Spectroscopic observations for asteroseismology

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Abstract. Spectroscopic observations of stellar oscillations provide an indispensable input for asteroseismology. High-resolution and high signal-to-noise ratio time-series spectroscopy can reveal radial velocity variations as well as profile variations in stellar absorption lines which are caused by non-radial pulsations. Oscillations in solar-like stars have been detected in radial velocity measurements obtained with stabilized spectrographs. For hotter stars on the main sequence, besides for the purpose of abundance analyses, spectroscopy is mainly acquired to carry out mode identification, the assignment of the spherical degree $\ell$, and the azimuthal order $m$, to the observed pulsation frequencies. It has been demonstrated for several stars on the main sequence hotter than the sun that only combined spectroscopic and photometric time-series measurements can lead to successful seismic modeling. In this article, I will focus on the application of spectroscopic mode identification on pulsating stars and discuss some recent results.

1. Introduction
Spectroscopy provides essential information and tools to enable a successful application of asteroseismology and thus to improve our knowledge of the stellar interior. In general, asteroseismology is applied by matching observed and theoretical frequency values. The former can be derived from time-series measurements using photometry or spectroscopy, whereas the latter are computed from evolutionary seismic models. The seismic investigation of solar-like stars can be carried out by comparing the frequencies detected from radial velocity measurements with theoretical values. Due to asymptotic theory the frequency spacing of successive radial overtones of the high-order $p$-modes is regular and can be used to derive the pulsational quantum numbers, the spherical degree $\ell$, the azimuthal order $m$, and the radial order $n$. Small deviations from the regularity provide additional seismic information.

For stars on the main sequence hotter than the sun the situation is much more complicated. There is generally no regular frequency spacing present and a simple matching of observed and theoretical frequencies is in general not sufficient to pinpoint a single seismic model. The reasons for this complication are manifold. Objects like $\delta$ Scuti or $\beta$ Cep stars pulsate with low-radial order and low-degree $p$-modes where asymptotic theory does not apply. In theory, the period spacing should be regular in case of high-radial order $g$-mode pulsators such as the $\gamma$ Dor or the slowly pulsating B-stars, but such a situation has not yet been observed. Especially in more evolved stars\(^1\), only a fraction of the predicted pulsation frequencies is actually observed due to a yet unknown mode-selection mechanism. The rotational splitting is not symmetric and in fast rotators, the frequencies of rotationally split modes having successive radial overtone can

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\(^1\) With evolved, here stars close to the terminal age main-sequence are meant.
overlap. Eventually, in evolved stars, mixed modes that have $g$-mode character close to the core and $p$-mode character at the stellar surface furthermore complicate the frequency spectrum.

To limit the number of possible seismic models, we need to determine the pulsational quantum numbers of at least a few frequencies. We require a mode identification based on other observables than the frequency. Non-radial stellar oscillations give rise to intensity variations in absorption lines formed in the stellar atmosphere. A detailed study of the resulting line profile variations can reveal the pulsation frequency, $\ell$, $m$, the inclination of the rotation axis with respect to the observer, and rotational parameters.

Several different methods to study and analyze line profile variations of non-radially pulsating stars have been developed so far, among which the most successful have been the moment method ([1] [2] [3]), the intensity-period-search method (IPS method, [4]), and the pixel-by-pixel method (PbP method, [5]). Recently, the Fourier parameter fit method (FPF method, [6]) which extends the two latter methods by deriving the statistical confidence of obtained identifications, has been presented. These methods rely on the intensity variations of the wavelength bins across the line profile, which are caused by local deviations of the stellar atmosphere's velocity, temperature, and brightness. Successful mode identification requires high S/N (> 200) and high resolution (R > 40000) time-series spectra, which are ideally accompanied by photometry. Since the sensitivity of the different methods differs in term of the accuracy for the determination of $\ell$ and $m$, complementary application of at least two methods is highly advisable.

2. Spectroscopic mode identification

Mode identification, the assignment of $\ell$ and $m$ to at least some of the observed pulsation frequencies, is presently one of the most important side-fields of asteroseismology. The more frequencies we can identify, the better our constraint on the theoretical models becomes and the better we can determine the internal structure. From the study of the amplitude ratio and phase shift of frequencies measured in different photometric passbands ([7] [8]), the degree $\ell$, can be deduced. For the determination of $m$, it is necessary to study the profile variations of absorption lines caused by the non-radial pulsations. One of the main disadvantages of mode identification from photometry is its strong dependence on the applied oscillation theory. Spectroscopic methods basically only depend on the description of the pulsational velocity field, which is in generally assumed to be a superposition of spherical harmonics.

