a negligible external convective zone, the values are independent of α (this happens only for the $2.0\ M_\odot$ models here presented). But for cooler models the convection becomes more efficient, giving different phase lags and relative effective temperature variations for similar effective temperatures, as shown previously in (Balona & Evers 1999).

Plotting $|\delta \mathrm{T_{eff}}/\mathrm{T_{eff}}|$ versus $\log T_{eff}$ for all these models, we obtain Fig. 5. Here we see that each track has each own curve for this observable. It is possible to distinguish the behaviour of these quantities independently of the mass of the model, being here just a function of the evolution phase and α.

Nevertheless, displaying the value of $|\delta \mathrm{T_{eff}}/\mathrm{T_{eff}}|$ as a function of the growth rate (see Pamyatnykh 2000 for a definition) and the integral of the convective efficiency (Fig. 6) only for the overstable modes of the tracks, we observe that is possible to distinguish the behaviour of these quantities independently of the mass of the model, being here just a function of the evolution phase and α. These non-adiabatic observables are distributed along different slices of different α's, independently of the mass observed.

4. Conclusion

We have developed a new non-adiabatic pulsation code using equilibrium models from CESAM. We have applied the code to the particular study of δ Scuti stars. This new non-adiabatic code devotes special care to the treatment of pulsation in the stellar atmosphere. Therefore the photospheric observables are now determined as a solution of

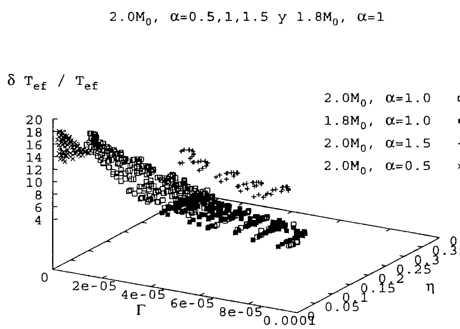

Figure 6. $|\delta T_{\rm eff}/T_{\rm eff}|$ *as a function of the growth rate and the integral of the convective efficiency for the overstable modes of the complete tracks for* 2.0 $M_\odot$ *models with* $\alpha = 1.5, 1.0, 0.5$ *and a track with mass* 1.8 $M_\odot$ *with* $\alpha = 1$.

a set of differential equations, which takes into account the pulsation-atmosphere interaction as described in Dupret et al. (2002). This non-adiabatic code allows us to determine the photometric observables ($|\delta T_{eff}/T_{eff}|$, $|\delta g_e/g_e|$ and the "phase lag" ϕ^T).

It appears that our non-adiabatic results are very sensitive to the characteristics of the superficial convective zone, parameterized throughout the mixing length parameter α.

Theoretical photometric amplitude ratios and phase differences are very sensitive to these non-adiabatic predictions. As a consequence, our improved non-adiabatic treatment of the atmosphere allows better photometric mode identifications. Furthermore, by searching for the best fit between theory and observations it would be possible to constrain the MLT parameter α.

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