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Photometric Modeling of Slowly Pulsating B Stars

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Abstract. Highlights are presented from a theoretical study of the photometric characteristics of slowly pulsating B stars. One outstanding result is the discovery, for $\ell \geq 2$ modes, of cancellation between the flux variations originating from surface temperature perturbations, and those arising from radius perturbations. In addition to reducing greatly the variability generated by such modes, the cancellation introduces significant phase differences between the flux changes in each passband. On the grounds that similarly-large phase differences are not seen in observational data, it is suggested that the light variations of slowly pulsating B stars might be due primarily to $\ell = 1$ modes.

1. Introduction

Recent interest in the slowly pulsating B-type (SPB) stars has been stimulated by the observational discovery of many new members of the class (e.g., Waelkens et al. 1998), along with theoretical developments (e.g., Pamyatnykh, 1999) which have consolidated our understanding of the κ-mechanism instability responsible for their pulsation. A task which lies ahead is to secure reliable mode identifications for the $\sim$ 100 known SPB stars, thereby opening them up to scrutiny using asteroseismological techniques. This paper presents highlights from an ongoing theoretical study of SPB-star photometric characteristics, aimed at paving the way for future attempts at mode identification. Full details of the project will appear in a forthcoming paper (Townsend, 2002).

2. Method

A canonical relaxation technique (Unno et al., 1989) was used to solve the nonradial nonadiabatic pulsation equations in $\sim$ 500 stellar models, covering the mass interval $M = 3.0 \ldots 6.5\,\mathrm{M}_{\odot}$ and extending from zero-age main sequence up to the cessation of core hydrogen burning. For those modes of harmonic degrees $\ell = 1 \ldots 4$ found to be overstable, parameters were obtained characterizing the surface perturbations to radius, temperature and pressure. Using Watson's (1988) semi-analytical formula, these nonadiabatic parameters were combined with static model atmospheres from Kurucz (1993), to synthesize light curves in the seven passbands of the Geneva photometric system.

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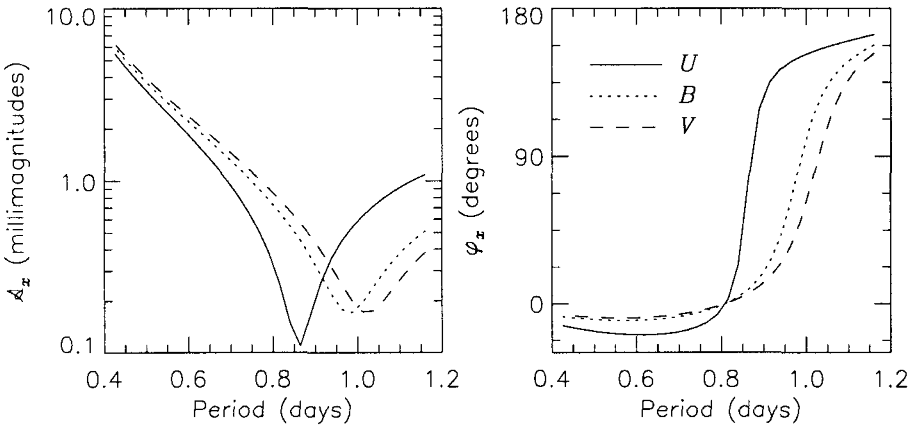

Figure 1. The semi-amplitude $\mathcal{A}_x$ and phase φ_x of the light variations in the Geneva U, B and V passbands, due to unstable $\ell = 4$ modes of an $M = 4.5\,\mathrm{M}_\odot$ stellar model (see text).

3. Results

As a representative example of the photometric data synthesized, Fig. 1 shows the sinusoidal semi-amplitude $\mathcal{A}_x$ and phase φ_x of the light variations in the Geneva U, B and V passbands, plotted as a function of pulsation period, for the overstable $\ell = 4$ modes of a somewhat-evolved $M = 4.5\,M_\odot$ stellar model ($\log L/L_\odot = 2.70$, $\log T_{\rm eff}/\mathrm{K} = 4.16$). The outstanding aspect of this figure is the appearance of distinct minima in the light-amplitude data, occurring at periods 0.86 d, 0.99 d and 1.01 d in the U, B and V bands, respectively.

The minima are a consequence of destructive interference between the flux changes arising from temperature perturbations, and those originating from radius perturbations. In SPB stars, these two contributions towards the total light variations are in approximate antiphase, and their magnitudes exhibit opposite dependencies on the pulsation period: that of the former grows with increasing pulsation period, and vice-versa for the latter. Combined, these facts open up the possibility that, at some intermediate period where the two contributions are of approximately-equal magnitude, they can cancel with one another to produce a minimum in the resulting light amplitude. It should be remarked that such behaviour is by no means unique to the stellar model considered in Fig. 1; similar minima were found in the synthetic photometry of a large number of the other $\ell = 2 \ldots 4$ modes examined in the study. However, cancellation was not found in any of the $\ell = 1$ modes, for which the radius contribution in all cases is identically zero.

