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Mode identification

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Pulsational mode identification from multi-colour photometry – an observer's point of view

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Abstract

We review the methods available to perform mode identification from time-series photometric measurements. Following the developments in time, we discuss the roots of the method, its basic methodology, extensions and improvements. Suggestions on the optimal choice of filters to apply the method are quoted and several practical applications are cited, with a focus on how additional astrophysical information was obtained at the same time. Finally, some practical considerations concerning observational mode discrimination from photometry are given, some pitfalls are discussed and a brief glimpse at future space data is made.

Individual Objects: 12 Lac, G226-29, PG 1351+489, 44 Tau, ν Eri, θ Oph

Why do we need observational mode identifications?

The goal of any proper asteroseismic study is the gain of knowledge of stellar structure and evolution. This is facilitated by the comparison of observed pulsational mode spectra with those predicted by theoretical models. The decisive requirement for any stellar model that deserves to be called *seismic model* is its uniqueness: each individual oscillation mode observed must be identified with its pulsational quantum numbers k, ℓ and m beyond any doubt, and (within reasonable limits) only one stellar model exists that can explain them all.

Unfortunately, the pulsation modes in real stars do not come labelled with their k, ℓ and m. In some cases, we are lucky to observe a fairly complete set of pulsational signals over some range of frequency. Because the frequencies of the stellar eigenmodes are not randomly distributed, frequency groups that have certain structure (e.g., frequency ratios of radial modes, equidistantly spaced frequencies/periods of p/g modes, rotationally split frequency multiplets) can aid the identification of the pulsation modes that cause them. This technique is called *pattern recognition* and has been applied successfully to white dwarf stars (e.g. Winget et al. 1991, 1994).

For most pulsators, the observed mode spectra are too sparse or too complicated (e.g. if rotationally split patterns of modes with different k and/or ℓ overlap in frequency) to facilitate pattern recognition. In such cases, we must resort to observational methods that give additional clues towards ℓ and m. Both photometric and spectroscopic techniques have been developed for this purpose. Whereas the latter are reviewed by Telting (2008), we will discuss the photometric methods in what follows.

Numerous excellent reviews on photometric mode identification are present in the literature, most recently by Daszyńska-Daszkiewicz (2008). Because the latest overview articles emphasized the theoretical aspects of mode identification, we here attempt to stress the issues relevant to observation.

A cautionary tale

Even in the presence of sparse observational mode spectra, it is tempting to apply pattern recognition methods (also named "mode identification by magic numbers", Breger 1989). One (in)famous example is the β Cephei star 12 Lacertae. Its five dominant pulsation frequencies have been known for a long time (Jerzykiewicz 1978).

Among them, an exactly equally spaced frequency triplet is present, and the obvious assumption is that it is due to rotational splitting. However, all interpretations in this direction failed because the splitting was "too equidistant". Therefore, hypotheses concerning resonant mode coupling were invoked to explain this triplet, and several papers were written on the subject.

Besides the equally spaced triplet, the present author noticed that the frequency ratio of two of the five then known pulsation modes was consistent with that of radial fundamental and first overtone mode pulsations - to the fourth digit! This would also solve the dilemma of the equally spaced triplet as the hypothesized first overtone mode corresponded to one of the triplet components.

Consequently, a photometric multisite campaign on 12 Lacertae was organized (Handler et al. 2006). From its multicolour data it became clear that the apparent rotationally split mode triplet consisted of an $\ell = 1$, an $\ell = 0$, and an $\ell = 2$ mode. The suspected radial modes both turned out to be $\ell = 2$. A spectroscopic multisite campaign (Desmet et al. 2008) confirms these results.

We conclude: apparent recognition of frequency patterns where there are none can lead to a lot of unnecessary work.

The basic idea

Dziembowski (1977) expressed the flux variations of a nonradially oscillating star mathematically. He then pointed out that the Baade-Wesselink method (developed to determine the radii of Cepheids by combining radial velocity and two-colour photometry over the pulsation cycle) can be used to infer the stellar radius if the spherical harmonic degree ℓ of the oscillation is known or, vice versa, to infer ℓ if the star's radius is known.

Buta & Smith (1979) and Balona & Stobie (1979a, b) reformulated Dziembowski's (1977) expressions for easier use with observational data and presented the first applications of the method. In particular, Balona & Stobie (1979b) showed that pulsation modes of different ℓ separate in a photometric amplitude ratio vs. phase shift diagram.

Robinson et al. (1982) adapted the calculations to the light variations of pulsating white dwarf stars and refined the method by including stellar model atmospheres, replacing the previously used blackbody spectral distributions or empirical colour-brightness relations, and at the same time providing a more realistic limb-darkening law. This work had two important "side" results: first, Robinson et al. (1982) showed that the oscillations of white dwarf stars are caused by g-mode (as opposed to r-mode) pulsation and second, that these are due temperature variations only.

General considerations and optimal use of the method

Watson (1988) explored the behaviour of photometric amplitudes and phases for a large variety of pulsating star models. He started with the expression for the flux change for nonradial pulsation in the linear regime:

$$\Delta m(\lambda, t) = -1.086\epsilon P_{\ell,|m|}(\mu_0)((T_1 + T_2)\cos(\omega t + \psi_T) + (T_3 + T_4 + T_5)cos(\omega t)),$$

where $\Delta m(\lambda, t)$ is the time and wavelength dependent magnitude variation of an oscillation, -1.086ϵ is an amplitude parameter transformed from fluxes to magnitudes, $P_{\ell,|m|}$ is the associated Lagrange polynomial, μ_0 is the cosine of the inclination of the stellar pulsation axis with respect to the observer, ω is the angular pulsation frequency, t is time and ψ_T is the phase lag between the changes in temperature and local geometry. The term T_1 is the local temperature change on the stellar surface, T_2 is the temperature-dependent limb darkening variation, T_3 is the local geometry change on the stellar surface, T_4 is the local surface pressure change and T_5 is the gravity-dependent limb darkening variation.

The relative importance of the T_i terms was evaluated for models of different types of pulsators, ranging from white dwarf to R CrB stars, Miras and Cepheids, δ Scuti and β Cephei stars, as well as solar-like oscillators and roAp stars. For instance, the geometry term was found to be of virtually no importance for the high radial overtone pulsators (Watson 1988). The results of this work allow an optimal choice of photometric filters for efficient mode discrimination: one wants to observe at one wavelength where the geometry variation is significant, while the temperature term is well constrained at the same time.

Finally, Watson (1988) computed "areas of interest" in amplitude ratio vs. phase shift diagrams, i.e. the loci in which modes of a given ℓ would be contained (also called "diagnostic diagrams" in the literature). Such diagrams are still in use for mode identification today.

Adaptations, extensions, improvements and additional astrophysics

After this very broad work, specialists on various classes of pulsators took the stage. Garrido et al. (1990) performed computations of diagnostic diagrams for δ Scuti stars in the Strömgren photometric system, trying to find the most efficient filter combinations for mode identification (using two filters, v and y seem to be best). Later, Heynderickx et al. (1994) tested β Cephei models in the Geneva and Walraven systems, finding that the mode discrimination is best done via the evaluation of amplitude ratios, and that knowledge of ultraviolet amplitudes is crucial.

