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Progress in understanding and exploiting stellar oscillation spectra

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Abstract.
Rich oscillation spectra of dwarf-like pulsators contain a wealth of information about the object interiors and, in particular, about macroscopic transport processes, which is the most difficult aspect of stellar physics. Examples of extracting such information from data on solar-like and opacity driven pulsators are given. Problems in understanding new oscillation spectra are discussed. Importance of employing various data on excited mode is emphasized.

Key words. Stars: oscillations – Stars: interiors – Stars: individual α Cen, η Boo, PG 1605+072, FG Vir, ν Eri

1. Introduction

Multimode low-amplitude variability is the most common form of stellar pulsation. Though typical for dwarfs, it is found also in giants. Much hope is attached to observations of objects exhibiting this form of pulsation because each frequency of a known mode is an independent high precision probe of stellar interior. However, mode identification in oscillation spectra is often a difficult task, which requires additional observables, such as amplitudes in various passbands, or theoretical arguments based on stellar model and oscillation calculations. Thus, the impressive progress in detecting low amplitude variability and measuring individual mode frequencies was not yet reciprocated in wider exploitation of the new data.

The most important application of frequency data is deriving constraints on stellar interior physics and, more specifically on slow macroscopic flows, which are so important for chemical evolution of stars, but so difficult for laboratory or numerical simulations. Successes of helioseismology in probing flows are encouraging but we have to keep in mind the difference in number of measured frequencies and the role of high-degree p-modes, which will not soon be detected in distant stars. The method of asteroseismic probing is the construction of *seismic models*, that is, models whose oscillation frequencies reproduce data and whose global parameters are consistent with non-seismic data. Free parameters describing internal structure and theoretical uncertainties in stellar modeling are treated as adjustable quantities. Typically, there is also a freedom in oscillation mode identification.

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Multimode stellar pulsation is a complicated phenomenon, only partially understood. The current status of our understanding is briefly reviewed in the next section. The rest of this paper is focused on data interpretation for five objects. I believe that the problems encountered in these cases are sufficiently diverse to show the main research direction where progress has been achieved, and where we still have outstanding questions to answer.

2. Physics of multimode pulsation

Multimode pulsation may arise in two distinct ways. One is a stochastic excitation by turbulent convection in outer layers. Modes driven in this way are termed *solar-like oscillations*. The other, which may be referred to as *self-excited oscillations* arises as a result of linear instability of oscillatory modes. We usually know which of the two driving mechanisms operates in the star. Only in the case of the common low amplitude variability in red giants, the issue may still be regarded as open. For most of self-excited mode pulsators, we believe that we understand the physics of driving effect, which most often is the usual opacity mechanism working in different opacity bump zones. However, our understanding of observed oscillation spectra is still far from being satisfactory, as it requires nonlinear theory implying much higher level of difficulties in modeling.

The goal of reproducing the gross features, such as frequency dependence of peak amplitudes and widths of the observed oscillation spectra for solar-like pulsators is not achieved yet. This has been clearly seen in the attempt by Samadi et al. (2004) to apply the stochastic excitation theory scaled on the sun to α Centauri. Observed power of individual modes turned out larger than predicted by large factors (2 to 7). Furthermore, there is a significant discrepancy between observed and predicted widths of the peaks (Bedding et al. 2004).

Very little is known about nonlinear development of unstable modes. We can identify possible amplitude-limiting effects, such as changes in the mean structure induced by pulsation or resonant coupling to stable modes, but model calculations taking to account both effects have yet to be done. Therefore, we still cannot explain why, in spite of essentially the same driving mechanism, certain stars choose high-amplitude monomode pulsation while others choose low-amplitude multimode pulsation. Observations tell us that the difference is related to evolutionary status. The theory suggests the clue may be very different properties of nonradial modes which change drastically with the advance of evolution. However, realistic modeling of mode interaction is still ahead of us.

3. Solar-like pulsators

Oscillation spectrum of α Centauri A, obtained by Bedding et al. (2004), resembles first spectra of solar low-degree modes obtained about 25 years ago. Like in the case of the solar spectra, mode identification in the α Cen spectrum is unambiguous. There are also oscillation data on the lower mass component of the binary α Cen system. In addition, we have also excellent constraints on the two star masses and radii from orbital and interferometric data.

In a recent work, Miglio & Montablán (2005) present a comprehensive survey of models subject to seismic and non-seismic constraints. The conclusions are somewhat disappointing for asteroseismology. A number of models were found, which within the observational errors reproduce all the data. There is a marginally significant discrepancy in the small separations d_{01}, which are sensitive to structure of the interior. The most interesting result, namely the determination of the convection parameter, $\alpha_{\rm con}$, for two stars, relies entirely on the non-seismic constraints.

