Precision Asteroseismology
Proceedings IAU Symposium No. 301, 2013
J. A. Guzik, W. J. Chaplin, G. Handler & A. Pigulski, eds.

doi:10.1017/S1743921313014166

Identification of pulsation modes from spectroscopy

Katrien Uytterhoeven[1,2]

[1]Instituto de Astrofísica de Canarias,
38205 La Laguna, Tenerife, Spain
email: katrien@iac.es

[2]Departamento de Astrofísica, Universidad de La Laguna,
38200 La Laguna, Tenerife, Spain

Abstract. Time-series of high-resolution spectra of massive main-sequence pulsators contain information on the degree l and azimuthal number m of a pulsation mode. I present an overview of existing mode-identification techniques that have been developed to derive l and m from spectroscopic data. I also discuss the data quality needed to perform such a study. Through some examples from the literature I show that the optimal way to identify modes in heat-driven non-radial pulsators is by 1) using multi-site campaign data, 2) combining different spectroscopic mode-identification techniques, and 3) combining results from photometric and spectroscopic mode-identification studies.

Keywords. stars: oscillations, methods: data analysis, techniques: spectroscopic, line: profiles, stars: variables: δ Scuti, stars: variables: other

---

1. Introduction

Well-defined oscillation frequencies and their associated mode degree l, preferably in combination with constraints on the azimuthal number m, are indispensable for asteroseismic modelling. In case of the Sun, solar-like oscillators, and white dwarfs, the values (l, m) can be derived from equidistant frequency or period spacings. Other methods are needed to determine (l, m) for heat-driven non-radial pulsators such as β Cephei, δ Scuti, γ Doradus, and Slowly Pulsating B (SPB) stars. Generally, their frequency spectra do not show particular frequency patterns, and can be sparse or dense (see, e.g., Uytterhoeven *et al.* 2011; Balona *et al.* 2011). I present here an overview of existing mode-identification (mode-ID) techniques that mainly are applicable to massive ($M > 1\,M_{\odot}$) main-sequence pulsators. Note that some of the techniques have also been successfully applied to subdwarf B-type (sdB) stars (Telting *et al.* 2008).

Most mode-ID techniques are based on a comparison between observations and oscillation theory. The observables used are generally the frequency of the oscillation, its associated amplitude in a specific passband or in radial velocity, and the phase with respect to a reference epoch. Techniques used for mode identification based on multi-colour photometry are discussed in the overview by Breger (these proceedings). Here I focus on techniques based on high-resolution spectroscopy.

The advantage of spectral time-series is that they contain information on both l and m values through the principle of Doppler Imaging. As there is a one-to-one correlation between the position on the stellar surface and the position in the line profile of a rotating star, stellar pulsation velocity field variations on the stellar surface and photospheric pulsational temperature and gravity variations give rise to so-called line-profile variations (LPVs). Through an analysis of LPVs wave numbers can be identified.

2. Spectroscopic mode-identification techniques

I discuss here the main features, advantages, and disadvantages of the three main mode-ID techniques that have been developed since the 1970s, and refer to other reviews for additional discussion on the different spectroscopic techniques that are in use (e.g. Aerts & Eyer 2000; Mantegazza 2000; Telting 2003).

2.1. *Line Profile Fitting*

The Line Profile Fitting technique was developed following the advent of the first high-resolution spectra in the late 1970s–early 1980s (Smith 1977; Campos & Smith 1980a,b; Baade 1982, 1984; Smith 1983). This technique relies on a comparison between observed LPVs and theoretical profiles, whereby the theoretical line profiles are computed for a large grid of the pulsational and rotational parameters. Disadvantages of the Line Profile Fitting technique include: 1) the calculation of the theoretical profiles is very time-consuming; 2) there are many free parameters involved in the fitting; 3) there is no unique solution as several combinations of (l, m) might give similarly good results; 4) the selection of the *best* set of parameters is subjective, unless the code includes the calculation of a standard deviation per wavelength pixel; 5) the fitting is limited to mono-periodic pulsators. The main advantage of Line Profile Fitting is that it is an excellent tool to fine-tune parameters that are already constrained. The advice is hence to use the Line Profile Fitting technique in combination with other mode-ID techniques.