Cugier et al. (1994), also examining models of β Cephei stars, performed nonadiabatic calculations of photometric and radial velocity amplitude variations and phase shifts for the first time. Their results implied that these parameters may be dependent on stellar mass and that discrimination of the overtone of radial modes may also be possible.

An apparent setback for mode identification of δ Scuti stars was discussed by Balona & Evers (1999): the shallow convection zones of these stars affect the theoretical predictions of the photometric observables, depending on the assumed convective efficiency. However, Daszyńska-Daszkiewicz et al. (2003) realized that this dependence may be turned into an asset: when introducing a suitable third filter into the observations, one can constrain the convective efficiency simultaneously with obtaining pulsational mode identifications. In other words, one can learn additional physics when applying the photometric method.

The photometric method has been extended further and further in the recent past. For instance, Garrido (2000) modernized Watson's (1988) work with a focus on δ Scuti stars, and presented diagnostic diagrams for γ Doradus stars for the first time. Balona et al. (2001) pointed out that the incorporation of Johnson I filter data greatly improves the relative accuracy of the measured phase shifts and therefore provided clearer mode discrimination for δ Scuti stars.

On the side of theory, Townsend (2003) and Daszyńska-Daszkiewicz et al. (2007) formulated the method for gravity modes in rapidly rotating stars, where rotation can no longer be treated with a perturbation approach. Dupret et al. (2005) included their time-dependent convection model to derive mode identifications for δ Scuti stars, and later applied it to γ Doradus stars as well (Dupret et al. 2006).

Daszyńska-Daszkiewicz et al. (2005) combined the photometric method with radial velocity data, and suggested a χ^2-test (Daszyńska-Daszkiewicz et al. 2003) for mode discrimination in the combined measurements. This increases the objectivity of the process: previously, identifications were obtained by visual inspection of the amplitude/phase vs. wavelength behaviour and often critically depended on the wavelength of the normalization, which could sometimes mislead the eye.

The potential of photometric mode identification has also been recognized for the pulsating subdwarf B stars (Randall et al. 2005). These authors computed amplitude ratios and phase shifts for a wide range of parameter space, including long- and short-period sdB pulsators as well as nonadiabatic effects, and examined the systematics thoroughly. Similar to the β Cephei stars, that are similar in temperature to the sdB oscillators, amplitude ratios are the observational quantity most sensitive to ℓ, but data of high accuracy are required and discrimination between the modes of $\ell \leq 2$ is difficult to obtain.

Applications to different types of pulsators

Starting with the pulsating white dwarf stars, it must be mentioned that limb darkening is by far the strongest contributing factor to the wavelength dependence of pulsation amplitudes. Ultraviolet measurements are necessary to achieve good mode discrimination. Combining ground-based photometry and ultraviolet spectroscopy from the HST, Kepler et al. (2000) derived mode identifications for the DA white dwarf star G226-29, and at the same time determined its $T_{\rm eff}$ and $\log g$ by combining the amplitude information from all modes. In the same paper, Kepler et al. (2000) could not find a unique ℓ assignment for the strongest mode of the DB pulsator PG 1351+489, but resolved the ambiguity by considering the spectroscopic $\log g$ value of the star. These two examples again illustrate that additional astrophysical information can be obtained when applying mode identification methods.

Along similar lines, the potential to learn something about surface convection using multicolour data on δ Scuti stars has already been pointed out. In their study of 44 Tau, Lenz et al. (2008) identified several low-ℓ modes, and at the same time constrained the mixing length parameter with $\alpha_{MLT} \leq 0.2$ within their treatment of surface convection.

As a final example, Pamyatnykh et al. (2004) used their knowledge of the radial mode detected in the β Cephei star ν Eridani, combined with the frequencies of the three $\ell = 1$ triplets, to constrain the star's position in the HR diagram and to obtain a tight constraint on the convective core overshooting parameter.

Practical considerations, pitfalls and space data

The reader should not get the impression that observational identifications of *all* observed pulsation modes of any given star are required for successful asteroseismology. It is just necessary to identify a *sufficient* number of modes to rule out all possible alternative interpretations and models.

As another example, seven pulsation modes were detected for the β Cephei star θ Ophiuchi (Handler et al. 2005), but only four of them had unique determinations of ℓ from photometry. However, these identifications sufficed to tag all modes as: one radial mode, a rotationally split $\ell = 1$ triplet, and three components of a rotationally split $\ell = 2$ quintuplet, with an ambiguity which m the observed components would have. Spectroscopy came to the rescue (Briquet et al. 2005): with the photometric ℓ values, parameter space could be sufficiently restricted to obtain m for the strongest $\ell = 2$ mode.

The problem that misinterpretations of mode identification diagrams can be caused by visual inspection has already been mentioned. Another problem one must be aware of is the accuracy of the underlying data. Examinations of multisite time series photometry suggest that formal error estimates may underestimate the real errors by about a factor of 2 (Handler et al. 2000, Jerzykiewicz et al. 2005), probably a consequence of correlated noise. However, when considering amplitude ratios and phase shifts between different filters, at least part of the correlated noise may cancel and therefore the formal error estimates may not be too far from the truth (Breger 2008). In any case, the use of more than two photometric filters may help to investigate the possible occurrence of systematic errors.

Asteroseismology puts enormous hope on dedicated space missions, which will yield (and do already yield) time-resolved photometry of extremely high precision. However, the presently active asteroseismic space missions operate in a single colour only, and the colour information of CoRoT in the exoplanet fields is crude. This means that asteroseismic modelling may still be difficult despite a wealth of frequency information. The first space mission that will be able to provide accurate colour information is BRITE-Constellation (e.g. Zwintz & Kaiser 2008) that hopefully will have been launched when these proceedings are published; Daszyńska-Daszkiewicz (2008) thoroughly examined the prospects of mode identification with BRITE-Constellation.

Some (trivial) conclusions

Photometric mode identification methods have now matured to a point where they can be widely applied to different classes of pulsators. Successes have been obtained for pulsating white dwarf and subdwarf stars, and along the main sequence for γ Doradus, δ Scuti, SPB and β Cephei stars. In several cases, interesting astrophysical information has been obtained as a "by-product" such as that white dwarf pulsate in g modes rather than in r modes, constraints on the efficiency of surface convection of δ Scuti stars were found, and $T_{\rm eff}$ and $\log g$ determinations were made for some stars.

The choice of the most suitable set of filters for mode identification is a crucial point in planning observations; at one wavelength the geometry variation should be significant, and the temperature variation should be well constrained in the combination with a second filter (Watson 1988).