This is not the end of α Cen seismology. More accurate frequency measurements should yield precise values of d_{01}. If the discrepancy is confirmed, we will have an interesting problem to solve. The problem we have now is the conflict between expected and observed mode amplitudes and life-times mentioned in the previous section.

More promising but much harder to interpret are spectra for more massive and more evolved objects, Procyon and η Bootis. In these cases we have a prospect for precise probing of the deep interior employing mixed mode frequencies. With progress of stellar evolution, the g-mode frequency increase leads to the *avoided crossing* phenomenon, which in the context of modeling η Bootis was discussed by Di Mauro et al. (2004). Occurrence of the mixed mode destroys the rhythm of p-modes which complicates interpretation of the spectrum but the reward is the high sensitivity of the avoiding crossing frequencies to the structure of the deep interior.

Prospect for sounding interior of intermediate mass stars ($1.2 - 1.8 M_\odot$) is appealing because, unlike in more massive objects, the convective core recedes during main sequence evolution. This may lead to the formation of a semiconvective zone, or a nearly discontinuous rise of hydrogen abundance (Popielski & Dziembowski (2005) and reference herein). It is also possible that the distribution of elements is smoothed by overshooting or by the rotation induced mixing. We do not know which is true.

η Boo is the first distant star where solar-like oscillation were definitely detected and mode frequencies were measured (Kjeldsen et al. 1995). Already in this first data there was some evidence for mode departing from ordinary p-mode pattern. There are newer oscillation spectra for this star but still there is no credible measurement of the avoided crossing frequency.

4. Seismic models without observational constraints on modes

In recent years there has been considerable interest in observations and interpretation of oscillations in pulsating B-type subdwarfs. The objects, which are believed to belong to the extreme horizontal branch, are indeed attractive targets for asteroseismology. They are truly multimodal and there is a prospect for detection of traces of the previous evolutionary phases in the internal structure.

In Fig. 1, we may see a schematic oscillation spectrum for the sdB pulsator PG 1605+072 from Charpinet et al. (2005). The spectrum lacks repeating spacings, which could be used as a clue to mode identification. The authors based their mode identification on the double-optimization method developed by the Montreal group and used in their earlier works cited in the paper. The method consists in considering oscillation frequencies in a four parameter family of stellar envelopes in thermal and diffusion equilibrium. The parameters are the total mass, M, the mass of the hydrogen-rich outer layer, M_H, the effective temperature, $T_{\rm eff}$, and the surface gravity, g. For each model a combination of low-degree ($\ell \leq 3$) modes is found which minimizes the weighted distance between the observed and calculated frequencies,

$$\chi^2 = \sum_k \left(\frac{\nu_{k,\rm obs} - \nu_{k,\rm cal}}{\sigma_k} \right)^2 .$$

The subsequent minimization of χ^2 with respect of the stellar parameters leads to identification of modes and best values of M, M_H, $T_{\rm eff}$, and g. The values of the last two parameters are known from spectroscopy which, in the case of PG 1605+072, allowed to choose between two χ^2 minima of a comparable depth. The parameters which may be determined only by means of seismology are M_H and (in this case) M. Only with these two parameters determined we have sufficient constraints on the evolutionary history of the objects.

Except of the upper limit of ℓ, which comes from the visibility argument, the set of considered modes was constrained by the condition of mode instability, which sets an upper limit on mode order, n. An argument was given that rotation is negligible hence the azimuthal order, m, was irrelevant. However, the argument for slow rotation, which is the lack of side peaks, is not satisfactory because at the level of linear theory modes of different m are independent and not all multiplet components must be excited.

All the peaks in the spectrum are explained in terms of unstable low order p-modes. The instability range extends to much higher orders ($n = 6$ at $\ell = 0$). The fact that all detected modes may be associated with unstable modes is very encouraging and must be regarded as a support for models assuming chemical element

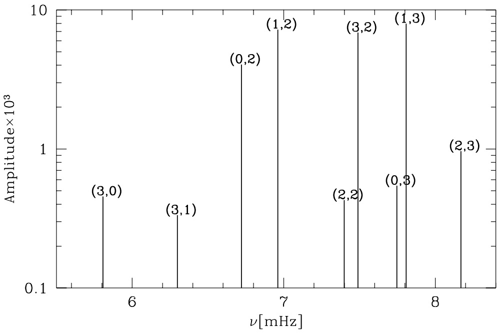

Fig. 1. Oscillation spectrum of PG 1605+072. The numbers in the bracket give (ℓ, n) - the degree and radial order of the mode. The data and mode identifications are from Charpinet et al. (2005). At $\ell = 0$ the mode count begins here with $n = 1$.

distribution determined by the diffusion equilibrium with radiative levitation taken into account. The fact that not all unstable low-degree modes are detected is typical for stars having a large number of unstable modes. However, some aspects of the proposed mode identification are causing concern.

