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Theoretical *UBVI* Light Curves of Pulsating Stars

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Abstract. By performing detailed frequency-dependent radiative transfer computations we are able to calculate light curves in particular bandpasses from stellar pulsation models calculated by the Vienna nonlinear convective pulsation code. As a sample application we discuss *UBVI* light curves of RR Lyrae stars. The properties of these light curves are analyzed by means of standard Fourier decomposition, and a comparison to recent observations is performed. As main results we find a good agreement with important observed RR Lyrae properties like pulsation amplitudes and Fourier parameters in *B*, *V*, and *I* bands. Additionally, from the synthetic color curves we derive linear transformation laws between amplitudes as well as Fourier parameters in the different bandpasses.

1. Introduction and Overview

As by-products of the microlensing projects MACHO, OGLE and EROS, the available observational data about pulsating stars increased considerably in amount and quality in the past years. The majority of these new experimental data comprises light curves of galactic and extragalactic objects with excellent phase coverage. For the analysis, interpretation and explanation of these data theoretical models are needed which are able to reproduce observational constraints with a similar accuracy. In this context nonlinear pulsation models are of particular importance, as theoretical light curves can be computed.

While observed light curves are given in certain spectral bands (mostly *B*, *V*, *R* or *I*), theoretical pulsation calculations are mainly performed by adopting gray (i.e. frequency-integrated) opacities, yielding bolometric light curves. Consequently, a detailed comparison is lacking because of this difference in spectral information. Depending on the particular bandpass employed, differences vary a few percent to considerable deviations.

In this article we present models of pulsating stars calculated by the Vienna nonlinear pulsation code (Feuchtinger 1999a). Key ingredients comprise the full nonlinear system of radiation hydrodynamics, including a time-dependent gray radiative transfer and time-dependent turbulent convection. The correspond-

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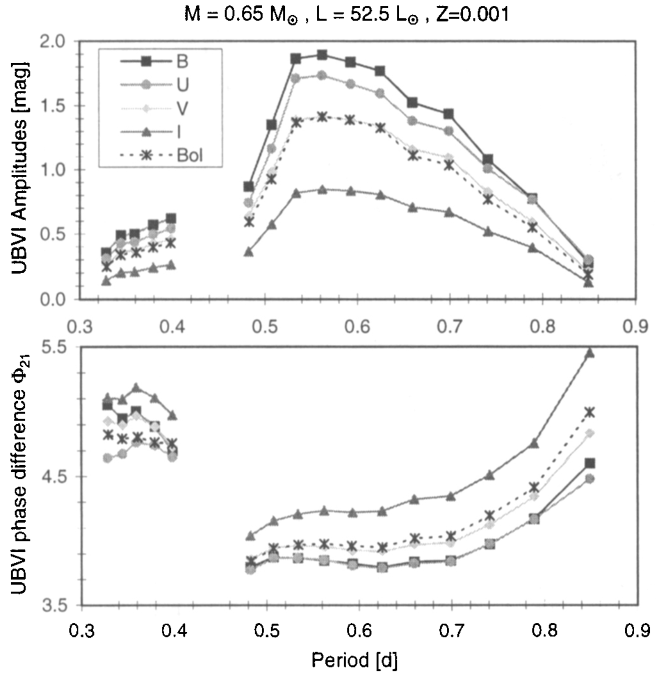

Figure 1. *UBVI* and bolometric pulsation amplitudes and phase differences Φ_{21} versus pulsation period for fundamental and first overtone limit cycles of sequence A.

ing nonlinear system of differential equations is discretized on an adaptive grid and solved implicitly. The computed bolometric light curves are transformed into the desired bandpass (as given by observational demands) by computing a frequency-dependent radiative transfer on top of the nonlinear models (Dorfi & Feuchtinger 1999). For that we solve the time-independent radiation transfer equation in spherical symmetry by integrating along characteristics (Yorke 1980). The frequency grid comprises 1212 frequency points, and opacities according to Kurucz (1993) are used. For each instant during one pulsation cycle we obtain a theoretical spectrum, and a convolution of these synthetic spectra with the corresponding filter curves leads to synthetic color curves. Further details can be found in Dorfi & Feuchtinger (1999).