To be able to estimate the possible effects of systematic measurement errors, redundancy should be sought, i.e. a third photometric filter would aid the reliability of the mode identification and can, in some cases, provide additional astrophysical information. External constraints, such as temperature or gravity estimates of the target object, can also assist in the correct mode identification. Finally, if feasible, photometric mode identification should go hand in hand with spectroscopic observations to provide the largest possible set of information to the asteroseismologist.

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DISCUSSION

Zahn: Have there been recent determinations of internal rotation profiles, using multiple modes?

Handler: There is convincing evidence for differential rotation in a number of β Cep stars, but we have too small a number of modes to obtain something that deserves the name "rotation profile".

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Constraints on angular numbers of pulsation modes from spectroscopy

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Abstract

Asteroseismology relies on accurate observational mode identification. High-resolution spectroscopy allows to detect such crucial information as the pulsational degree ℓ, the azimuthal number *m*, and pulsation amplitudes, directly from time series of observations. The advantage of using both standard photometric techniques and high-resolution spectroscopy is that not only pulsational temperature variations can be detected, but also the pulsational velocity field, yielding valuable extra information.
In this paper I review the spectroscopic mode-identification methods that have been developed over the last decades, with emphasis on the application to hot stars.

Individual Objects: Balloon090100001

Introduction

The study of stellar pulsations provides a promising tool to further refine our knowledge of the internal structure of stars. Provided that one can conclusively derive pulsational parameters from the observations, asteroseismology can constrain stellar structure and evolution models.

In general, there are two *complementary* and *independent* methods to derive observational mode identifications:

- photometric/spectroscopic amplitude ratios, a technique that probes the pulsational variations of temperature, gravity, and more recently also radial velocity, and that aims to derive the degree ℓ of the modes.

- line-profile variability, a technique that probes the 3D pulsational velocity field, and that aims to derive the degree ℓ and the azimuthal number *m* of the modes.

It has become evident that the most conclusive results have been obtained from applying both methods simultaneously. Here I will focus on the topic of spectroscopic mode identification; see Handler (2008) for a review on photometric methods.

The theory of nonradial pulsation was developed by Lord Kelvin (Thomson 1863) before that of radial pulsation. Through the interest in Cepheids, the theory of radial pulsation made a lot of progress in the first half of the previous century; the lack of applicability kept the development of nonradial oscillation theory at a slow pace. It was only in the 1950's that Ledoux (1951) suggested that the observed variability in the broadening of the spectral lines of β CMa (a prototype of the β Cephei variables) is due to nonradial pulsations. Osaki (1971) calculated line profiles of nonradially pulsating stars and compared them with observations available at that time. With the work of Smith (1977), who used a similar model to fit line-profile variations, the field of spectroscopic pulsation-mode identification got off the ground. Furthermore, the work of Vogt & Penrod (1983) sparked the application of the Doppler-imaging technique for spectroscopic mode identification.

All over the Hertzsprung-Russell diagram there are types of stars that pulsate in nonradial modes. The mode identification methods discussed in this paper are mostly based on high-resolution spectroscopy and are typically applied to early-type stars, such as δ Scuti variables and β Cephei variables. These stars have apparent pulsation periods of about 20 minutes to a few hours, and with the present observing facilities harmonic degrees up to $\ell \sim$20 can be derived spectroscopically (Doppler imaging). More recently, applications to longer-period g-mode pulsators such as γ Doradus stars and Slowly Pulsating B-stars have been presented in the literature. Very recently high-resolution spectroscopy has been applied to the relatively faint subdwarf B stars, which have pulsation periods of a couple of minutes to hours, for pulsation-mode identification (see next sections).

Even for DAV white dwarfs, it has been shown that the harmonic degree can be identified using time-series of low-resolution spectroscopy (see next sections).

Excellent in-depth reviews on modern analysis methods for spectroscopic pulsation-mode identification were presented by Aerts & Eyer (2000), Balona (2000), and Mantegazza (2000). The aim of this current paper is to list the latest developments since the review presented by Telting (2003).

High-resolution spectroscopy for pulsation-mode identification

Stellar pulsations are reflected as line-profile variations in absorption lines formed in the photosphere. For slowly-rotating stars, modes with $\ell \lesssim$4 give rise to detectable line-profile variations. In rotating stars, where the Doppler-imaging principle applies, the line-profile variations due to nonradial pulsations appear as blue-to-red moving bumps (Vogt & Penrod 1983), and modes with $\ell \lesssim$20 can be detected. In general, the line-profile variations are caused by the stellar pulsational velocity field, and by the photospheric pulsational temperature variations. Effects induced by local surface gravity variations are usually neglected, which is a valid assumption if hydrogen lines are not used in the analysis, nor any other lines near the cores of the hydrogen lines.

The temperature variations give rise to local changes in brightness, and to local changes of the equivalent width (EW) of the intrinsic stellar line profile (e.g. Buta & Smith 1979, Lee et al. 1992). For absorption lines with low thermal broadening and small intrinsic EW variations the pulsational line-profile variations are dominated by velocity effects, implying that thermal pulsational effects may be neglected in the modelling of the profile variations. Such absorption lines provide the ideal case, as the 3D pulsational velocity field is relatively simple to model (see e.g. Schrijvers & Telting 1999), *and allows to derive both the degree ℓ of the mode as well as the azimuthal number m of the mode*.

In rotating stars, the pulsational velocity field cannot be described by a single spherical harmonic. In the case of slow rotation, toroidal terms are induced due to the Coriolis force (e.g. Aerts & Waelkens 1993); in the case that the pulsation frequency in the corotating frame, $\omega_{\rm cor}$, is comparable to the rotation frequency, Ω, a whole series of spherical harmonic functions is needed to describe an eigenfunction (Lee & Saio 1990, Townsend 1997).

A further complication in the interpretation of line-profile variations is that the inclination angle of the star, i, is generally not known. Other parameters that play a role in the appearance of the line-profile variations are: the limb-darkening coefficient, the intrinsic profile width, the equatorial rotational velocity, the ratio of horizontal to vertical pulsational motion, the amplitude of the local brightness variations, the amplitude of the local equivalent width variations, and the non-adiabatic phase lag between velocity and temperature variations. Not all of these are free parameters: some parameters depend on the value of others, and some can be modelled with line-profile synthesis codes and with non-adiabatic pulsation codes.

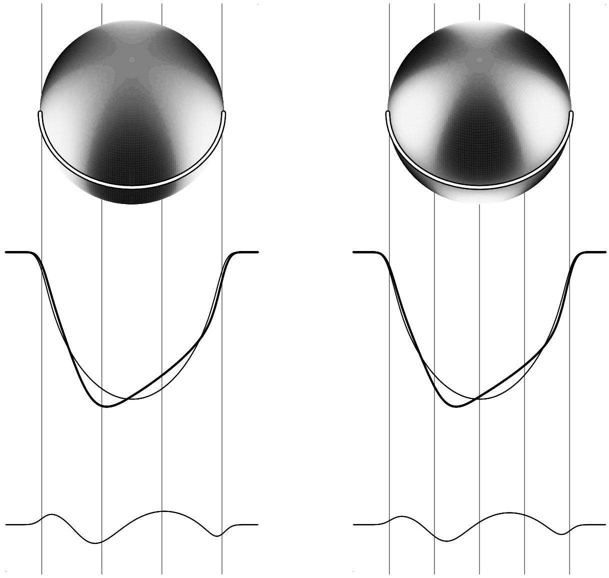

Figure 1: Line profiles at one particular phase of an (ℓ=3,$|m|$=3) and a (ℓ=4,$|m|$=3) (right) mode. All other stellar and pulsational parameters, except the pulsation amplitude, are the same. It is evident that for pole-on inclinations (here I used i=35°) the pulsationally distorted line profiles of (ℓ,m) and (ℓ+1,m) modes look very similar.