The idea of utilizing the moments of a line as mode discriminator was introduced by Balona [1], refined by Aerts et al. [9] and optimized for multi-periodic pulsators by Briquet & Aerts [3]. This method has been successfully applied to several slowly rotating $\beta$ Cep (see [10]) and slowly pulsating B stars (see [11]). It relies on the fact that the line profile can be completely described by its first three moments, which correspond to radial velocity, the width of the line profile and its skewness. The identification is carried out by minimizing a discriminant, which is calculated on the basis of the error-weighted comparison between the observationally and theoretically derived time-series of the first three moments. The present version of the moment method takes first order effects of the rotation into account and can be applied to multi-periodic stars having up to six pulsation frequencies. A persisting problem of this method is the impossibility to take into account confidence limits which could enable to select between the many competing solutions.

Since the moments are integrated values across the line, this method can be applied to very slowly rotating stars and to stars having radial velocity amplitudes of the order of their projected rotational velocity. The moment method can be applied to identify pulsation modes with a degree $\ell \leq 4$.

The other mentioned set of methods, the IPS, PbP and FPF methods, rely on the rotational Doppler broadening of the line profile and thus permit a better mode discrimination for rotating stars having a $v \sin i$ above 10 km s$^{-1}$. These methods make use of the fact that the intensity
of every pixel across a line profile varies with the period of each pulsation mode. It is thus possible to use, e.g., Fourier techniques to search for pulsation frequencies and to compute a multi-periodic least-squares fit for each wavelength bin and derive zero-point, amplitude and phase as a function of the position in the line profile. The resulting red-to-blue distribution of amplitude and phase depend on $\ell$, $m$, the amplitude, the inclination and $v \sin i$.

The FPF method is a generalization of the IPS and the PbP method and introduces a statistical criterion to select between the solutions by taking into account the uncertainties of the observed amplitude and phase. The observed zero-point, amplitude and phase are fitted with corresponding values which are determined from synthetic line profiles and a best solution is determined by applying chi-square minimization methods. The FPF method can be applied both to stars pulsating with low-degree and high-degree modes. It provides a better constraint on $m$ for slow rotators, whereas for fast rotators the constraint is better on the value of $\ell$. This method has been applied to the $\delta$ Sct star FG Vir [12], where 12 non-radial pulsation modes could be identified and the inclination angle determined, and to a sample of SPB stars ([13]; De Cat et al. 2008, in preparation)

In the following I will summarize some important results obtained from spectroscopy of different types of pulsators.

3. Solar-like stars
Since the first confirmed discovery of solar-like $p$-mode oscillations in $\alpha$ Cen A by Bouchy & Carrier [14], in at least 15 other stars solar-like oscillations have been detected. These oscillations are caused by stochastic excitation due to convection and thus the pulsation modes have limited life-times. The oscillations have periods between a few minutes and about two hours and radial velocity amplitudes from the order of m $s^{-1}$ to as low as a few cm $s^{-1}$. Of course the detection of such low amplitudes requires stabilized spectrographs and the combination of thousands of absorption lines by cross-correlation techniques to acquire a sufficient signal-to-noise ratio. Most discoveries have been acquired with iodine or thorium cell calibrated spectra obtained with stabilized Echelle spectrographs such as HARPS, CORALIE, UVES or UCLES.

One of the best examples is $\alpha$ Cen A which pulsates with more than 40 frequencies having amplitudes between 10 and 50 cm $s^{-1}$. A mode identification was acquired by Bedding et al. [15] who identified spherical degrees $\ell$ between 0 and 3. Fletcher et al. [16] and Bazot et al. [17] have recently found evidence of rotational splitting in $\alpha$ Cen A.

Solar-like oscillations have been reported in $\epsilon$ Oph [18] and $\eta$ Set [19]. By analyzing the amplitude and phase across the line profile of the pulsation modes detected in $\epsilon$ Oph, Hekker et al. [20] showed the non-radial nature of the oscillations.

