High-Precision Spectroscopy of Pulsating Stars

C. Aerts[1,2], S. Hekker[1,3], M. Desmet[1], F. Carrier[1], W. Zima[1], M. Briquet[1],
and J. De Ridder[1]

[1] Institute of Astronomy, Catholic University of Leuven, Celestijnenlaan 200D,
B-3001 Leuven, Belgium `conny@ster.kuleuven.be`
[2] Department of Astrophysics, Radboud University Nijmegen, P.O. Box 9010,
6500 GL Nijmegen, The Netherlands
[3] Leiden Observatory, P.O. Box 9513, 2333 RA Leiden, The Netherlands

Summary. We review the methodology currently available to interprete time series of high-resolution high-S/N spectroscopic data of pulsating stars in terms of the kind of (non-radial) modes that are excited. We illustrate the drastic improvement of the detection treshold of line-profile variability thanks to the advancement of the instrumentation over the past two decades. This has led to the opportunity to interprete line-profile variations with amplitudes of order m/s, which is a factor 1000 lower than the earliest line-profile time series studies allowed for.

1 Line-Profile Variations due to Pulsations

In the recent research domain of asteroseismology, one tries to probe the internal structure parameter of stars from their observed pulsation properties. Prerequisites to succeed in that are accurate pulsation frequency values and an unambiguous identification of the spherical wavenumbers (ℓ, m) of at least two, but preferrably many more, non-radial pulsation modes. Asteroseismology has been applied successfully across the whole HR diagram. For a recent extensive overview of its successes so far, we refer to Kurtz (2006).

The introduction of high-resolution spectrographs with sensitive detectors in the 1980s had a large impact on the field of pulsation mode identification. Spectroscopic data indeed offer a very detailed picture of the pulsation velocity field. Mode identification requires that moderate to large telescopes be available during a long time span. Indeed, it remains a challenge to obtain time-resolved spectra with a high resolving power and with a high signal-to-noise ratio (> 300) covering the overall beat period of the multiperiodic pulsation. The required temporal resolution must be such that the ratio of the integration time and the pulsation period(s) remains below a few percent. The latter condition is necessary in order to avoid smearing out the effects of the pulsations in the line profiles during the cycle. This requirement is difficult to meet for rapid pulsators with periods of order minutes. This is the reason why spectroscopic mode identification has been achieved mainly for massive main sequence stars with spectral type from O to F and with pulsation modes excited by the κ mechanism with periods above one hour. An example of a nice data set is shown in Fig. 1. The application to stars

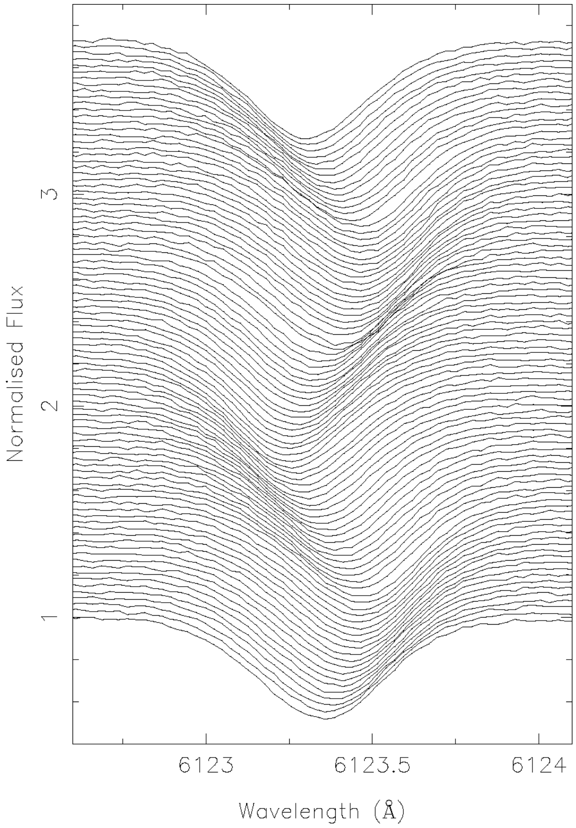

Fig. 1. Observed line-profile variations of the δ Sct star ρ Puppis obtained in 1995 with the Coudé Auxiliary Telescope of the European Southern Observatory in Chile. Data taken from Mathias et al. (1997).

with stochastic excitation, to magnetic pulsators and to compact pulsators has only recently been attempted and needs further improvements.