Nevertheless, it is clear that in order to get reliable values for the three parameters that one wants to obtain from high-resolution spectroscopy, the degree ℓ, the azimuthal number m, and the pulsational velocity amplitude, one has to perform a very careful analysis on a data set with high signal-to-noise ratio. Depending on the line-profile shape, the degree of the mode, and the identification method that one uses, a spectral resolution of R=20000–60000 is sufficient for mode-identification. Doppler imaging and profile-fitting methods used for modes with high ℓ values require the highest spectral resolution. The ideal data set is such that one-day aliasing does not play a role, and that all the intrinsic frequencies as well as the harmonic, sum and beat frequencies, that are caused by the non-linear mapping of the stellar variations onto the line profiles, are unambiguously resolved. In reality, most data sets are far from ideal, but experience has shown that from the best data sets we are able to estimate values of ℓ and $|m|$ with an accuracy of $\pm$1 or better. For any mode-ID method based on line-profile variations it is difficult to distinguish a mode (ℓ,m) from a mode (ℓ+1,m), especially for pole-on orientations of the symmetry axis of the mode (see Figure 1).

High-resolution spectroscopy: new developments of mode-ID methods

I refer to the review presented by Telting (2003) for a general and less concise description of the most-used spectral analysis and mode-identification techniques (Moment Method, Doppler imaging, IPS/PPM method, etc.). It is important to realise that many implementations of these methods still rely on a simple description of the pulsational-velocity field of a non-rotating star, possibly without accounting for the pulsational temperature/gravity effects mentioned above. Therefore it is crucial to select the best absorption lines, i.e. those lines that are not affected by these effects, typically lines of elements heavier than Helium.

The Moment Method (MM, see e.g. Balona 1986, Aerts 1996) analyses the velocity moments of the line profiles; moment variations are detectable for modes with $\ell \lesssim 4$. The MM is more sensitive to zonal modes (m=0) than to sectoral modes ($|m|=\ell$).

The IPS/PPM method (see e.g. Gies & Kullavanijaya 1988; Telting & Schrijvers 1997) analyses the intensity variations (or bumps) across the line profile; bumps can be seen for modes with $\ell \lesssim 20$. The IPS/PPM method is more sensitive to sectoral modes than to zonal modes. The latter implies that the MM and IPS/PPM methods are complementary to each other, and should both be applied in order to get the best results.

Special attention has to be given here to the latest extension of the IPS method by Zima (2006ab), who applied the new method to identify numerous modes in the δ Scuti star FG Vir. Zima has developed an elaborate fitting method (the FPF method), to fit the amplitude and phase diagrams that together form the prime diagnostic of the IPS method. Furthermore, the FPF method is available as part of the freely accessible FAMIAS package (Zima 2008), which also comprises an implementation of the MM method.

A recent refinement to the Moment Method, to account for multi-periodicity in the MM, was presented by Briquet & Aerts (2003) who applied the improved method to the multi-periodic stars: β Cru, EN Lac, HD 74195. Kochukhov (2005) discussed the MM for the case of oblique pulsators. Schoenaers & Lynas-Gray (2008) introduced the synthetic moment method (SMM), to account for pulsational temperature/gravity effects in sdB-star atmospheres, and in particular for the g-mode pulsating subdwarf HD 4539.

Kochukhov (2004) developed a method to make Doppler-Imaging maps of surface-velocity fields, and found for the bright roAp star HR 3831 that the LPV are due to oblique axisymmetric ℓ=1 modes.

Low-resolution spectroscopy for pulsation-mode identification

Low-resolution spectroscopy can be used for pulsation-mode identification, *aiming to derive the pulsational degree ℓ of the mode*. Information on the azimuthal number m and the inclination of the symmetry axis of the mode (usually the stellar rotation axis) cannot be derived from low-resolution spectroscopy. Some newly developed methods have been applied recently.

As presented by Daszyńska-Daszkiewicz (2005) for the β Cep stars δ Cet and ν Eri, radial-velocity measurements obtained from time series of low-resolution spectroscopy, obtained simultaneously with the photometric data, can be used to drastically improve the diagnostic value of the photometric mode-ID methods.

Clemens et al. (2000) measured chromatic amplitudes (pulsation amplitude at each wavelength bin) across the hydrogen Balmer lines in the DAV white dwarf G29-38, and demonstrated that spectral variations can indeed be used to identify the spherical degree. Using this method, Thompson et al. (2008) find that 4 out of 11 spectroscopically identified modes in G29-38 have $\ell > 1$.

A recent application: the subdwarf B star Balloon090100001

Telting et al. (2008) obtained time series of high-resolution spectroscopy on the relatively bright (V=12.1) pulsating subdwarf B star Balloon090100001, in 2006 at the Nordic Optical Telescope. The dominant mode in this star has a pulsation period of 356 seconds, and a radial-velocity amplitude of about 14.5 km/s (in 2006). After folding the individual spectra to pulsational phase, and after combining the pulsational variations of about 60 heavy-element absorption lines, the resulting combined profiles have high enough signal-to-noise ratio for mode identification (see Figure 2).