One consequence of cancellation is that a mode may be excited to a significant amplitude in an SPB star, and yet produce levels of variability which fall below typical observational detection thresholds. However, as can be seen in Fig. 1, the periods at which light minima occur are different in each passband.

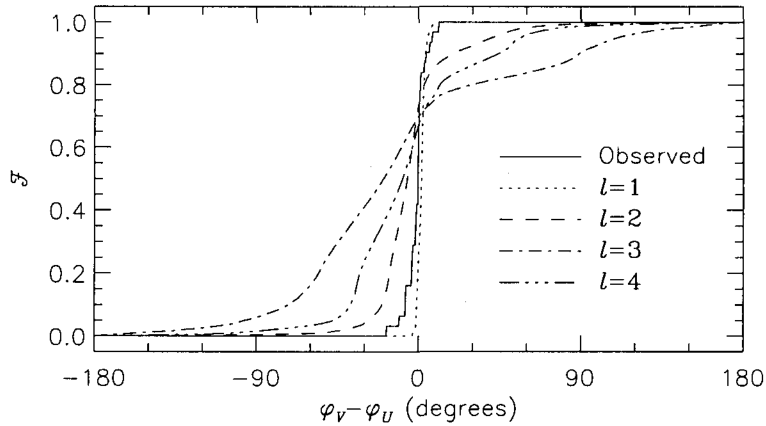

Figure 2. The cumulative probability distribution $\mathcal{F}$ of the phase difference $\varphi_V - \varphi_U$, at the four values of the harmonic degree ℓ considered in the modeling. Overplotted is the corresponding distribution of the SPB modes observed by North & Paltani (1994) and De Cat & Aerts (2002).

This is because the temperature contribution in B-type stars increases with decreasing wavelength; therefore, moving towards bluer photometric colours, the light minimum is shifted towards ever-shorter periods. As a consequence of this wavelength dependence, it seems unlikely that a mode could remain undetected during observations in two or more passbands; therefore, *multicolour* surveys represent the best approach to ensuring that no modes are overlooked in future searches for variability.

Across a light minimum, the phase of the variations changes by approximately 180°, as temperature perturbations replace radius perturbations as the dominant contributor towards the variability. Since these changes occur at different periods in alternative passbands, large phase differences can result between the light variations in each passband. This effect is clearly seen in Fig. 1: over the period range where cancellation is most pronounced, the variations in the U band lead those in the other two bands by as much as 120°. Correspondingly-large phase differences were found in many of the other $\ell = 2 \ldots 4$ modes considered in the study, but not in the $\ell = 1$ modes, which remain unaffected by cancellation.

The latter findings are of particular significance, in light of the fact that observations of SPB stars have been characterized (North & Paltani, 1994) by small or non-existent phase differences between the variations in each passband. This point is illustrated in Fig. 2, which shows the cumulative probability distribution of the $\varphi_V - \varphi_U$ phase difference, for the modes observed by North & Paltani (1994) and De Cat & Aerts (2002) in thirteen different SPB stars. Overplotted are the corresponding distributions of the synthetic $\ell = 1 \ldots 4$ modes considered in the study. The small phase differences found in the observational data lead to the sharp rise seen in the cumulative probability distribution around $\varphi_V - \varphi_U \approx 0$. Evidently, out of the alternative harmonic degrees considered, it is the synthetic $\ell = 1$ modes with best reproduce this behaviour; the large phase differences predicted for the $\ell = 2 \ldots 4$ modes, arising as a consequence of cancellation, make it difficult to reconcile the observations with the excitation of such modes.

4. Discussion

The notable absence of phase differences in observations of SPB stars would appear to favour an $\ell = 1$ identification for the majority of modes detected. This result must be be verified with more-intensive modeling, before it can be considered reliable; however, if it is revealed to be correct, what explanation could there be for the apparent prevalence of $\ell = 1$ modes in these stars ? Is there some as-yet-unknown mechanism which preferentially promotes these modes to detectable amplitudes, while suppressing overstable modes of larger harmonic degree ? Alternatively, are the latter excited to significant amplitudes, but overlooked in observations due to the combined effects of cancellation and disk-averaging ? A third possibility is that there exists a problem with the outer boundary conditions used in the modeling; these boundary conditions can have a significant impact on theoretically-predicted light variations, since they govern directly the behaviour of pulsation at the visible stellar surface.

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Discussion

W. Dziembowski : Could you specify the problem you see in the outer boundary condition used in the standard treatment of stellar oscillation ?

R. Townsend : At this stage, I really can't say. However, the fact that there remain difficulties in reproducing the asymmetric power distributions seen in line-profile variations, suggests that something may be wrong with current treatments of the outer boundary.