Radial and Nonradial Pulsations as Probes of Stellar Physics
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Astero - Oscillometry: Gauging Stars with Oscillations[1]

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Abstract. Astero - oscillometry is presented as a new method for deriving stellar parameters on the basis of a physical modeling of line profile variability (*lpv*) caused by nonradial pulsation (*nrp*). First applications to rapidly rotating B-type stars show that the method is able to yield reasonable stellar parameters. The radii are systematically smaller compared to those derived by conventional methods. This could be attributed to possible effects of rapid rotation on stellar evolution. Since the method requires only one or a few pulsation modes to be excited, it is ideally suited to investigating early-type stars.

1. Introduction

The quantitative modeling of spectroscopic observations of nonradial pulsation (line profile variability) depends critically on the adopted fundamental stellar parameters. Experience shows that catalog data are insufficient for this purpose. A better approach is to bootstrap the parameters to be used as input for the modeling directly from the spectra to be modeled.

Astero - oscillometry has been developed as a method for gauging stellar parameters on the basis of a physical modeling of pulsationally induced *lpv*. The modeling procedure requires five stellar and, for each mode, five pulsational parameters to describe the *nrp* variations. In case of monoperiodic variability, the phase parameter becomes trivial, however. Theoretical models of stellar structure and evolution do not have to be considered.

Since Astero - oscillometry can be applied to single- and multi-mode pulsators, it is ideally suited to early-type stars, which normally show too few frequencies to become subjects of astero - seismological studies.

[1]Based on observations obtained at the European Southern Observatory, La Silla, Chile, prop. Nos. 62.H-0319 and 64.H-0548

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2. Astero - oscillometry

The method requires series of observed spectra with large wavelength coverage and is performed in three steps (see also Rivinius et al., 2001):

Modeling: Grids of model line profiles are calculated for several lines of different ions for all plausible sets of stellar and pulsational parameters

Comparing: The residuals of the phase-binned observed and modeled line profiles from their respective means are compared by cross correlation. To achieve reliable results, the observed spectra must have high resolution and S/N ratio and must suitably sample the pulsation cycle

Validating: The identification of the best matching model(s) is based on a χ^2–test. Besides a minimal χ^2–value, the best model must satisfy the following additional conditions:

- The resulting stellar parameters must be plausible *and* the same for *all* modes and *all* modeled lines
- The modeled *lpv* must match the observed one in general, and also match prominent features like spikes and ramps for all observed spectral lines
- The observed photometric variability must be matched in principle

The method was first applied to three B-type stars that are known as fast rotators showing rapid *lpv*, μ Cen (B2 IV-Ve), 28 CMa (B3 IVe), and HR 4074 (B3 III). The codes BRUCE and KYLIE by Townsend (1997), specifically developed for fast rotating early-type stars, were used for the modeling. BRUCE calculates the local surface parameters of a star, taking into account rotation and pulsational perturbations, using mass M, polar radius $R_{\rm pol}$, polar temperature $T_{\rm pol}$, equatorial rotation velocity $v_{\rm eq}$, and inclination i as stellar and pulsation period $\mathcal{P}$ and phase ϕ, mode indices ℓ and m, and the maximum velocity amplitude of the pulsation, $A_{\rm max}$, as pulsational input parameters. Using the output of BRUCE as input, KYLIE synthesizes line profiles on the basis of synthetic line profile grids, calculated with ATLAS 9 model atmospheres and BHT, an LTE code for spectral synthesis of intrinsic line profiles (Gummersbach et al., 1998).

The modeling results include not only the stellar and pulsational parameters corresponding to the best matching model, including disentangled values for velocity and inclination, but also, among other parameters, pulsation frequencies in the co-rotating frame.

3. Results

As shown for 28 CMa (Fig. 1, see also Rivinius et al., these proceedings), the *lpv* can be modeled very well and in great detail. The preliminary best modeling results for selected parameters of all modeled stars are listed in Table 1. For HR 4074 see also Štefl et al. (these proceedings). The derived stellar parameters are within the limits of standard calibrations of the MK classification scheme. However, all radii are lower than these calibrations and canonical evolutionary