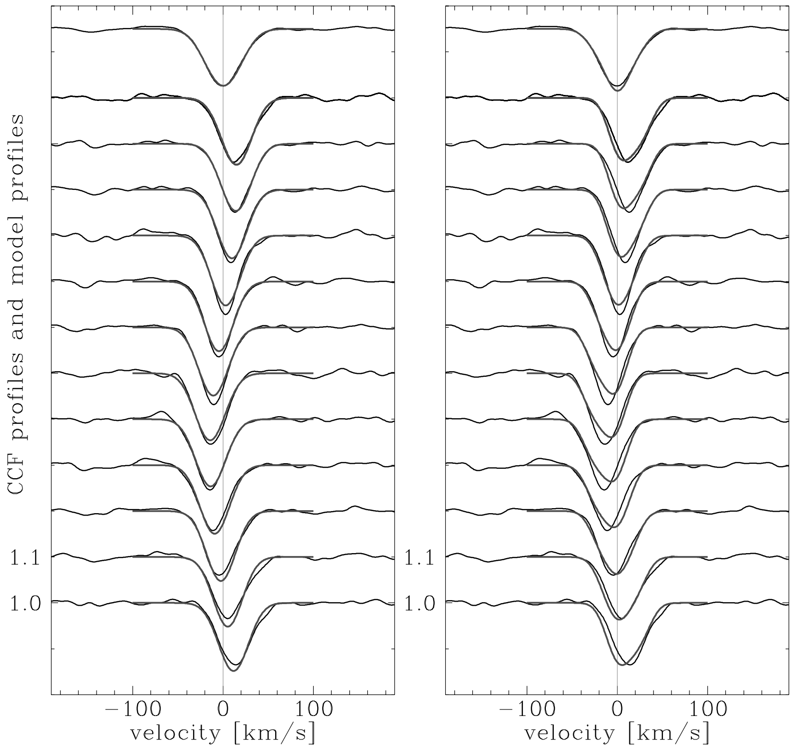

Figure 2: Best-fit radial pulsation model (left), and best-fit ℓ=2 model (right), overplotted on processed time-resolved high-resolution spectra of the pulsating subdwarf Balloon09010000 (V=12.1). Pulsational phase is running upwards, and the average spectrum is plotted at the top. The model on the right does not fit the data as good as the model on the left. Based on such fits, Telting et al. (2008) exclude an $\ell \geq 2$ origin for the dominant mode in this sdB star.

Based on χ^2 minimisation of model fits, Telting et al. (2008) conclusively constrain the modal parameters of the dominant pulsation in this sdB star, implying the first successful application of high-resolution spectroscopy for mode-identification in sdB stars. They can exclude an $\ell \geq 2$ origin for the dominant mode in this sdB star, which is in good agreement with the results of photometric mode-identification techniques (Baran et al. 2008; Charpinet et al. 2008).

Animations for presentations, education and public outreach

Based on the model of the pulsational eigenfunction described in Schrijvers et al. (1997) and Schrijvers & Telting (1999), I have made a WWW form that allows you to make a colour animation of a pulsating star with corresponding line-profile variation, i.e. the animated form of the plots shown in Figure 1. The WWW form allows for many different stellar and pulsational parameters to be specified, and can currently be found at http://staff.not.iac.es/~jht/science/nrpform/. Please be patient when using this feature: the generation of the animation is a bit slow.

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DISCUSSION

Bruntt: Your work on an extensive sample of B-type stars shows that 50% or more are variable. However, in the MOST photometry it is found that more than 50% B stars are non-variable. Is this simply due to your method being more sensitive to high-l modes?

Telting: That is probably part of the explanation. It is important to note that our sample is full in a narrow range in spectral type, while the MOST sample includes all B-type stars.

Weiss: A remark concerning the history: The DI-technique was introduced by Armin Deutsch in the 1960's, developed further by Michel Floquet (Paris) and Vera Khokhlova (Moscow) in the 1970's.

Telting: Thank you for your comment. I did not intend to give the impression that the DI method was solely developed in the Vogt & Penrod (1983) paper. I only wanted to state the importance of this paper for mode identification methods.

Michel: I just want to call your attention to a work where we investigate to which extent the moment method can be applied to solar-like pulsation (see poster).

Telting: Thank you for your comment.

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High-resolution spectroscopy and mode identification in non-radially pulsating stars

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Abstract

We have obtained high-resolution spectroscopic data of a sample of non-radially pulsating stars with the HERCULES spectrograph on the 1.0-m telescope at the Mt John University Observatory in New Zealand. We have developed and used a new technique which cross-correlates stellar spectra with scaled delta function templates to obtain high signal-to-noise representative spectral line profiles for further analysis. Using these profiles, and employing the Fourier Parameter Fit method, we have been able to place constraints on the degree, ℓ, and azimuthal order, *m*, of the non-radial pulsation modes in one β Cephei star, V2052 Oph and two γ Doradus stars, QW Pup and HD 139095.

Individual Objects: V2052 Oph, QW Pup, HD 139095

Introduction

Slowly pulsating B stars and γ Dor stars can be considered as the g-mode counterparts of the β Cep stars and δ Sct stars respectively. The theoretical frequency spectra of g-modes are much denser compared to those of p-mode pulsators and their pulsation periods are generally longer (0.3–3.0 d^{-1}). Since most of the g-mode pulsators are multi-periodic, the observed variations have long beat-periods and are generally rather complex. Hence, large observational efforts are required for in-depth studies of these stars. Our recent interest has been to develop an observing programme and various analysis tools to study pulsation modes in a sample of non-radially pulsators, including the γ Dor and β Cep stars.

Instrumentation and observing programmes at MJUO

Observations at the Mt John University Observatory (MJUO) are carried out with the 1.0-m telescope equipped with the fibre-fed High Efficiency and Resolution Canterbury University Large Echelle Spectrograph (HERCULES, Hearnshaw et al. 2002). HERCULES allows stable, high-precision, high-resolution spectroscopy which is ideal for mode identification of reasonably bright (V<8) targets (Pollard et al. 2007). As an example, we have been able to monitor line profile variations in a V=7.5 star in 30 minutes, with S/N of ∼120–150. Our ability to acquire long sequences of observing time means we are able to undertake interesting single-site studies of pulsating stars. In addition, the southerly latitude (44° S) and the useful longitude (170° E) means that MJUO can make significant contributions to multi-site spectroscopic campaigns.

The scaled delta function cross correlation technique

When carrying out high-resolution spectroscopic observations for asteroseismology, it is important to obtain a good temporal coverage of the stellar variability whilst maintaining reasonable S/N. Extensive simulations were carried out to determine which methods of extracting a high S/N line profile from an echelle spectrum were best. Simulated spectra with different numbers of lines, line density, line depth, line position, amounts of noise and normalisation errors were created and the various methods of extracting a representative line profile were compared with the input line profile using a statistical test. We compared the best single line profile and the resulting representative lines profiles and found that the scaled delta function cross-correlation profile performed best and was an excellent representation of the input line profile. In this method, an object's spectrum is cross-correlated with a template of delta functions which are positioned at the correct wavelength and depth of each line (Wright et al. 2007, Wright 2008), thus optimizing the S/N whilst preserving the scientific integrity of the stellar line profiles.

It should be noted that this technique is only valid for lines similarly distorted by the pulsation since we do not wish to add together lines which exhibit different variation with pulsational phase. We verified that this method was applicable to the γ Dor stars by visually examining many line profiles from the relevant spectra. In the β Cep star V2052 Oph, the behaviour of the He I lines and Si III lines were quite different, with the line depths varying almost in antiphase. Thus, for V2052 Oph, three individual line profiles were examined and analysed.

Results of the mode identification analysis

Once high S/N stellar line profiles were obtained, the frequencies present in the variation of the line profiles were determined using the pixel-by-pixel period analysis package included in the FAMIAS software (Zima 2008). For each frequency, the variations in the observed line profiles were matched to those in synthetic line profiles for various non-radial modes using the Fourier Parameter Fit (FPF) method in FAMIAS. We applied this mode identification analysis to one β Cep star, V2052 Oph, and two γ Dor stars, QW Pup and HD 139095.