2.2. *Moment Method*

The Moment Method is based on the analysis of the time variations of the velocity moments of a line profile, which determine the shape of the line profile in a quantitative way. For instance, the first moment $\langle v \rangle$ is a measure for the centroid of the line profile, i.e. the radial velocity, the second moment $\langle v^2 \rangle$ defines the variance of the line profile, i.e. the equivalent width, and the third velocity moment $\langle v^3 \rangle$ measures the skewness of the line profile. This method was first proposed by Balona (1986a,b; 1987), and was further developed by Aerts *et al.* (1992), Aerts (1996), and Briquet & Aerts (2003). In the latest version by Briquet & Aerts (2003), the observed moments and their amplitudes are compared with theoretically calculated moments using an elaborate weighing function, called discriminant. The lower the value of the discriminant, the better the fit. In addition to an identification of (l, m), the Moment Method provides also constraints on the inclination angle between the stellar rotation axis and the line of sight (i), the projected rotational velocity ($v \sin i$), and the intrinsic width of the line profile (σ). The expected accuracy on the determined values is $l \pm 1, |m| \pm 1$.

Disadvantages of the Moment Method are: 1) the method is restricted to the identification of low-degree modes ($l \leqslant 4$); 2) there does not exist a statistical criterion to quantify the significance of the obtained solutions. As a result, several of the highest-ranked solutions need to be considered for further analysis. Further constraints on the best (l, m)-couple can be obtained by confrontation with Line Profile Fitting. Advantages are: 1) the method works well for multi-periodic stars; 2) the method works also for slow rotators.

As a side note I mention a spin-off technique of the Moment Method developed and applied to B-type stars by Cugier *et al.* (1994), Cugier & Daszyńska (2001), and Daszyńska-Daszkiewicz *et al.* (2003, 2005). The technique is based on both observed velocity moments and photometric observables in combination with linear non-adiabatic pulsation models, and allows the unambiguous identification of l through the construction of a parameter f that describes the ratio between the relative luminosity variations and the

https://doi.org/10.1017/S1743921313014166 Published online by Cambridge University Press

relative radial displacement of the stellar surface. The method has also been successfully applied to a pulsating subdwarf (Baran *et al.* 2008).

2.3. *Doppler Imaging*

The third and most used mode-ID technique is Doppler Imaging, which relies on the Fourier analysis of the observed intensity variations at each position in the line profile. The LPVs in Fourier space can be described by the distributions of the amplitude and phase variations across the line profile for each detected frequency, which are a direct measure for the mode parameters l and m. No modelling is involved in the direct application of this technique. The first concept of the Doppler Imaging technique was outlined by Vogt & Penrod (1983), and since then several versions have been developed (e.g. Gies & Kullavanijaya 1988; Kennelly *et al.* 1992; Telting & Schrijvers 1997; Mantegazza 2000; Zima 2006). I focus here on two of the best known versions of the Doppler Imaging technique, the Intensity Period Search (IPS) method and Fourier Parameter Fit (FPF) method, and compare their performance.

• **Intensity Period Search (IPS) Method** (Telting & Schrijvers 1997): (l, m)-values are determined for each frequency relying on the concept that the phase difference of a frequency ν in the phase diagram is an indicator for the value of the degree l, while the phase difference of its first harmonic (2ν) is a measure for $2|m|$. Also high-degree modes (up to $l \leqslant 20$) can be identified with the IPS method. The expected accuracy on the determined values is $l \pm 1, |m| \pm 2$.