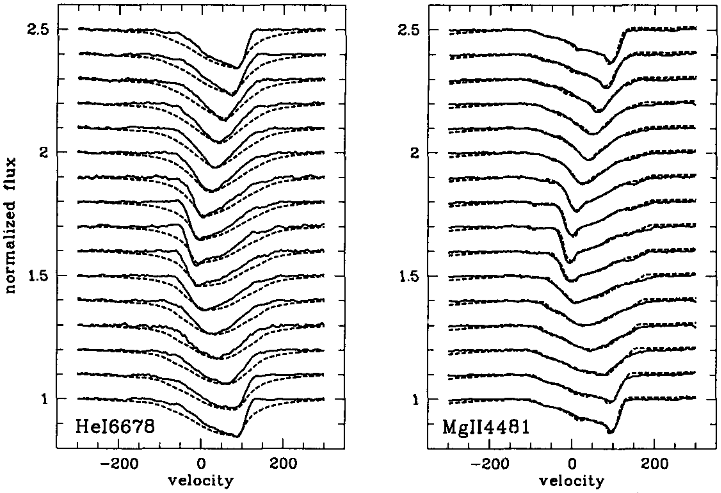

Figure 1. Modeled (dashed) versus observed (solid) line profiles of 28 CMa. The observed spectra are binned into 16 equally spaced phases. The average line profile of each bin is compared to the synthetic profile, modeled for the corresponding phase step. The phase is increasing from bottom to top. A contribution of circumstellar emission is obvious in the wings of He I 6678. Mg II 4481 is blended with Al III.

radii. On the other hand, theoretical values (Claret, 1995) also tend to be lower. If the present results are correct it would, therefore, be possible that rapid rotation modifies the standard relations between $T_{\rm eff}$ and R, for instance by enhanced mixing.

4. Conclusion and future work

Astero-oscillometry as a new method for the quantitative gauging of fundamental stellar parameters has fully passed its feasibility check. The observed *lpv* of rapidly rotating early-type stars is in good agreement with the corresponding best matching pulsation models. The derived stellar parameters are reasonable. Smaller radii compared to conventionally determined ones are a hint that stellar evolution could be influenced by fast rotation, but these small radii need to be ascertained more thoroughly. To make the method more objective, additional goodness-of-match parameters need to be included. For instance, a necessary condition for an acceptable model is that the mean stellar spectrum is well reproduced. (Note that the modeling itself is restricted to the *residuals* only!) The models presented here do satisfy this criterion; but in the current procedure it is not yet used to evaluate the quality of the results. The sensitivity of the global results to individual parameters as well as possible degeneracies between different parameter sets still need to be investigated.

Table 1. Preliminary best modeling results for selected parameters. For the multi-periodic star μ Cen only those pulsation parameters are given that correspond to the main pulsation mode. For the meaning of a negative period see Maintz et al. (2000) and Rivinius et al. (2001).

	μ **Cen**	**28 CMa**	**HR 4074**
Mass, M	$9\,M_\odot$	$11\,M_\odot$	$7\,M_\odot$
Polar radius, R_{pol}	$3.4\,R_\odot$	$5.0\,R_\odot$	$5.8\,R_\odot$
Polar temperature, T_{pol}	23 000 K	18 000 K	17 500 K
Equatorial rotation velocity, v_{eq}	$440\,\text{km s}^{-1}$	$250\,\text{km s}^{-1}$	$352\,\text{km s}^{-1}$
Inclination, i	19°	23°	13°
Observed Period, $\mathcal{P}_{\text{obs}}$	–0.502 d	–1.37 d	–2.32 d
Mode indices, ℓ, m	2, +2	2, +2	2, +2
Velocity amplitude, A_{max}	$15\,\text{km s}^{-1}$	$45\,\text{km s}^{-1}$	$45\,\text{km s}^{-1}$
Apparent radius, R_{app}	$4.15\,R_\odot$	$5.37\,R_\odot$	$7.92\,R_\odot$
Apparent temperature, T_{app}	20 760 K	17 287 K	15 173K
Apparent luminosity, $\log L_{\text{app}}$	$3.46\,L_\odot$	$3.37\,L_\odot$	$3.48\,L_\odot$
Co-rotating Period, $\mathcal{P}_{\text{co-rot}}$	0.47 d	0.91 d	0.76 d

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Discussion

W. Dziembowski : First of all, I do not like the term "astero-oscillometry" to describe your work. Secondly: how much differ the minimum values of χ^2 between various choices of ℓ and m?

M. Maintz : χ^2 is calculated for each parameter set as a total. It is not clear yet to what extent the resulting models and therefore χ^2 are affected by individual parameters. This still has to be investigated.

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