4. $\gamma$ Doradus stars
The $\gamma$ Dor stars are located just outside the cool border of the $\delta$ Sct domain and pulsate multi-periodically with $g$-modes of high radial order and low degree. Presently, about 70 bona fide objects of this class are known [21]. Their pulsations map the central regions around the core. Due to their periods of around one day they are very challenging targets for observational studies. At least four hybrid $\gamma$ Dor/$\delta$ Sct stars that simultaneously show $p$ and $g$-modes have been detected ([22] [23] [24] [25]). These stars have a great potential for asteroseismology since their pulsations probe at the same time the outer layers and the central regions.

Several systematic spectroscopic studies dedicated to $\gamma$ Dor stars have been carried out in the past few years, e.g., by Mathias et al. [26], Henry et al. [27], De Cat et al. [28] and Henry et al. [29]. They revealed radial velocity variations with amplitudes of up to 4 km $s^{-1}$ and in some targets line profile variations having periods between 0.3 and 1.9 d$^{-1}$. About a third of the sample are spectroscopic binaries in which generally only the primary component shows pulsations.
Most published spectroscopic observations are in fact field studies covering a large number of objects from a single observing site. It would be highly advisable to dedicate a combined photometric/spectroscopic campaign to a single target in the future in order to resolve the close frequency beating present in many $\gamma$ Dor stars and enable a mode identification.

5. $\delta$ Scuti stars

The $\delta$ Sct stars are pulsating variables in the stage of H core-burning located on and above the zero age main sequence and inside the classical Cepheid variability strip. The multi-periodicity of $\delta$ Sct star makes them excellent targets for the application of asteroseismology to main-sequence objects.

Especially the lack of successful seismic modeling of these stars led to an increased interest in spectroscopic mode identification in the past 15 years. In several rapid rotators, high-degree modes have been detected that elude photometric observations due to geometric canceling. Examples are V837 Cen [30] with $v \sin i = 132$ km s$^{-1}$ and BV Cir [31] with $v \sin i = 96$ km s$^{-1}$ that show pro-grade high-degree modes with $m$-values up to 14.

Significant advance in the study of $\delta$ Sct stars has been acquired with combined photometric/spectroscopic campaigns that have been organized for the slow rotators FG Vir and 44 Tau. More than 80 frequencies of FG Vir have been detected photometrically by Breger et al. [32] having Stromgren $y$ amplitudes between 20 and 0.2 mmag. A simultaneous spectroscopic multi-site campaign in 2002 lasting three months revealed 14 frequencies coincident with already detected photometric terms [12]. By means of the FPF method, twelve pulsation modes were identified as low-degree modes ($\ell \leq 3$, $-2 \leq m \leq 1$) and the inclination angle was determined to be 19°. By combining the photometric and spectroscopic data, Daszynska-Daszkiewicz et al. [33] concluded that convective transport in FG Vir’s envelope is inefficient. Seismic modeling of this object is currently ongoing.

![Figure 1](image-url)

**Figure 1.** Line profile variations of the $\delta$ Sct star 44 Tau measured at the Nordic Optical Telescope (La Palma, Spain, red lines) and at Tautenburg Landessternwarte (Germany, green lines) during 2004 Nov. 26/27. For a better representation, spectra taken at consecutive times are shifted vertically.

Another similar campaign of the $\delta$ Sct star 44 Tau revealed photometrically 13 independent
pulsation frequencies [34] of which 12 were also found from high-resolution spectroscopy [35]. Figure 5 shows high-resolution spectra of 44 Tau displaying the profile variations of three FeI lines. This star is an extremely slow rotator ($v \sin i = 2 \, \text{km s}^{-1}$) and seven of its pulsation modes were identified spectroscopically with low-degree modes, most of which seem to be axisymmetric. Independent seismic modeling, carried out by Lenz & Pamyatnykh [36] and Garrido et al. [37], showed that this star seems to be in a post-main-sequence stage of evolution, having moderate overshooting and inefficient convection.

6. roAp stars
The rapidly oscillating Ap stars are among the most peculiar and fascinating pulsators. Among the peculiarities of roAp stars are strong magnetic fields (kG), a generally non-uniform surface element distribution and a peculiar atmosphere element composition with rare earth elements (REE). According to present theory ([38] [39] [40]) these stars are oblique pulsators, i.e., the pulsational symmetry axis is not aligned with the rotation axis - as is the case for most other pulsating stars - but often aligned with the axis of the quasi-dipolar magnetic field. Most objects appear to be mono-periodic and pulsate with high-radial order low-degree ($\ell = 1$, $m = 0$) $p$-modes having periods between 6 and 21 min.

