Photometric amplitudes and phases of B-type main sequence pulsators: sources of inaccuracy

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We discuss all possible sources of uncertainties in theoretical values of the photometric amplitudes and phases of B-type main sequence pulsators. These observables are of particular importance because they contain information about the mode geometry as well as about stellar physics. Here, we study effects of various parameters coming both from theory of linear nonadiabatic oscillations and from models of stellar atmospheres. In particular, we show effects of chemical composition, opacities and, for the first time, effects of the NLTE atmospheres.

1 Introduction

To construct a seismic model of a star, knowledge about the geometry of observed modes is a precondition. In the case of B-type pulsators, mode identification cannot be done directly from oscillation spectra because they are sparse and lack equidistant patterns. An alternative way is to make use of the fact that information about the mode degree, ℓ, and the azimuthal order, m, is embedded in the photometric and spectroscopic variations of a pulsating star. Ones of the most popular tools to identify a pulsation mode are the amplitude ratios and phase differences in various photometric passbands. In the case of zero-rotation approximation, these observables are independent of the azimuthal order, m, and inclination angle, i.

The semi-analytical expression for the bolometric light variation was formulated by Dziembowski (1977) Balona & Stobie (1979) and Stamford & Watson (1981) expanded this expression for the light variation in photometric passbands. They showed that modes with different values of ℓ are located in separated parts on the amplitude ratio vs. phase difference diagrams based on multicolour photometry. Subsequently, this method was applied to various types of pulsating stars by Watson (1988) Cugier, Dziembowski & Pamyatnykh (1994) improved the method by including nonadiabatic effects in calculations for the β Cephei stars. Effects of rotation on photometric observables were studied by Daszyńska-Daszkiewicz et al. (2002) for close frequency modes and by Townsend (2003) and Daszyńska-Daszkiewicz, Dziembowski & Pamyatnykh (2007) for long-period g-modes.

The goal of this paper is to examine all possible effects on theoretical values of the photometric amplitude ratios and phase differences for early B-type pulsators. As an example, we consider the main sequence models with a mass of 10 M⊙ and low degree modes, ℓ=0, 1, 2. All effects of rotation on pulsation are neglected. In Section 2, we recall basic formulas and describe our models. Effects of parameters coming from linear nonadiabatic theory of stellar pulsation are presented in Section 3. Effects of atmospheric parameters are discussed in Section 4. The last section contains Conclusions.

2 Pulsational changes of a star’s brightness

Stellar pulsations cause the changes of temperature, normal to the surface element and pressure. If all effects of rotation on pulsation can be ignored, then the total amplitude of the light variation in the passband λ can be written in the following complex form (Daszyńska-Daszkiewicz et al. 2002):
$\mathcal{F}_\lambda$ is the flux in the passband $\lambda$ and $b^\lambda_\ell$ is the disc averaging factor defined by

$$b^\lambda_\ell = \int_0^1 h_\lambda(\mu)\mu P_\ell(\mu) d\mu$$

where $h_\lambda(\mu)$ is the limb darkening law and $P_\ell$ is the Legendre polynomial. Other parameters have their usual meaning.

From the above expressions, one can see that two inputs are needed to compute theoretical values of the photometric amplitudes and phases. The first input comes from the nonadiabatic theory of stellar pulsation and this is the $f$-parameter (Eq. 1 and 3). The second input is derived from models of stellar atmospheres and these are the flux derivatives over effective temperature and gravity (Eq. 2 and 5), as well as limb-darkening and its derivatives (Eq. 2 and 6).

All computations were performed using the Warsaw-New Jersey evolutionary code and the linear nonadiabatic pulsation code of Dziembowski (1977). We considered opacity tables from OPAL (Iglesias & Rogers [1996] and OP (Seaton 2005) projects, and two determinations of the solar chemical composition: GN93 (Grevesse & Noels 1993) and A04 (Asplund et al. 2005). For models of stellar atmospheres, we used Kurucz models (Kurucz 2004), computed within the LTE approximation, and TLUSTY models (Lanz & Hubeny 2003) which include the NLTE effects. Here, we adopted nonlinear limb darkening law as defined by Claret (2000)

$$h_\lambda(\mu) = \frac{2}{1 - \frac{\sum_{k=1}^{4} a^\lambda_k (1 - \mu^{k/2})}{1 - \frac{\sum_{k=1}^{4} k^2 a^\lambda_k}{4}}}.$$  

In the case of Kurucz models, we relied on the limb darkening coefficients of Claret (2000). For TLUSTY models, we determined these coefficients by ourselves and these results will be published elsewhere (Daszyńska-Daszkiewicz & Szewczuk 2010).