The main disadvantage of the IPS method is that only l and m are constrained, with no information on other parameters such as i, $v \sin i$, or σ. Advantages are: 1) there is no modelling involved; 2) the method works for both mono- and multi-periodic stars; 3) the method can handle fast rotation.

• **Fourier Parameter Fit (FPF) Method** (Zima 2006): (l, m)-values are determined for each frequency by computation of the zero point, the amplitude, and phase for every wavelength bin across the line profile and by comparison with theoretically calculated values using a χ^2-test to assess the significance. For $m \leqslant 2$, the azimuthal number is unambiguously identified. For other values, the expected accuracy is $l \pm 1, |m| \pm 1$. The FPF method works best for slow to moderate rotators ($v \sin i < 100$ km s^{-1}).

The main disadvantage of the FPF method is that it is very time consuming given the computation of the theoretical values. Advantages are: 1) the $|m|$-value is extremely well constrained; 2) the method provides additional constraints on i and $v \sin i$; 3) the method works for both mono- and multi-periodic stars.

2.4. *Comparison between the different methods*

In Table 1 I provide a schematic comparison between the different spectroscopic mode-ID techniques discussed. The main conclusions are that the Moment Method and Doppler Imaging technique are complementary, and that the Line Profile Fitting technique is only efficient when the parameters are already constrained. In that case Line Profile Fitting helps to narrow down the number of possible (l, m) solutions.

Finally, I point out that there exists a freely available software package FAMIAS†, created by Zima (2008), aimed for the frequency analysis and mode identification of main-sequence pulsators, that includes the Moment Method and FPF method.

† The software package FAMIAS is freely downloadable from http://www.ster.kuleuven.be/~zima/famias/.

https://doi.org/10.1017/S1743921313014166 Published online by Cambridge University Press

Table 1. Comparison between different spectroscopic mode-ID techniques (+: yes; −: no; .: ?).

	Line Profile Fitting	Moment Method	IPS method	FPF method
can handle fast rotators	+	−	+	−
can handle slow rotators	+	+	−	+
sensitive to sectoral modes ($\vert m\vert = l$)	.	−	+	+
sensitive to zonal modes ($m = 0$)	.	+	−	−
modelling involved	+	+	−	+
can handle multiperiodicity	−	+	+	+
constraints on extra parameters	+	+	−	+
detection limit l	.	$\leqslant 4$	$\leqslant 20$	$\leqslant 4$

3. Quality requirements of the spectral time-series and challenges

The mode-ID techniques described above are applied to spectral time-series. Below is a list of the main requirements of the spectra and related challenges.

3.1. *High-resolution spectra*

Spectral mode identification requires time-series of high-resolution spectra. A spectral resolution of at least $R = 40\,000$, preferably $R > 60\,000$, is needed to properly resolve the LPVs caused by the oscillations. Unfortunately, not many specialized spectroscopic instruments are available for long-term monitoring. High-resolution spectrographs are mainly attached to 1 to 2-m class telescopes, with the consequence that currently spectral mode identification is generally limited to bright targets ($V \leqslant 8$ mag for pulsators with pulsation periods of the order of a few hours or shorter).

3.2. *High signal-to-noise spectra*

A second requirement to perform an analysis of LPVs is a signal-to-noise ratio (SNR) per pixel of preferably at least 200. How easy a high-SNR value is obtained in a reasonable exposure time depends on the efficiency of the spectrograph. To have a good phase coverage of the oscillation period, the exposure time should not exceed 10% of the pulsation period. Again, this implies that spectroscopic time-series are only feasable for bright targets with 2-m class telescopes. The use of cross-correlation techniques, such as the Least-Squares Deconvolution (LSD) method (Donati *et al.* 1997), has allowed the analysis of LPVs from low-SNR spectra as the spectral information of all available lines in the spectrum is collapsed into one cross-correlation profile of much higher SNR. The disadvantage of cross-correlation techniques is that information on individual lines formed in different layers of the atmosphere is lost. On the other hand, the main advantage is that mode identification has become possible for slightly fainter stars ($V \leqslant 9.5$ mag for pulsators with pulsation periods of order of a few hours; $V \leqslant 11$ mag for pulsators with pulsation periods of order of a day, when using 2-m-class telescopes). As a side note I want to add that it is extremely difficult to obtain a high-quality spectral time-series for *Kepler* targets as most of them are fainter than $V = 11$ mag.