Recently obtained time-series spectroscopy of these stars has revealed that the line profile variability depends on the element considered. Generally, REE show the largest amplitudes whereas iron lines show low or no evident radial velocity variations (see, e.g., [41] [42] [43]). This behavior is best explained by a combination of element stratification in the outer atmosphere and a kind of Van Hoof-effect. Different lines probe different vertical layers in the stellar atmosphere and we can see the signature of the outwards propagating magneto-acoustic wave. Detailed spectroscopic analyses of these stars thus will enable us to directly map the atmosphere in three dimensions, something which yet has only been possible for the sun.

A full description of the observed line profile variations in roAp stars will require the consideration of the oblique pulsation, of a variable element abundance across the surface, and of depth effects in the present standard line synthesis codes.

7. Slowly pulsating B stars
Similar to the $\gamma$ Dor stars, the slowly pulsating B (SPB) stars pulsate with high-radial order $g$-modes which makes them excellent targets for the seismic study of the regions close to the convective core. Observational obstacles are their long periods of the order of days and a sparse detection of pulsation frequencies, which is in contrast to the thousands of modes that are predicted by seismic models.

A large scale study of southern SPB stars was carried out by De Cat et al. [44], who detected 7 mono-periodic and 6 multi-periodic objects. They utilized both, multi-color photometry and time-resolved high-resolution spectroscopy to search for pulsation frequencies and to provide mode identifications. Their results from applying photometric mode identification, the moment method [11] and the FPF method [13] showed that in most cases the pulsation can be described with a prograde dipole-mode ($\ell = 1$, $m = +1$).

Present ambiguities in the spectroscopic mode identification mainly arise due to the generally unknown rotation frequency and possible effects of recently detected magnetic fields in SPB stars [45].

8. $\beta$ Cephei stars
These massive B-stars pulsate with radial or non-radial low-radial order $p/g$-modes having periods of a few hours. In comparison to the $\delta$ Sct stars their structure is relatively simple due to the fact that only one convective region exists at the core. For some slow rotators successful seismic modeling could be achieved, among them HD 129929 ([46] [47]), $\nu$ Eri ([48] [49]) and $\theta$
Oph [50]. Mode identification from time-resolved high-dispersion spectroscopy, primarily with the moment method, has played a major role in successful seismic modeling of these β Cep stars. An extensive review about the status of β Cep stars from a spectroscopic point of view can be found in Aerts & De Cat [10].

A recent example where spectroscopic mode identification helped in the seismic modeling is θ Oph. A photometric campaign [51] led to the detection of seven pulsation frequencies between 7 and 8 d$^{-1}$. One radial mode was unambiguously identified from photometry but seismic modeling was ambiguous due to unknown $m$-values of an $\ell = 2$-multiplet. Spectroscopic data had been obtained during a three-year period between 2000 and 2003 [52]. Briquet et al. identified one component of the $\ell = 2$-multiplet by means of the moment method as ($\ell = 2, m = -1$), which enabled the identification of the complete multiplet. Seismic models based on the detected frequencies and the obtained photometric/spectroscopic mode identification [50] enabled to constrain the mass of the θ Oph, its central hydrogen abundance, the amount of core overshooting and the equatorial velocity.

Slow rotators are easier to model because higher order perturbations of the displacement field due to rotation may be neglected during modeling. This is the main reason why successes have been achieved with seismic modeling of slowly rotating β Cep stars, yet. Unfortunately, there is still a lack of multi-site spectroscopy of rapidly rotating β Cep stars which would permit to study effect of rotation on mode selection or on the internal element mixing.

9. The future
The future of time-resolved spectroscopy of pulsating stars looks very promising. More and more observing campaigns are organized to assist the seismic modeling with robust mode identifications. The next important steps from a point of modeling line profile variations will be the inclusion of the effects of fast rotation on the displacement field (see, e.g., [53], Daszynska-Daszkiewicz 2007, these proceedings), oblique pulsation in the presence of a magnetic field, surface abundance inhomogenities, and inclusion of the vertical structure of the velocity field.

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