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Mode identification using photometry and spectroscopy

Joris De Ridder[1], Conny Aerts

Institute of Astronomy, Katholieke Universiteit Leuven, Celestijnenlaan 200B, B-3001 Leuven, Belgium

Marc-Antoine Dupret[2]

Instituto de Astrofísica de Andalucía – CSIC, c/ Camino Bajo de Huétor 24, 18008 Granada, Spain

Abstract. We tested a stepwise approach to combine photometry and spectroscopy for mode identification where we first used the photometric amplitude ratios to restrict the degree ℓ, then did a spectroscopic mode identification, and finally fitted the photometric amplitudes to restrict the list of candidate modes. For the spectroscopic mode identification, we implemented an efficient multi-mode moment method variant. We conclude that this new variant works well, but that the photometric amplitudes are too model sensitive to do any additional mode discrimination.

1. Introduction

For B-type stars it was recently shown that frequency fitting can achieve strong model constraints, for example on the mass of the star (Aerts et al. 2003). The process of frequency fitting is, however, usually not an easy one. Frequencies can be quite close, specifically the $\ell = 0$ and the $\ell = 2$ frequencies, so that it is not always easy to distinguish. We also often don't know which component of the rotationally split multiplet is observed, as not all components need to be excited. Specifically, we often don't know whether we are dealing with an $m = 0$ peak, which is the only one we can theoretically compute because the corresponding frequency is not affected by rotation in a first approximation.

This is why we need *mode identification.* The aim is to help narrow down the set of candidate models to facilitate frequency fitting by finding the degree ℓ of the zonal modes. Frequency fitting can specifically benefit from identified radial modes.

What we are investigating in this paper is whether combining photometry and spectroscopy can lead to a more discriminative mode identification. Photometry on its own can give information on the degree ℓ, and spectroscopy can, in principle, give information on both the degree ℓ and the azimuthal order m.

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[1] Postdoctoral Fellow of the Fund for Scientific Research, Flanders

[2] Marie Curie Postdoctoral Fellow, European Union

2. Using both spectroscopy and photometry

What we tested is a stepwise approach: first using the photometric amplitude *ratios* which are independent of the intrinsic amplitude ϵ and the inclination angle i, to restrict the degree ℓ, then doing a spectroscopic mode identification, and finally going back to photometry to fit the photometric amplitudes themselves to restrict the list of candidate solutions.

For the spectroscopic mode identification, there are currently 3 options: direct line profile fitting, the moment method and phase fitting (IPS). As we are concentrating on slowly rotating stars with low degree ℓ, we chose for the moment method because for these kind of stars it is the best suited and the fastest method. The moment method applied to *multiple* modes is nevertheless quite slow, because there are many parameters to estimate, and because the computation of the χ^2-function is still quite heavy. For this reason we developed a new code that implements a variant of the moment method that is more efficient. The main new features of this variant are the following:

1. We compute shifted moments with respect to the average position of the line instead of the central wavelength λ_0. The advantage is that the shifted moments depend on one parameter less than the old moments.

2. We now also standardize the moments, which leads to an improved goodness-of-fit function, where one moment does not dominate the other.

3. We also use an improved parameter-space-scanning algorithm which was recently published by Sambridge (1999). Instead of scanning with a rectangular grid, this algorithm divides the parameter space in special cells, and samples the promising cells more, with the special feature that the cell boundaries change *dynamically*. The advantage is that the algorithm is more time-efficient, and that it is less likely to miss the minimum.

Concerning the computation of photometric amplitudes and amplitude ratios, we used the formalism as outlined by Dupret et al. (2003), with Kurucz (1993) flux spectra and the non-linear limb-darkening law of Claret (2000).

3. Test Applications

We applied our approach to the β Cephei star 16 Lac and to the SPB star HD 123515. As both stars gave the same qualitative results, we only show the results for 16 Lac.

In Fig. 1 we show the photometric amplitude ratios for the Johnson passbands U, B and V. The circles are the observed ratios obtained by Jerzykiewicz (1993) where the size of the circles corresponds to the uncertainty. The lines are the theoretical amplitude ratios for different degrees ℓ for several models in the error box of the star in the HR diagram. The amplitude ratios clearly point towards a radial mode for the first frequency. It is less obvious for the second and the third modes, but we can safely say that they are not $\ell = 4$ modes.

For the input of the spectroscopic mode identification code, we thus assumed $\ell = 0$ for the first mode, and $\ell = 0$, 1 or 2 for the two other modes. Thanks to the photometric diagram, we therefore needed to check only 81 mode combinations. For each of these combinations we scanned a parameter space of real-valued parameters such as the inclination angle i, and the equatorial rotational velocity v_e.

The moment method shows that the second frequency ν_2 is likely a zonal mode (and thus useful for frequency fitting), but the code could not easily distinguish between the degree $\ell = 1$ and $\ell = 2$. Also for the third frequency ν_3 we find several (ℓ, m) combinations which fit almost equally well.