2. Application to RR Lyrae Stars

As a sample application we discuss the case of RR Lyrae stars. For two sets of stellar parameters ($M = 0.65\,M_\odot$, $L = 52.5\,L_\odot$, $Z = 0.001$, sequence A, as well as $M = 0.75\,M_\odot$, $L = 52.5\,L_\odot$, $Z = 0.0001$, sequence B) the fundamental and

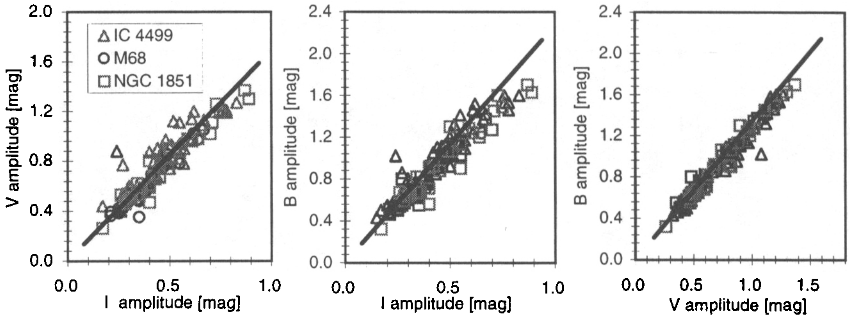

Figure 2. Theoretical *VBI* interrelations (thick lines) compared to observational data from three globular clusters (IC 4499: Walker & Nemec 1996; M68: Walker 1994; NGC 1851: Walker 1998).

the first overtone limit cycle solutions have been calculated for effective temperatures ranging from 6000 K to 7200 K (Feuchtinger 1999b). The resulting bolometric light curves have been transformed to the standard Johnson *UBVI* system; for sequence A the results are illustrated in Fig. 1, depicting the luminosity amplitude and the Fourier phase difference Φ_{21} throughout the instability

Table 1. Transformation between bolometric and U, B, V, and I amplitudes (both fundamental and first overtone). R^2 denotes the quadratic correlation coefficient.

$A(X) = a + b\,A(\mathrm{Bol})$			
X	a	b	R^2
U	0.019	1.253	0.993
B	0.046	1.347	0.996
V	0.036	1.004	0.998
I	0.023	0.590	0.992

strip (see Simon & Lee 1981 for a definition of Fourier phase differences). Both for pulsation amplitudes and Φ_{21} a clear dependence on the particular filter in use is visible, which stresses the need for an appropriate transformation between bolometric and photometric light curves, even for classically pulsating stars. We find similar dependences for all higher order Fourier phases, while Fourier amplitude ratios depend only weakly on the particular filter. It is interesting to note that bolometric amplitudes closely resemble V amplitudes for both model sequences and both pulsation modes, somehow justifying the comparison of theoretical bolometric light curves with V observations commonly performed in the

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literature. For a more comprehensive discussion we refer to Dorfi & Feuchtinger (1999).

From the *UBVI* data we can derive linear relations between bolometric and *UBVI* light curve parameters; as an example, transformations for the pulsation amplitudes are given in Table 1. Elimination of the bolometric amplitudes in these relations allows for a comparison with observed globular cluster data, which, as illustrated in Fig. 2, yields good agreement. Similar relations for the Fourier parameters and a corresponding comparison with observations can be found in Dorfi & Feuchtinger (1999).

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Discussion

Pawel Moskalik: Do you plan to perform similar calculations for classical Cepheids?

Michael Feuchtinger: Yes, as soon as we have a complete picture of classical Cepheids, which turn out to be much more complicated to model than RR Lyrae stars, we want to do a larger survey.

Géza Kovács: Have you been able to verify the empirical relation between [Fe/H], P, and ϕ_{31} as derived for field RRab stars? If you did such a test, did you fix all stellar parameters and let only [Fe/H] vary, or did you change all parameters in some way?

Michael Feuchtinger: The models calculated so far change both the stellar parameters together with [Fe/H], and haven't tested the [Fe/H]-dependence alone.