It is difficult to justify disregarding modes with $\ell > 3$ in the situation when three of the nine peaks were identified as $\ell = 3$ and one of them is among the dominant ones. The large rise of the cancellation effect due to disc averaging occurs between $\ell = 2$ and 3. Between 3 and 4, the rise is much smaller and, in certain cases, the trend may be even reversed. Therefore, it is very important to get an independent assessment of the mode degrees.

5. Application of amplitude and phase data

The oscillation spectrum of the δ Scuti star FG Virginis, containing 67 independent frequencies obtained by Breger et al. (2005), presents the greatest challenge to theory. In spite of the large number of peaks, the spectrum lacks repeating spacings. However, unlike for sdB pulsators, we have accurate amplitude and phases for a number of peaks. Such data allow, at least in principle, to determine ℓ and m values of the modes associated with the peaks. Inference on the ℓ value is fairly straightforward and may be done in various ways. Here I briefly outline the way applied recently to the FG Vir data by Daszyńska-Daszkiewicz et al. (2005) which in addition to ℓ yields additional constraints on the star. As in all other methods, it is assumed that the atmosphere remains plane-parallel and in thermal equilibrium during pulsation and that the changes in the atmospheric parameters, $\delta\mathcal{F}_{\rm bol}$ and δg, are related to the displacement of the photospere, which is given in the form

$$\delta r(R, \theta, \varphi) = R\mathrm{Re}\{\varepsilon Y_\ell^m \mathrm{e}^{-\mathrm{i}\omega t}\},$$

where ε is a complex unknown. Then, we have

$$\delta\mathcal{F}_{\rm bol} = \mathcal{F}_{\rm bol}\mathrm{Re}(\varepsilon f Y_\ell^m \mathrm{e}^{-\mathrm{i}\omega t})$$

and

$$\delta g = -\left(2 + \frac{\omega^2 R^3}{GM}\right)\frac{\delta r}{R},$$

where f, another complex unknown, is a new seismic observable of specific diagnostic properties.

Light amplitude and phases in individual passbands are calculated with the atmosphere model data calculated around specified $\mathcal{F}_{\rm bol}$ and g. Amplitude and phase of the disc-averaged radial velocity variation are determined by δr and the limb-darkening law. The problem is cast in the form of the linear relations between measured complex amplitudes and the unknowns $\tilde{\varepsilon}$ and $\tilde{\varepsilon} f$, where $\tilde{\varepsilon} = \varepsilon Y_\ell^m(i, 0)$. The coefficients in this relations depend on the central values of the atmospheric parameters and on ℓ but not on m nor on the aspect angle, i. The values of ℓ, $\tilde{\varepsilon}$ and $\tilde{\varepsilon} f$ are determined by $\chi^2(\ell)$ minimization.

For all the 12 modes with accurate photometric and spectroscopic data, the degrees $\ell > 2$ could be be rejected at a high confidence level. In half of the cases the identification was unique at the 80% confidence level. In two cases the most likely values are $\ell = 0$. In addition, fitting the dominant peak sets stringent limits on the allowed $T_{\rm eff}$ range. Future seismic models of FG Vir should take into account all these constraints in a probabilistic form.

At the present stage, the only direct seismic probe of the star interior came from the f's determined for the twelve modes. These quantities probe only the outer layers including the hydrogen and helium ionization zones, where convection carries part of the energy flux. Thus, a comparison of the values derived from data with those determined from linear nonadiabatic calculations of stellar oscillation yields a constraint on modeling convection. Daszyńska-Daszkiewicz et al. (2005) showed that models assuming inefficient convection ($\alpha_{\rm conv} \leq 0.5$) reproduce very well observational values across the the whole frequency range extending from 9.2 to 24.2 c/d covered the twelve modes.

We understand certain aspects of the FG Vir oscillation spectrum. The dominant peaks are explained in terms of low-degree modes, which all are found unstable in the models consistent with the data. However, there are other significant peaks of which majority must have $\ell > 2$ and most likely $\ell >> 2$ (Daszyńska-Daszkiewicz et al., in this volume). Model calculations predict p-mode and low-ℓ g-mode instability of frequencies from about 5 c/d to about 30 c/d. The whole range, with varying density, is populated by the observed peaks. There is also a number of peaks with amplitudes ~ 0.2 mmag detected between 30 and 45 c/d which could not be interpret as second order peaks of lower frequency modes. Only f-modes with $\ell > 70$ are unstable in this high frequency range. Without nonlinear calculations we cannot tell whether this excitation of such modes is a plausible interpretation. Another puzzling aspect of the spectrum pointed out by Breger & Pamyatnykh (in this volume) is the occurrence of very close peaks near frequencies expected for consecutive radial modes.

