Spectroscopic observations of pulsating stars

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Abstract

During the past three decades, astronomers have been gathering extensive time series of high-precision spectroscopy of pulsating stars. In contrast to one-shot spectra, which provide the fundamental parameters, time-resolved spectroscopy offers a much broader variety of input for asteroseismology. The most important applications encompass the determination of the radial-velocity amplitudes and phases of the modes, the detection of modes that are invisible in photometry, the identification of the azimuthal orders through specialised methodology, the unravelling of pulsational and orbital motions, and, since a few years, the detection of solar-like oscillations in various types of stars. We discuss the input that spectroscopic time series can provide for asteroseismic modelling, for various types of pulsators. We end with some future prospects of how spectroscopy can help to push seismic applications beyond the present achievements.

Individual Objects: β Cep, β CMa, ν Eri, θ Oph, δ Cet, FG Vir, Procyon, η Boo, α Cen A, β Hyi

Spectra for fundamental parameter determination

Time-resolved spectroscopy alone usually does not yet imply sufficient information to interprete the oscillation spectra of stars. The limited number of detected frequencies and lack of unambiguous mode identification on the one hand, and the limitations of the validity of the theoretical models on the other hand, require us to consider additional information to limit the grids of models for seismic tuning. This additional information usually consists of the fundamental parameters of the star, such as its effective temperature, gravity, luminosity, rotation velocity and abundances. A high-precision determination of the fundamental parameters of asteroseismic targets remains of importance. This can be achieved partly through photometric data, but the abundances and rotation information must come from high-resolution spectroscopy. Large systematic differences occur when comparing quantities derived from photometric calibrations and from spectroscopic diagnostics (e.g., De Ridder et al. 2004). It is obvious that photometric data, even for well-calibrated narrow filter systems, can never deliver the same accuracy as high signal-to-noise high-resolution spectroscopy. On the other hand, uncertainties in atmosphere model computations (e.g. in terms of atomic data, non-LTE effects, line blocking, mass loss effects, etc.) along with imperfect continuum normalisation imply systematic uncertainties.

Modern applications of spectroscopic fundamental parameter determination for various pulsators are available in, e.g., Gillon & Magain (2006), Morel et al. (2006), Lefever et al. (2007), Bruntt et al. (2008). These works all show that such type of classical work remains of importance, since more precise results are found each time the data
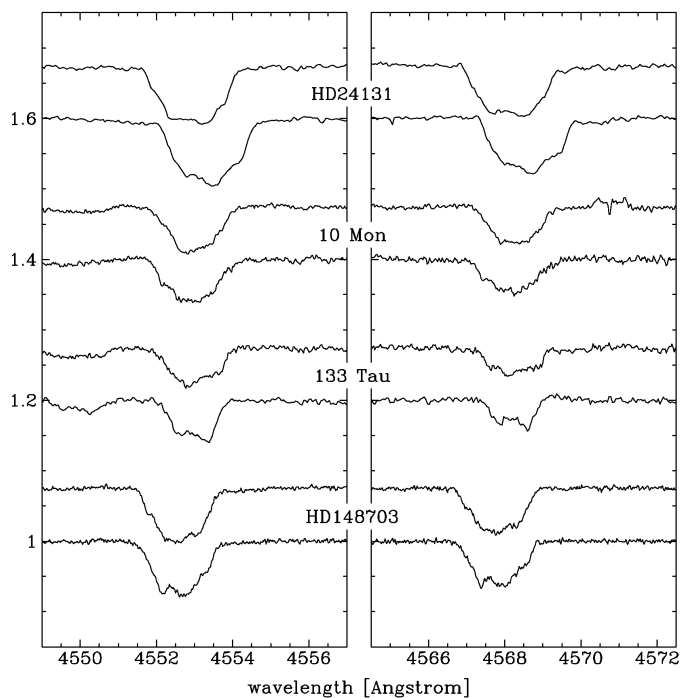
Figure 1: Snapshot spectra from the line-profile survey of bright B-type stars by Telting et al. (2006).

quality and model atmosphere computations improve. In particular, the addition of polari-
metric information besides classical spectroscopy has revealed a number of surprises, such as
the discovery of magnetic fields in hot Be stars (e.g., Neiner 2007 for a review) and in half
of the slowly pulsating B stars (Hubrig et al. 2006).

Precise abundance determinations are also relevant in the context of the discovery of
massive pulsators in the Magellanic Clouds (e.g. Kołaczkowski et al. 2006, Karoff et al. 2008,
Sarro et al. 2008). For the modes in such stars to be excited, a higher-than-average SMC
metallicity is needed (Miglio et al. 2007). This implies that the opacities are still too low
and/or atomic diffusion processes (Montalbán & Miglio 2008) are not yet well included in the
models.