The β Cep star V2052 Ophiuchi

V2052 Oph is a B1-2 IV-V β Cep star with two previously identified pulsation modes: an ℓ=0 radial mode at f_1=7.164 d^{-1} (Cugier et al. 1994, Heynderickx et al. 1994, Neiner et al. 2003) and an ℓ=3 or 4 non-radial mode at f_2=6.82 d^{-1} (Neiner et al. 2003). V2052 Oph was observed at MJUO as part of a multi-site campaign organised by Aerts et al. (2004) with ν Eridani as the primary target. We obtained 88 spectra over the time span of two months (2004 May–July) with typical exposure times of 10 minutes giving S/N$\sim$200.

Three spectral lines were used in the analysis: a 4553 Å Si III line, and two He I lines at 4713 Å and 5876 Å. Clear profile variations were seen in all lines. Figure 1 shows the pixel-by-pixel Fourier transform of the 4713 Å He I line. From analysing the selected spectral lines, the consistently detected frequencies were: f_1=7.148$\pm$0.005 d^{-1}, the rotation frequency (f_2=f_{rot}=0.2748$\pm$0.03 d^{-1}), twice the rotation frequency (f_3=2f_{rot}=0.5496$\pm$0.03 d^{-1}) and f_4=6.827$\pm$0.02 d^{-1}, which can all be associated with frequencies identified by Neiner et al. (2003).

The FPF mode identification technique (Zima 2006) was then applied to the data. For the dominant frequency, f_1=7.148 d^{-1}, the best fit to the zero point profile and phase and amplitude across the profile is a ℓ=1, m=0 non-radial pulsation mode (see Figure 2). From the FPF optimization it is clear that f_1 is a m=0 mode, though it is less obvious whether ℓ=0, 1 or 2. The ℓ=1 mode gives the best fit, but the ℓ=0 fit is only marginally worse and

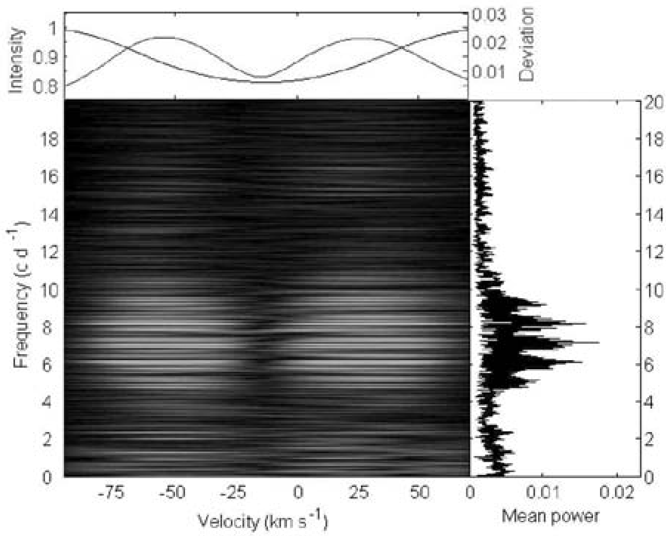

Figure 1: Pixel-by-pixel frequency analysis applied to the He I 4713 Å line in V2052 Oph (main panel). The top panel shows the mean line profile and the standard deviation. Variations in the line profile are symmetric about the line core, with maximum deviations in the red and blue wings and little variation in the line core itself. The mean frequency spectrum (right panel) shows a strong peak at f_1=7.148 d^{-1}.

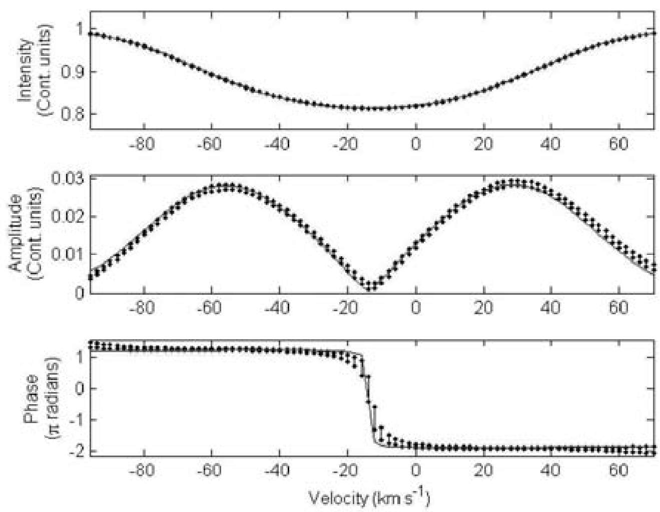

Figure 2: The best fit (solid line) to the line profile zero point, and amplitude and phase across the profile for frequency f_1=7.148 d^{-1} is an l=1, m=0 non-radial mode.

is consistent with previous photometry which unambiguously identified this as a radial mode. We quote ℓ=0±1 and m=0 as our final mode identification. The line profile residuals phased to the f_1=7.148 d^{-1} frequency are in excellent agreement with theoretical profiles, giving us confidence in the derived best fit parameters and the mode identification.

For the second pulsational frequency at f_4=6.827 d^{-1}, the best fit is a non-radial ℓ=4, m=2 mode. Although the best fitting mode was a ℓ=4, m=2 mode, the next best fit was an ℓ=4, m=4 mode. After an examination of the best fits for different ℓ and m combinations, we give a mode identification of $l = 4 \pm 1$ and $m = 2 \pm 2$.

The γ Dor star QW Puppis

QW Pup (HD 5589) has been classified as a γ Dor star by Poretti et al. (1997) based on the presence of line profile variations in its spectra and the four independent frequencies around 1 day from multi-site photometry. No previous mode identification has been published. We obtained 179 spectroscopic observations of QW Pup from two sites (MJUO and SAAO, South Africa) over a time span of two months (2004 Feb–April). Typical exposure times were 15 minutes. We used the scaled delta function cross-correlation technique to define high S/N line profiles for analysis.

Clear line profile variability was observed in QW Pup (Figure 3). A pixel-by-pixel frequency analysis was carried out and eight frequencies detected. An examination of the zero point phase and amplitude fits for the three strongest frequencies (2.122, 2.038, 6.229 d^{-1}) shows reasonable fits for the first two frequencies and line profile variations consistent with non-radial pulsations, but a poor fit for the third frequency. We continued with a mode identification for the first two frequencies. The best fits are for ℓ=8, m=6 and ℓ=8, m=4 for the 2.122 and 2.038 d^{-1} frequencies respectively. Although the zero point profile and the phase were able to be fitted well, the amplitude was fitted less well in all cases. There was more variation in the extreme wings of the line profile when compared with the theoretical profiles. This is possibly due to the higher horizontal motions present in g-mode pulsations in the γ Dor stars or perhaps due to rotational effects. After an examination of the best fits for different ℓ and m combinations, we give a mode identification of ℓ=8±3, m=6±2 and ℓ=8±2, m=4±1 for the 2.122 and 2.038 d^{-1} frequencies respectively.