6. Seismology of β Cephei stars

For years, the main interest in β Cep pulsation focused on the search of driving mechanism. After the new opacity data essentially have solved the problem, the interest moved toward seismic sounding of the stars. New extensive multisite observations of several beta Cephei, revealed much richer oscillation spectra than has been known before. The new data enabled deriving reliable constraints on star interior structure and rotation but also created some problems that await solution.

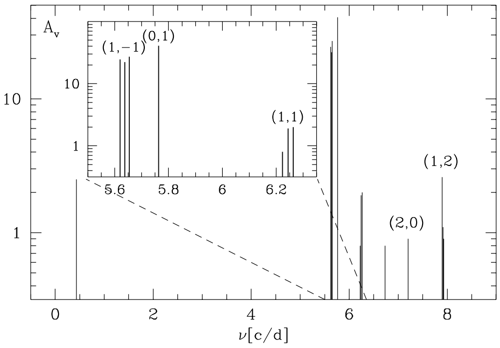

Fig. 2. Oscillation spectrum of ν Eridani with mode identification. Data are from Jerzykiewicz et al. (2005). The main new feature in comparison with data of Handler et al. (2004) is the prograde component of the (1,2) triplet. The mode identifications, shown as the (ℓ, n) values with $n = -1$ denoting the g_1-mode, are from De Ridder et al. (2004).

Here I will concentrate on one of these objects, ν Eridani, the target of recent photometric (Handler et al. 2004; Jerzykiewicz et al. 2005) and spectroscopic (Aerts et al. 2004) campaigns. Its oscillation spectrum is reproduced in a schematic way in Fig. 2. There is identification of three modes, $\ell = 0$, p_1, $\ell = 0$, p_1 and $\ell = 1$, g_1. For other two modes we know ℓ and n but not m. Constraints on the star interior from the mode frequencies were independently derived by Pamyatnykh et al. (2004) and by Ausseloos et al. (2004).

One significant seismic inference is a stringent limit on the extent of convective overshooting ($\alpha_{\rm ov} \geq 0.1$). The limit relies mainly on frequency difference between the $\ell = 1$, g_1 and p_1 mode, which is very sensitive to the element distribution in the layer outside the core. The difference between p_1 $\ell = 1$ and $\ell = 0$ mode frequency is sensitive to the metal abundance parameter, Z.

The other inference concerns the rotation rate in the same layer outside the core and it is based on the rotational splitting of the two $\ell = 1$ modes. Though the frequency difference is small (the models are near the avoided crossing), the difference in the kernels linking the splitting to the local rate, $\Omega(r)$, is large. Both kernels have maxima in the g- and p- mode propagation zones but their relative size differs. The g_1 mode splitting is much more sensitive to the rotation rate in the former zone, which encompasses the chemically inhomogenuous zone outside the core. It was found that the layer must rotate faster than envelope (factor 2.5 according to recent data).

The problem posed by the data is explaining mode excitation over the unusually wide frequency range. The seismic model yields $Z = 0.015$ and with the standard solar heavy element mix this implies mode instability in the frequency range from 4 to 6 c/d. All dominant modes are in this range but there is a definite detection of mode at 0.43 c/d and few modes above the upper limit. An *ad hoc* enhancement of the iron abundance by factor 4 in the opacity bump layer solves the problem (Pamyatnykh et al. 2004) but plausibility of such an enhancement has yet to be checked by means of evolutionary model calculations.

7. Final remarks

There has been some progress in exploitation of rich oscillation spectra in the context of unsolved problems of stellar interior physics. New constraints on element diffusion and mixing were derived from data on sdB and β Cep stars. Constraints on convection in outer layers were obtained from seismic data on a δ Scuti-type star. Available frequency data on solar-like pulsators are not yet accurate enough for similar applications but there are very interesting prospects for probing deep interior in moderate mass stars with expected more accurate data on η Boo and Procyon. Mode frequencies are not only seismic observables of interest. For unstable mode pulsators, important are simultaneous multicolor photometric and spectroscopic data on individual modes which are essential for constraining mode identification and, in addition, provide additional constraints on stellar modeling. For solar-like pulsators, data on peak amplitudes and widths provide unique information on subphotospheric convection. As Samadi et al. (2004) showed current models do not explain data for α Cen.

Understanding oscillation spectra means not only mode identification but also explaining origin and diversity in the form of observed oscillations. The very presence of oscillations sets a constraint on stellar physics as best demonstrated in the case of sdB pulsators (Charpinet et al. 2005). New data on ν Eridani (Handler et al. 2004) cast some doubts on current understanding of the linear driving mechanism in β Cep stars. Perhaps also in this case the same effect of iron accumulation as proposed for sdB pulsation must be invoked. Progress in nonlinear modeling is needed to explain puzzling features of oscillation spectra found in some opacity driven pulsators and, in particular, in the most multimode δ Scuti star FG Vir.

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