Spectroscopic surveys to discover pulsators from line features

While large-scale photometric searches for new pulsators have been ongoing since the 1950s,
we had to await for improvements in the efficiency of high-resolution spectroscopic instru-
mentation, which was achieved only since the mid 1980s, to start systematic searches for
line-profile variables. At first this was done in a biased way, in the sense that the results
from photometric surveys were used for the target selection of the spectroscopic surveys,
e.g., Solano & Fernley (1997) for δ Sct stars, Aerts et al. (1999) for slowly pulsating B stars,
Mathias et al. (2004) and De Cat et al. (2006) for γ Dor stars, Kurtz et al. (2006) for roAp
stars, Lefever et al. (2007) for hot supergiants, etc.

Unbiased high-resolution spectroscopic surveys are scarce and still limited to bright stars.
A notable achievement was the long-term survey assembled by Telting et al. (2006) who took
spectra for an almost complete sample of stars with spectral type between B0 to B3 and
with visual magnitude below 5.5. They discovered that line-profile features occur in 65%
of their 171 monitored stars. Examples are shown in Fig. 1. While not necessarily all of

them are pulsators, this is a much higher percentage of variability than the one found from photometric surveys. The explanation is that most line-profile variables turn out to have bumpy line features, which points to modes of degree above 2, which have amplitudes too low to be detected in ground-based photometry. This result is in full agreement with the survey of 27 monitored bright southern early-type Be stars by Rivinius et al. (2003), who find 25 of them to be nonradial pulsators.

As a side result, spectroscopic binaries were discovered from these spectroscopic surveys. Each of the discovered line-profile variables is in principle suitable for seismic tuning. This requires dedicated long-term follow-up spectroscopy as described below, but with the additional challenge that we cannot rely on photometric time series to deliver the mode degrees.

Time series for radial-velocity variations of solar-like pulsators

The oscillations of the Sun are caused by turbulent convective motions near its surface. Such oscillations are thus expected to occur in all stars with outer convection zones. The first firm detection of individual frequencies was achieved from time-resolved spectroscopy of the G5IV star η Boo (Kjeldsen et al. 1995). Even though Brown et al. (1997) could not establish a confirmation of this detection, the result was confirmed by Kjeldsen et al. (2003) and Carrier et al. (2005). Solar-like oscillations were also definitely established in Procyon (Martić et al. 1999), in the G2IV star β Hyi (Bedding et al. 2001) as well as in the G2V star α Cen A (Bouchy & Carrier 2001).

With the availability of high-precision spectrographs, built mainly for planet hunting, more discoveries were made. Several review papers on this topic already exist, so we refer the reader to those rather than repeating them here (e.g., Bedding & Kjeldsen 2007). Meanwhile, solar-like oscillations have been firmly established in some 30 stars. Their position in the HR Diagram is provided in Aerts et al. (2008). Their frequency separations behave as expected from theoretical predictions and scaling relations based on extrapolations from helioseismology (e.g., Kjeldsen & Bedding 1995, Samadi et al. 2005).

The level of sophistication in the seismic modelling of solar-like oscillators is still far from the one in helioseismology. However, given that the detections were established only recently and that the space missions CoRoT and Kepler will add numerous cases of stars with uninterrupted photometry, we expect a breakthrough in the near future.

Time series for mode identification of classical pulsators

Pulsators excited by the κ-mechanism usually do not give rise to many detected frequencies, nor to frequency separations. Before seismic modelling can be attempted for such stars, it is necessary to achieve empirical mode identification based on data. The gathering and interpretation of time-resolved high-resolution spectroscopy for mode identification was pioneered in the 1980s by M. Smith and his collaborators as well as by D. Baade. These teams obtained such type of data with the very first high-resolution spectrographs for various types of pulsating stars along the main sequence and compared these with theoretical predictions through line-profile fitting (e.g., Campos & Smith 1980a,b; Baade 1982, 1984; Smith 1983, 1985a,b, 1986; Smith et al. 1984).

To make the mode identification more objective, quantitative spectroscopic mode identification methods have been developed meanwhile. The idea is to compute carefully defined diagnostics from the observed line profiles and compare them with theoretical predictions based on the theory of stellar oscillations. One such method is based on the moment variations of the spectral lines and was first introduced by Balona (1986a,b, 1987) and further developed by Aerts et al. (1992), Aerts (1996), Cugier & Daszyńska (2001) and Briquet & Aerts (2003). This method has meanwhile been applied to many different types of pulsators along the

Table 1: Comparison of the results for the mode identification of the δ Sct star FG Vir, as available in the literature. Whenever more than one value for ℓ or m is given in a column, discrimination among them was impossible.