3.3. *Long time span*

To be able to resolve harmonic, sum and beat frequencies a sufficiently long time span of the spectral time series is needed. This means (continuous) monitoring of the target for several weeks to months. As long-term access to a single telescope is generally not feasible, unless when using a dedicated telescope such as the 1.2-m Mercator telescope with HERMES spectrograph on La Palma, and as single-site observations leave gaps in the time-series, the best way to go are multi-site campaigns. The success of dedicated observing campaigns using spectroscopic instruments at different observing sites for purposes of

https://doi.org/10.1017/S1743921313014166 Published online by Cambridge University Press

mode identification is proven by several examples (e.g. ν Eri: De Ridder *et al.* 2004; FG Vir: Zima *et al.* 2006; 12 Lac: Desmet *et al.* 2009; the *CoRoT* ground-based follow-up observations: Uytterhoeven *et al.* 2007). An alternative is the use of a dedicated network of robotic telescopes, such as the upcoming SONG network (Stellar Observations Network Group, Grundahl *et al.*, these proceedings; Uytterhoeven *et al.* 2012).

3.4. *Substantial number of spectra*

To successfully identify some of the observed pulsation modes, the time-series need to consist of a substantial number of spectra. The following empirical rule is valid: 'the more modes you want to identify, the more spectra you need'. There seems to be a correlation between the number of spectra in the time series and the number of modes that can be identified. Be aware that for each mode you want to identify, you need at least 200–300 spectra (accumulative).

4. Successful studies

Next, I present the successful application of spectroscopic mode-ID techniques using examples from the literature. The main aim is to illustrate the importance of, on the one hand, combining different techniques, and, on the other hand, combining photometric and spectroscopic data, to come to a unique mode identification.

4.1. *The power of combining multi-colour photometry and spectroscopy*

The hybrid β Cephei/SPB star 12 Lac was the subject of an extensive and dedicated photometric and spectroscopic multi-site campaign. From the 750 hours of available multi-colour photometric data Handler *et al.* (2006) constrained the degree l of *five* modes. Using the Moment Method and the FPF method on a time-series consisting of 1820 spectra Desmet *et al.* (2009) arrived at an unique identification of (l, m) for *four* of the highest amplitude modes. Subsequently, Daszyńska-Daszkiewicz *et al.* (2013) used amplitudes and phases from the different passbands and the first moment, the so-called non-adiabatic observables, to construct the f parameter (see Sect. 2.2). They arrived at an unique identification of l for *six* modes. This example shows that the maximum amount of information on the mode parameters only can be obtained by combining photometric and spectroscopic methods.

4.2. *The power of combining different spectroscopic mode-identification techniques*

From a photometric and spectroscopic multi-site campaign on the β Cep star HD 180642, resulting in 1234 multi-colour photometric points and 262 high-resolution spectra, Briquet *et al.* (2009) detected a dominant frequency and several low-amplitude frequencies. From photometry the dominant mode was identified as radial, while identification of l was possible for two additional non-radial modes. The spectroscopic mode-ID of the additional modes turned out to be very challenging due to the radial mode with very high amplitude that dominates the LPVs. Customized versions of the Moment Method and the FPF method were needed to arrive at a satisfactory solution. Only thanks to combining the results from the two spectroscopic mode-ID techniques it was possible to unambiguously identify one of the additional modes as a (3, 2)-mode.

4.3. *Recent results*

Finally, I provide a short overview of recent studies on spectroscopic mode identification in main-sequence pulsators.