In all comparisons, we used a reference model computed with: the OP opacity tables, the A04 mixture, hydrogen abundance of $X=0.7$, metal abundance of $Z=0.02$, without overshooting from a convective core, $\alpha_{\text{ov}}=0$, Kurucz models of stellar atmospheres with the metallicity of $[\text{m/H}]=0.0$ and the microturbulent velocity of $\xi_t=2 \text{ km/s}$.

3 Uncertainties from the pulsation theory

In the case of the B-type pulsating stars, values of the $f$-parameter are mostly sensitive to hydrogen and metal abundances, chemical mixture and hence opacities.

In Fig. 1, we show effects of the hydrogen abundance, $X$, and metallicity, $Z$, on photometric observables for the $10 M_\odot$ model in the course of its main sequence evolution. We considered the Strömgren $uy$ passbands and three first radial modes: $p_1$, $p_2$, $p_3$. In the left panel, we show the amplitude ratio, $A_u/A_y$, and in the right one the corresponding phase difference, $\phi_u - \phi_y$, as a function of $T_{\text{eff}}$. We show computations obtained with $Z=0.02$ vs. $Z=0.03$ and $X=0.7$ vs. $X=0.75$. As we can see, the amplitude ratios computed with $Z=0.03$ are larger than those obtained with $Z=0.02$, whereas increasing hydrogen abundance, $X$, decreases the amplitude ratios. Photometric observables of the radial fundamental mode, $p_1$, are most sensitive to the chemical abundance.

Effects of the opacity tables and chemical mixture for the radial modes are shown in Fig. 2. In this case, we compare photometric observables obtained with the OPAL vs. OP tables and the GN93 vs. A04 mixture. Again, the largest effects are for the $p_1$ mode. The amplitude ratios computed with the GN93 mixture are smaller than those obtained with A04, because of relatively higher abundance of iron in A04.

Allowing overshooting from a convective core does not affect significantly photometric observables.

Computations for modes with $\ell=1, 2$ showed that the above discussed parameters have much smaller influence on their photometric observables.

4 Uncertainties from the atmosphere models

The most important atmospheric parameters which can affect the photometric amplitudes and phases of a pulsating star are: the metallicity parameter, $[\text{m/H}]$, the microturbulent velocity, $\xi_t$, and effects of NLTE.

In Fig. 3, we show effects of $[\text{m/H}]$ and $\xi_t$. Here, we considered $[\text{m/H}]=+0.5$ and $\xi_t=8 \text{ km/s}$, in addition to our standard values: $[\text{m/H}]=0.0$ and $\xi_t=2 \text{ km/s}$. In general, effects of those parameters on photometric observables are smaller than effects discussed in the previous section.

Subsequently, we studied effect of the assumption of LTE in stellar atmosphere models. In Fig. 4 we compare computations with Kurucz LTE models and TLUSTY NLTE models, at the same values of $[\text{m/H}]$ and $\xi_t=2 \text{ km/s}$, for the radial modes. As we can see, the NLTE effects on photometric observables are relatively small and comparable to effects of the atmospheric metallicity, $[\text{m/H}]$, or the microturbulent velocity, $\xi_t$ (cf. Fig. 5).

In Fig. 5, we show effects of NLTE on photometric observable for nonradial modes with $\ell=1$ and 2, respectively.

5 Conclusions

The photometric amplitude ratios and phase differences of the early B-type main sequence pulsators strongly depend on chemical composition and opacities. The effects of the atmospheric parameters are smaller but may become important when the nonadiabatic parameter $f$ is determined from observations instead taken from the pulsation theory. Here, we studied for the first time the NLTE effects on photometric observables of the $\beta$ Cep star model.

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Fig. 1  Effect of the hydrogen (X) and metal (Z) abundance on photometric observables for the three radial modes as a function of the effective temperature for the 10 $M_\odot$ main sequence model. In the left panel, we plot the amplitude ratios in the Strömgren uy filters and in the right one the corresponding phase differences.

Fig. 2  The same as in Fig. 1 but effects of opacities and chemical mixture are presented.

Fig. 3  The same as in Fig. 1 but effects of the atmospheric metallicity, [M/H], and the microturbulent velocity, $\xi_t$, are presented.

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**Fig. 4** Effect of NLTE on photometric observables for the three radial modes as a function of the effective temperature for the $10 M_\odot$ main sequence model. In the left panel, we plot the amplitude ratios in the Strömgren $uy$ filters and in the right one the corresponding phase differences.

**Fig. 5** The same as in Fig. 4 but for the two $\ell=1$ modes: $p_1$ and $g_1$. Note different scale on the Y axis.

**Fig. 6** The same as in Fig. 4 but for the two $\ell=2$ modes: $p_1$ and $g_1$. Note different scale on the Y axis.

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