The γ Dor star HD 139095

HD 139095 has been classified as a multiperiodic γ Dor star with a dominant period of 0.634 d^{-1} from HIPPARCOS photometry (Handler 1999, Henry & Fekel 2002, Handler & Shobbrook 2002). HD 139095 was observed during the campaign for which QW Pup was the primary target. We obtained 57 spectra over three weeks at SAAO and MJUO. The analysis methods were very similar to that carried out for QW Pup, using scaled delta function cross-correlation to define the line profiles for analysis using the FPF software. Line profile variations were obvious. The pixel-to-pixel Fourier analysis showed many frequencies present in the dataset, although the data were very noisy, raising the possibility of spurious peaks. A number of frequencies which showed profile variations consistent with non-radial pulsations (f_1=2.353, f_2=9.560, f_3=8.638 and f_4=10.14 d^{-1}) were used in the FPF analysis. The best mode for frequency f_4=10.14 d^{-1} was ℓ=7±1, m=5±2 whilst the other frequencies had poor fits and are likely spurious. It is likely that the small quantity and poorer quality of the data is the main factor limiting the analysis and further, longer baseline and high S/N data will be required for a more precise analysis.

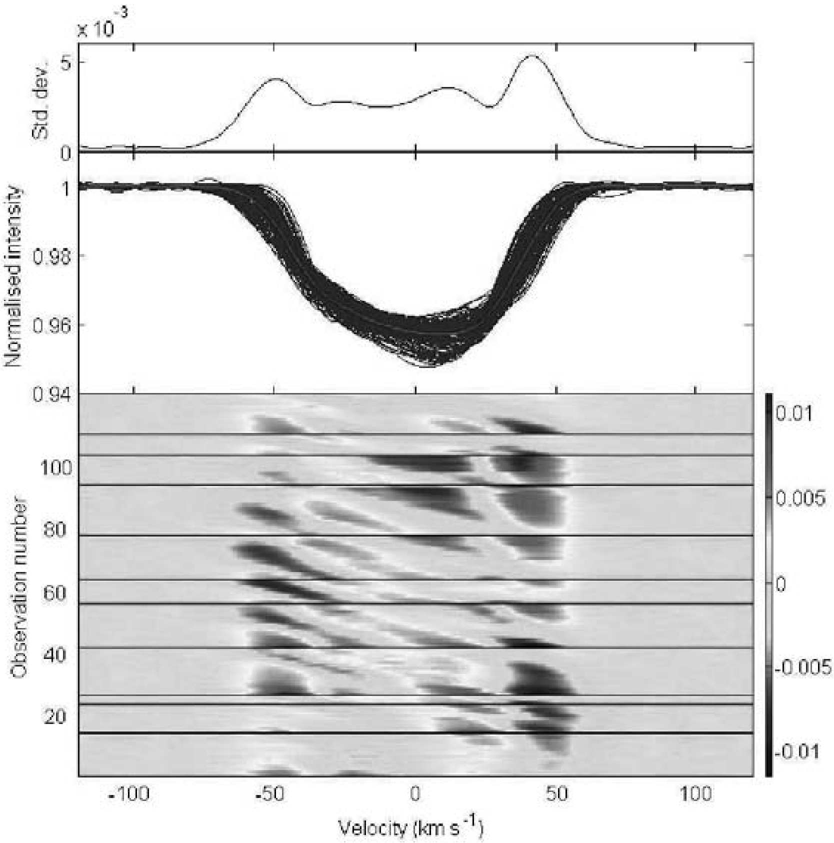

Figure 3: The line profile variation for QW Pup. The standard deviation from the mean profile (top), the set of cross correlation line profiles from SAAO spectra (middle) and the deviations from the mean profile plotted versus observation number (bottom).

Summary

As part of an observational study of a sample of non-radially pulsating stars, we have developed and tested a scaled delta function cross-correlation method (Wright et al. 2007, Wright 2008) which produces high S/N representative line profiles. We present the results from the subsequent mode identification analysis of one β Cep star and two γ Dor stars using the FPF method (Zima 2006). The FPF method gives excellent results for the β Cep star, but some discrepancies are seen in the analysis of the γ Dor stars, possibly due to the greater horizontal motion present in the g-mode pulsations or perhaps rotational effects. Further research is in progress.

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Coffee break between talks

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Spectroscopic mode identification of the δ Scuti star 4 CVn

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Abstract

We studied the δ Scuti star 4 CVn through time-series spectroscopy[1], since photometry alone is insufficient to provide a unique solution to mode identification. However, the combination of multifilter photometry and high-resolution spectroscopy, similar to the data we obtained and analyzed, allows the necessary reliable mode identification. We have obtained 38 nights of time-series high-resolution spectroscopy at the 2.1 m telescope at McDonald Observatory for 4 CVn. We have done mode identification for five independent frequencies detected by spectroscopy, which were previously detected with photometric observations.

Individual Objects: 4 CVn

Introduction

Asteroseismology is one of the most powerful tools to study structure and stellar evolution. Pulsations probe the internal structure of the stars, as every pulsational mode is, in principle, an independent measurement providing independent information. Even from just one pulsation mode, we can derive fundamental properties, such as stellar mass for pulsating white dwarfs (Castanheira & Kepler 2008). However, when many modes are excited and detected, the structure of a star can be determined in great detail (Dziembowski & Pamyatnykh 2008).

δ Scuti stars are the perfect targets to apply the full power of asteroseismology. These 1.5–2.5$M_\odot$ stars are on and above the main sequence, pulsating in radial and non–radial p and g–modes with periods between 0.4 and 8h. They are particularly suitable for studying the poorly understood hydrodynamical process occurring in stellar interiors, such as the extent of convective overshooting, the efficiency and treatment of convection (Daszyńska-Daszkiewicz et al. 2003, Montalbán & Dupret 2007), rotationally induced mixing of elements, and the redistribution of the angular momentum. A recent analysis of the solar spectrum by Asplund et al. (2004, 2005) led to a downward revision of the solar heavy element abundances, destroying the good agreement between the standard solar and helioseismic models. With the δ Scuti stars, we can test whether the new solar abundances or the seismological models are problematic. Their understanding is mandatory in constraining theoretical stellar models.

Finally, δ Scuti stars allow us to investigate why and how some pulsating stars show strong amplitude and small frequency variabilities. The hypothesis that the beating of two close modes causes this variability can be tested by the following two predictions it makes.

[1] Based on observations at McDonald Observatory of The University of Texas at Austin

First, amplitude and phase variations are related in time, according to beating. Second, due to cancellation effects, at a given observed frequency, the low-ℓ mode (few nodes on the surface) will be dominant photometrically, but spectroscopically the higher-ℓ mode is more likely to be seen. The first prediction has already been verified for δ Scuti (Breger & Bischof 2002, Breger & Pamyatnykh 2006) and RR Lyr stars (Guggenberger & Kolenberg 2007), but the second one requires large aperture telescopes with high-resolution time-series spectroscopy. That is the hypothesis we are investigating in this work.