The *CoRoT* ground-based spectroscopic follow-up observations allowed the identification of pulsation modes in the β Cephei stars HD 180642 (Briquet *et al.* 2009) and HD 43317 (Pápics *et al.* 2012), the Be stars HD 49330 (Floquet *et al.* 2009) and HD 181231 (Neiner *et al.* 2009), the δ Scuti stars HD 50844 (Poretti *et al.* 2009) and HD 50870 (Mantegazza *et al.* 2012), and the hybrid γ Doradus/δ Scuti star HD 49434 (Uytterhoeven *et al.* 2008).

Other spectroscopic multi-site campaigns were carried out on the γ Doradus stars HD 12901 and HD 135825 (see Brunsden *et al.*, this volume; Brunsden *et al.* 2012a,b) and the β Cephei star V2052 Oph (Briquet *et al.* 2012).

5. A view on the future and conclusions

5.1. *Near-infrared spectroscopy*

A new and innovative way of deriving mode parameters from spectra might be the use of near-infrared spectroscopic data. Near-infrared spectra probe different parts of line-forming regions in the atmosphere with respect to visual spectra, and might hence provide extra information for the identification of modes. This technique might be worth exploring for lower mass main-sequence stars, as they are cool enough to produce spectral lines in this wavelength region. A pilot study has already been performed by Amado (2007) for a high-amplitude δ Scuti (HADS) star, and LPVs have been detected in the near-infrared spectral region of CRIRES/VLT spectra. Additional observational and theoretical work is needed to investigate this option further. The future instrument CARMENES (Quirrenbach *et al.* 2012) at the 3.5-m telescope at Calar Alto observatory might be the perfect spectrograph for dedicated observing campaigns in the near-infrared.

5.2. *Network of robotic telescopes*

Upcoming networks of small robotic telescopes equipped with a high-resolution spectrograph such as SONG or LCOGT (Las Cumbres Observatory Global Telescope Network), dedicated to asteroseismic studies in the former case and to all types of variability studies in the latter case, will facilitate the gathering of continuous time-series needed for mode identification of main-sequence pulsators for selected bright targets ($V \leqslant 5$ mag).

5.3. *Spectroscopic mode identification for faint stars?*

Optimally, one needs easy access to 8-m class telescopes equipped with a high-resolution spectrograph for long-term monitoring to broaden the pool of targets that can be studied for mode identification from bright to fainter stars. However, this wish probably will not be granted in the coming few years.

5.4. *To conclude*

To conclude, it has become clear that the best way forward for obtaining a reliable mode identification in heat-driven main-sequence pulsators is the combined use of different techniques, whereby joining photometric and spectroscopic data.

Acknowledgements

KU acknowledges funding by the Spanish National Plan of R&D for 2010, project AYA2010-17803.