Frequency d^{-1}	Viskum et al. (1998)	Breger et al. (1999)	Daszyńska-Daszkiewicz et al. (2005b)	Zima et al. 2006	
9.199	$\ell = 2$	$\ell = 2$	$\ell = 2$	$\ell = 1, 2, 3$	$m = +1$
9.656	$\ell = 2$	$\ell = 1, 2$	$\ell = 2$	$\ell = 0, 1, 2$	$m = 0$
12.154	$\ell = 0$	$\ell = 0$	$\ell = 0$	$\ell = 0, 1, 2$	$m = 0, +1$
12.716	$\ell = 1$	$\ell = 1$	$\ell = 1$	$\ell = 1$	$m = 0$
12.794	–	–	$\ell = 2, 1$	$\ell = 2, 3, 4$	$m = -2$
16.071	–	–	$\ell = 0$	–	–
19.227	–	–	$\ell = 2, 1, 0$	$\ell = 1, 2$	$m = +1$
19.867	$\ell = 2$	$\ell = 2$	$\ell = 2, 1$	$\ell = 0, 1, 2$	$m = 0$
20.287	–	–	$\ell = 0, 1$	$\ell = 1, 2, 3$	$m = -1$
20.834	–	–	–	$\ell = 2, 3, 4$	$m = +1$
21.051	$\ell = 2$	$\ell = 2$	$\ell = 1, 0$	$\ell = 0, 1, 2$	$m = 0$
23.403	$\ell = 0$	$\ell = 0, 1$	$\ell = 2, 1$	$\ell = 2$	$m = 0$
24.227	$\ell = 1$	$\ell = 1, 2$	$\ell = 1$	$\ell = 0, 1$	$m = 0$

main sequence (Aerts & De Cat 2003). It is very powerful for low-degree modes ($l \leq 4$) in slow rotators ($v \sin i \leq 50\,\mathrm{km\,s^{-1}}$). Another quantitative method was introduced by Gies & Kullavanijaya (1988) and further developed by Kennelly & Walker (1996), Telting & Schrijvers (1997), Mantegazza (2000) and Zima (2006). Applications are available in, e.g., Telting et al. (1997) for the star β Cephei and in Zima et al. (2006) for the δ Sct star FG Vir. Its strength is the relatively easy application to fast rotators ($v \sin i \geq 50\,\mathrm{km\,s^{-1}}$) with high-degree modes ($l \geq 4$). Both methods were integrated in the software package FAMIAS (Zima 2008). We refer to the review paper by Telting (2008, these proceedings) for illustrations and more details on their use. Examples were presented during the workshop by Pollard et al., Castanheira et al., Lehmann et al., Oreiro et al., Østensen et al., Vučković et al., Wright et al., Tkachenko et al., illustrating the need of, and interest in empirical mode identification for asteroseismology of classical pulsators.

One of the problems that occurred in the past for empirical mode identification was the inconsistency in the results derived from photometric observables (see review talk by Handler 2008) and spectroscopy. Recent studies have shown, however, that fully consistent solutions are found if one uses data from multisite multitechnique campaigns (e.g., De Ridder et al. 2004, Zima et al. 2006), pointing out that the previous discrepancies were probably due to unresolved beating phenomena and/or too uncertain amplitudes. Zima et al. (2006) succeeded to identify twelve modes for the δ Sct star FG Vir (Table 1).

Whenever modes are detected in both multicolour photometry and high-resolution spectroscopy, one can do better than simply compare the mode identification results by exploiting the data simultaneously. Daszyńska-Daszkiewicz et al. (2005a) added the amplitude and phase of the first moment to the multicolour amplitudes and phases in order to obtain a safer mode identification for the β Cep stars δ Ceti and ν Eridani. For such an application, the data should be taken quasi-simultaneously to avoid different beat patterns to occur in the two types of data. Daszyńska-Daszkiewicz et al. (2005a) also derived information on the most appropriate opacities to explain the modes. Mazumdar et al. (2006) and Briquet et al. (2007) used a different integration of both types of data, by imposing the identified degree ℓ from photometric amplitude ratios into the spectroscopic mode identification, leading to secure identification of the azimuthal order m. It is this combined method that led to successful seismic modelling of the β Cep stars β CMa and θ Oph.

Future improvements

The examples discussed above show how to pave the way to seismic modelling of classical pulsators: perform multisite and/or space photometric observations along with spectroscopic campaigns that cover the beat patterns of the oscillations. This is why a large programme of spectroscopy has been set up to accompany the CoRoT space photometry (e.g., Uytterhoeven et al. 2008).

Besides such long-term spectroscopic campaigns, one can gain from an integrated spectroscopic/interferometric approach. Cunha et al. (2007) provided a list of bright stars for which a direct radius estimate with a relative precision better than a few % can be obtained from VLTI/AMBER. Similarly, the masses of SB2 binaries with a pulsating component can be derived with a precision of only a few % by combining interferometric and spectroscopic monitoring (e.g., Ausseloos et al. 2006). The future upgrades of VLTI should also allow, in principle, the modes to be identified from spectro-interferometric data (e.g., Jankov et al. 2001). Finally, the Gaia space mission will deliver us accurate distances and, by implication, luminosities and radii of a vast amount of pulsators too faint to be analysed with VLTI.

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DISCUSSION

Kovács: What are expected photometric amplitudes for spectral line variables based on their observed spectroscopic data?

Aerts: From the mode identification and velocity amplitudes derived from spectroscopy, we find typically modes with degrees $\ell > 2$ and these would result in photometric amplitudes typically below 1 and occasionally a few mmag. You can thus see them in a quite long photometric time series or not at all. This is in agreement with time series assembled by the WIRE and MOST which reach lower amplitudes than typical ground-based photometric campaigns.