There are three fundamental requirements to do seismology of δ Scuti stars. It is necessary to obtain high-accuracy multifilter photometry. We have obtained thousands of hours of data in the past years with dedicated automatic photoelectric telescopes (Breger et al. 2005), detecting more than 75 frequencies for some stars. Having detected that many frequencies, sophisticated models of stellar structure and pulsation are necessary. The models computed by our group/collaborators are state-of-the-art and constantly improving (Daszyńska-Daszkiewicz et al. 2005, Dziembowski 2006).

However, frequency information alone is insufficient to constrain all model parameters required for a unique model fit. Obtaining mode identifications (ℓ, m and n quantum numbers) for each mode used for seismological studies is the third requirement. Photometry alone can possibly constrain the ℓ value. Even with near-infinite amounts of photometry, the models would still not provide a unique solution. Fortunately, the combination of multifilter photometry and high-resolution spectroscopy allows reliable mode identifications.

Observations and data reduction

We have obtained 38 nights from January to May in 2008 of time-series high-resolution spectra using the Sandiford Cassegrain Echelle Spectrograph at the Otto Struve 2.1m telescope at McDonald Observatory. The integration times were between 7 and 15 minutes, depending on the weather conditions, to achieve S/N>200. The exposure times could not be longer than these values, because dominant modes have periods between 3 and 5 hours. The average readout plus the writing time is 32 s.

We used a resolving power of $R \sim 60\,000$. The grid was centered to $\sim 4\,500$Å, because 4 CVn is a fast rotator ($v \sin i > 120$ km/s). Therefore, most of the lines are blended. This is the best region to observe this star where a few unblended iron lines can be found.

We reduced the data with standard IRAF routines. First, we applied flat field and bias corrections. The wavelength calibration is a very important step to determine precise line profile variations. To correct for any variations in wavelength due to the Cassegrain mount, we took 2 to 3 s ThAr comparison spectra after each science frame.

Data analysis and preliminary mode identification

In the normalized spectral region, the only two lines that were not blended were the Fe II lines at 4508.2860Å and 4549.4790Å. The lines were converted to Doppler velocities and averaged out to study the effects of the pulsations in the line profile. The processed data were analyzed with the Fourier Parameter Fit Method developed by Wolfgang Zima using the FAMIAS software (Zima 2008).

In our data set, we found five independent pulsation modes. All of these periodicities have previously been detected by time-series photometry. One of the goals of this project was to check if the strong amplitude variation observed for 4 CVn could be explained by high degree (ℓ) frequencies close to the photometric ones. These high degree modes, due to cancellation effects, cannot be detected by time-series photometry. However, these modes, if present, could easily be seen in time-series high-resolution spectroscopy.

Using the FAMIAS software, we identified the most likely solutions for ℓ and m values for the spectroscopic modes (see Table 1). We are using the convention that $m > 0$ are prograde and $m < 0$ are retrograde.

Table 1: List of modes detected spectroscopically and the minima in χ^2 for the best ℓ and m solutions.

Photometric frequencies	Periodicity (cd^{-1})	ℓ	m	χ^2
f_5=5.8498	5.852	1	1	4.48
		2	1	4.65
f_2=7.3760	7.374	2	-1	3.05
		1	-1	4.44
f_3=5.0480	5.044	1	-1	3.32
		2	-1	3.34
f_1=8.5943	8.596	2	1	1.042
		1	1	1.270
f_8=6.9764	6.976	2	0	0.645
		0	0	0.697
		1	0	0.702

Because our data were obtained in only one site, we cannot look for pulsational frequencies smaller than one cycle per day nor multiples. The integration times of ≤ 15 min, the minimum to achieve the necessary signal–to–noise for mode identification (see Zima 2006 for details), do not allow us to look for frequencies larger than 48 cycles per day. From time-series photometry, the dominant modes are in the frequency range between 4 and 9 cd^{-1}.

For the five frequencies detected spectroscopically, we were able to univocally determine the m value.

Preliminary results

Having detected and identified five modes, these will be used to constrain the models for 4 CVn. This will allow us to learn more about the physical process, including convection, taking place in the interior of this star.

Our new mode identifications are in agreement with the previous ℓ=1 identification of f_1, f_2, and f_3 derived by means of photometric phase differences (Breger et al. 1999). As stated in Breger & Pamyatnykh (2002), the almost equal spacing of these $\ell = 1$ modes can be explained by mode trapping in the acoustic cavity. The model presented in their study predicts trapped ℓ=1 modes close to the observed frequency values, but with a mass of 2.4 $M_\odot$, the luminosity $\log(L/L_\odot) = 1.76$ is significantly higher than the value derived from observations (1.53 ± 0.065).

The additional knowledge of m values from spectroscopy can be used to improve the models of 4 CVn. Because of the uncertainties in ℓ determinations, it is not clear if components belonging to the same rotationally split multiplet are present. Consequently, the rotation of the star could not be fully constrained. Preliminary results show that the identified $\ell = 1$ modes can be fit by a model with 2.1 to 2.2 $M_\odot$ and a rotational velocity of 120 km/s and slightly above. This may suggest a high stellar inclination which would explain the non-detection of non-radial $m = 0$ modes. The predicted luminosity of these models is in better agreement with the observed values than for the old model.

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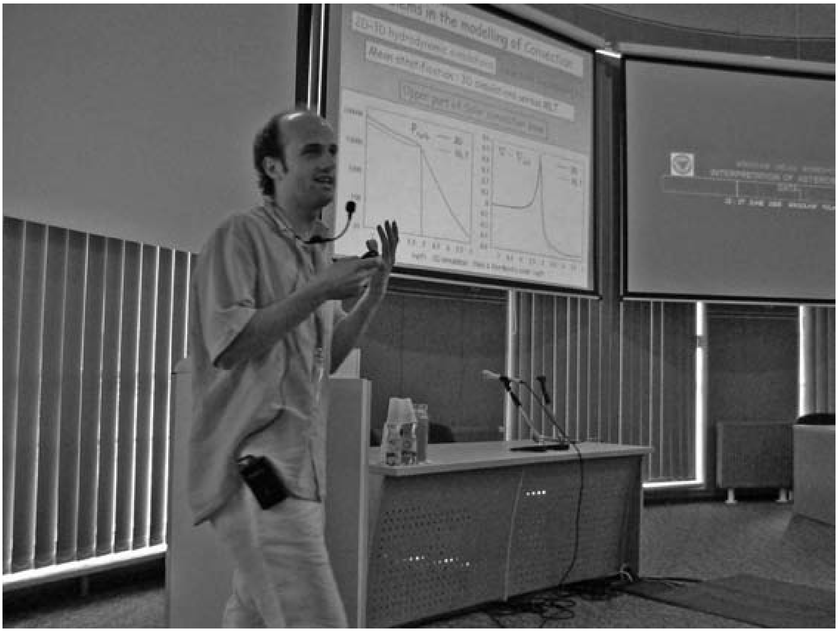

Marc-Antoine Dupret …

…

and his audience.