References

Aerts, C. 1996, *A&A*, 314, 115

Aerts, C. & Eyer, L. 2000, *ASP-CS*, 210, 113
Aerts, C., de Pauw, M., & Waelkens, C. 1992, *A&A*, 266, 294
Amado, P. J. 2007, *CoAst*, 151, 57
Baade, D. 1982, *A&A*, 105, 65
Baade, D. 1984, *A&A*, 135, 101
Balona, L. A. 1986a, *MNRAS*, 219, 111
Balona, L. A. 1986b, *MNRAS*, 220, 647
Balona, L. A. 1987, *MNRAS*, 224, 41
Balona, L. A., Pigulski, A., De Cat, P., *et al.* 2011, *MNRAS*, 413, 2403
Baran, A., Pigulski, A., & O'Toole, S. J. 2008, *MNRAS*, 385, 255
Briquet, M. & Aerts, C. 2003, *A&A*, 398, 687
Briquet, M., Uytterhoeven, K., Morel T., *et al.* 2009, *A&A*, 506, 269
Briquet, M., Neiner, C., Aerts, C., *et al.* 2012, *MNRAS*, 427, 483
Brunsden, E., Pollard, K. R., Cottrell, P. L., Wright, D. J., & De Cat, P. 2012, *MNRAS*, 427, 2512
Brunsden, E., Pollard, K. R., Cottrell, P. L., Wright, D. J., De Cat, P., & Kilmartin, P. M. 2012, *MNRAS*, 422, 3535
Campos, A. J. & Smith, M. A. 1980a, *ApJ* 238, 250
Campos, A. J. & Smith, M. A. 1980b, *ApJ* 238, 667
Cugier, H. & Daszyńska, J. 2001, *A&A*, 377, 113
Cugier, H., Dziembowski, W. A., & Pamyatnykh, A. A. 1994, *A&A*, 291, 143
Daszyńska-Daszkiewicz, J., Dziembowski, W. A., & Pamyatnykh, A. A. 2003, *A&A*, 407, 999
Daszyńska-Daszkiewicz, J., Dziembowski, W. A., & Pamyatnykh, A. A. 2005, *A&A*, 441, 641
Daszyńska-Daszkiewicz, J., Szewczuk, W., & Walczak, P. 2013, *MNRAS*, 431, 3396
De Ridder, J., Telting, J. H., Balona, L. A., *et al.* 2004, *MNRAS*, 351, 324
Desmet, M., Briquet, M., Thoul, A., *et al.* 2009, *MNRAS*, 396, 1460
Donati, J.-F., Semel, M., Carter, B. D., Rees, D. E., & Collier Cameron, A. 1997, *MNRAS*, 291, 658
Floquet, M., Hubert, A.-M., Huat, A.-L., *et al.* 2009, *A&A*, 506, 103
Gies D. R. & Kullavanijaya A. 1988, *ApJ*, 326, 813
Handler, G., Jerzykiewicz, M., Rodríguez, E., *et al.* 2006, *MNRAS*, 365, 327
Kennelly, E. J., Walker, G. A. H., & Merryfield, W. J. 1992, *ApJ*, 400, L71
Mantegazza, L. 2000, *ASP-CS*, 210, 138
Mantegazza, L., Poretti, E., Michel, E., *et al.*, 2012, *A&A*, 542, A24
Neiner, C., Gutiérrez-Soto, J., Baudin, F., *et al.* 2009, *A&A*, 506, 143
Pápics, P. I., Briquet, M., Baglin, A., *et al.* 2012, *A&A*, 542, 55
Poretti, E., Michel, E., Garrido, R., *et al.* 2009, *A&A*, 506, 85
Quirrenbach, A., Amado, P. J., Seifert, W., *et al.* 2012, in: *Ground-based and Airborne Instrumentation for Astronomy IV*. Proceedings of the SPIE, Vol. 8446, 84460R
Smith, M. A. 1977, *ApJ*, 215, 574
Smith, M. A. 1983, *ApJ*, 265, 338
Telting, J. H. 2003, *Ap&SS*, 284, 85
Telting J. H. & Schrijvers C. 1997, *A&A*, 317, 723
Telting, J. H., Geier, S., Østensen, R. H., *et al.* 2008, *A&A*, 492, 815
Uytterhoeven, K. & Poretti, E., the *CoRoT* SGBOWG 2007, *CoAst*, 150, 371
Uytterhoeven, K., Mathias P., Poretti E., *et al.* 2008, *A&A*, 489, 1213
Uytterhoeven, K., Moya, A., Grigacène, A., *et al.* 2011, *A&A*, 534, A125
Uytterhoeven, K., Pallé, P. L., Grundahl, F., *et al.* 2012, *AN*, 333, 1107
Vogt S. S. & Penrod G. D. 1983, *PASP*, 95, 565
Zima, W. 2006, *A&A*, 455, 227
Zima, W. 2008, *CoAst*, 155, 12
Zima, W., Wright, D., Bentley, J., *et al.* 2006, *A&A*, 455, 235