The fact that spectroscopic mode identification techniques (not only the moment method) do not give one clear identification, but a list of candidate solutions, is rather common. We therefore asked ourselves: "Given the output parameters of the candidate solutions of the moment method, can we use them to compute the photometric amplitudes (not ratios) and perhaps exclude some of the solutions to shorten the list?"

In Fig. 2 we show the photometric amplitudes for the second frequency ν_2 of 16 Lac, for the Johnson U, B and V passbands. The circles are the observations of Jerzykiewicz (1993). The theoretical amplitude ranges for $\ell = 0$, 1 and 2 were computed with output parameters from the moment method, together with the same models used for the amplitude ratios. As can be seen, the theoretical amplitudes are quite model sensitive. As each one of them contains the observed amplitude, we *cannot* exclude any candidate solutions on this basis. The same holds for the other passbands and also for the third frequency of 16 Lac.

We end with the remark that the amplitude diagram (Fig. 2) does not contain any information about m. The reason is the following. Each photometric amplitude can be computed as an intrinsic amplitude ϵ times a surface cancellation factor $P_\ell^m(\cos i)$ times a factor that only depends on the degree ℓ and the model. The information to compute $\epsilon P_\ell^m(\cos i)$ can only come from spectroscopy. Although the (ℓ, m) selection is done with three moments, the amplitude ϵ is (given the inclination angle i) almost only determined with the moment with the highest S/N, which is the first moment. However, the first moment has the same $\epsilon P_\ell^m(\cos i)$ dependence. In other words, concerning m (and only concerning m), the radial velocity acts just like another photometric passband, and does not allow the extraction of additional information about m.

References

Aerts, C., Thoul, A., Daszynska, J., Scuflaire, R., Waelkens, C., Dupret, M.-A., Niemczura, E., Noels, A. 2003, Science, 300, 5627, 1926

Claret, A. 2000, A&A, 363, 1081

Dupret, M.-A., De Ridder, J., De Cat, P., Aerts, C., Scuflaire, R., Noels, A., Thoul, A. 2003, A&A, 398, 677

Jerzykiewicz, M. 1993, Acta Ast., 43, 13

Kurucz, R.L. 1993, Atlas9 Stellar Atmosphere programs and 2 km/s grids, Kurucz CD-ROM No 13

Sambridge, M. 1999, Geophys. J. Int., 138, 479

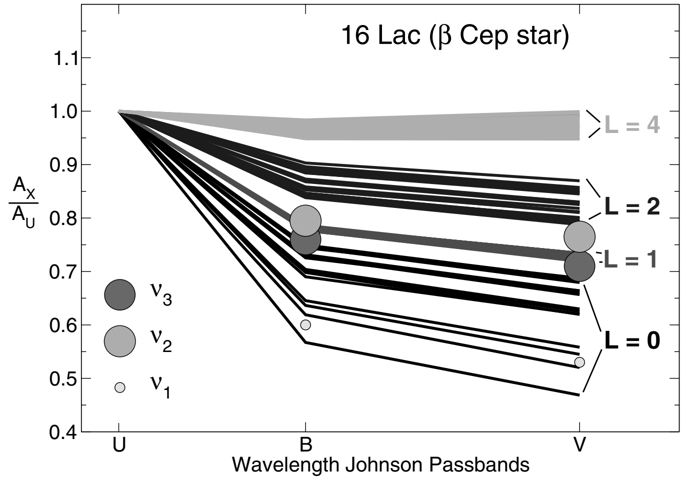

Figure 1. Theoretical (lines) and observational (circles) photometric amplitude *ratios* for three modes of 16 Lac. The theoretical amplitude ratios were computed for several models in the error box of the star in the HR diagram.

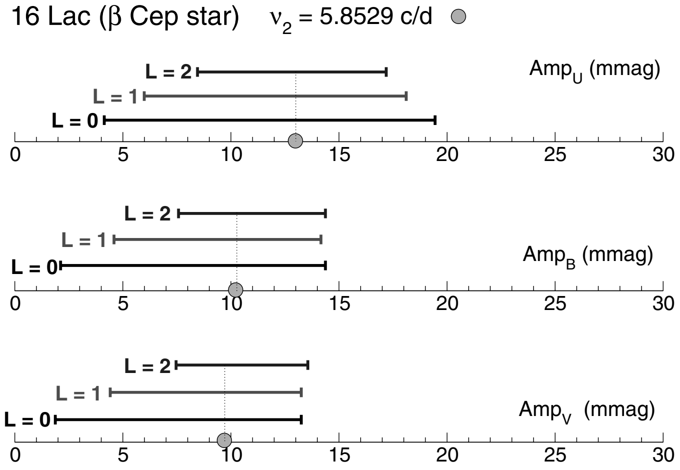

Figure 2. Theoretical (lines) and observational (circles) photometric amplitude for the second frequency of 16 Lac. The theoretical amplitude ranges were computed from the same models as used in Fig. 1 and with the output of the moment method.