2 Methodology for Line-Profile Analysis

The pulsation velocity due to a spheroidal pulsation mode with infinite lifetime in the approximation of a non-rotating star equals

$$\boldsymbol{v}_{\rm puls} = (v_r, v_\theta, v_\varphi) = N_\ell^m v_{\rm p} \left(1, K\frac{\partial}{\partial\theta}, \frac{K}{\sin\theta}\frac{\partial}{\partial\varphi}\right) Y_\ell^m(\theta,\varphi) \exp\left({\rm i}\omega t\right) , \qquad (1)$$

when a system of spherical coordinates (r, θ, φ) with origin at the centre of the star and with polar axis along the rotation axis is used. In this expression, N_ℓ^m

is a normalisation factor for the $Y_\ell^m(\theta,\varphi)$, $v_{\rm p}$ is proportional to the pulsation amplitude, ω is the cyclic pulsation frequency, and K is the ratio of the horizontal to the vertical velocity amplitude: $K = GM/(\omega^2 R^3)$. This velocity acts together with rotational broadening and with intrinsic line broadening due to pressure and temperature effects. Moreover, we only detect the velocity component projected onto the line-of-sight. This leads us to the conclusion that line-profile variations due to a single pulsation mode are determiend by six unknown parameters among which two are integer numbers (ℓ, m). For each additional mode, three unknowns are added in the linear approximation ignoring non-linear coupling between the modes. The above Exp. (1) is far too simple when Coriolis, centrifugal or Lorentz forces come into play.

It is clear from these arguments that the derivation of the full details of the pulsational velocity field from observed line-profile variations cannot be a simple task. Nevertheless, the richness of the information in these type of data is such an asset compared to photometric data (which essentially only allow estimation of ℓ) that spectroscopic mode identification has become an entire subfield by itself within asteroseismology.

Fairly recent overviews of the methodology for spectroscopic mode identification, ideally suited for the unexperienced reader, are available in Telting & Schrijvers (1997), Aerts & Eyer (2000), and Mantegazza (2000). Rather than repeating what is available in these papers, we point out two newer versions of the methods available since then. One is the numerical implementation of the so-called moment method (Briquet & Aerts 2003). In this work, the authors have generalised previous versions of this technique, which is based on the time-variations of the lowest-order moments of a line profile and which works well for slow rotators, to multiperiodic pulsators. It has meanwhile been applied to several stars whose pulsational broadening dominates over rotational and intrinsic broadening. Zima (2006), on the other hand, generalised the Telting & Schrijvers (1997) method, which is based on the amplitude and phase variations of the modes across the line profile, to include a statistical significance criterion for the mode identification and applied it to the rapidly-rotating δ Sct star FG Vir (Zima et al. 2006). A recent combined application of both methods to the pulsations of the β Cep star ν Eri, observed during a multisite campaign, was made by De Ridder et al. (2004), while De Cat et al. (2005) applied both techniques to the observed line-profile variations of several slowly pulsating B stars.

In all of the abovementioned examples, one carefully selected isolated and unblended spectral line was used for the analysis. This is a good strategy whenever pulsation amplitudes above a few km/s are encountered and when the required temporal resolution is achieved. For lower-amplitude pulsators, however, or when time-resolved spectroscopy leads to a too low signal-to-noise ratio, one may also apply the methodology discussed above to a time series of cross-correlation functions (CCFs) derived from different lines in the spectrum. This induces complications, however, because one takes a weighted average over a much more extended line-forming region in the stellar atmosphere compared to the case where one uses only one line. The pulsation amplitude and phase may have slightly different behaviour across this whole region, such that one models their average value in that case. This works fine on the condition that no nodal surfaces of the pulsation eigenfunction occur in the line-forming region. An adaptation of the moment method in such a case was already made by Mathias & Aerts (1996), who applied it to the low-amplitude ($< 5\,$km/s) $\delta\,$Sct star 20 CVn. More recently, Aerts et al. (2004) and De Cat et al. (2006) also used CCFs to analyse extensive spectroscopic data of a sample of $\gamma\,$Dor stars, with pulsation amplitudes typically below 2 km/s.

3 Towards lower amplitudes

The first and so far only application of the line-profile methodology to solar-like oscillations with finite lifetimes was made by Hekker et al. (2006). They used extensive time series of CCFs of four pulsating red giants derived from CORALIE spectra obtained with the 1.2m Euler telescope in an attempt to identify the pulsation modes. Their results are based on a simulation study in which they assessed the effect of the finite mode lifetime on the line-profile diagnostics, resulting in the conclusion that the phase across the CCF can no longer be used for mode identification. Due to this, and the very low amplitudes of $\sim$m/s, only an estimate of (ℓ, m) of the dominant mode could be obtained. This led to the surprising result that these stars seem to have non-radial modes, while it was assumed so far in the modelling that the frequencies were due to radial modes. The application to solar-like pulsators is of relevance for exoplanet search as well, since a Keplerian radial-velocity shift is then superimposed on the pulsation velocity. It remains to be studied how well one can separate between those two effects at such low amplitudes.

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