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The impact of asteroseismology on the theory of stellar evolution

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Abstract

We summarize the theory of stellar evolution, highlighting key physics to be resolved at various stages in a stellar lifetime. The rôle of asteroseismology in testing theory is illustrated by discussion of pulsations in highly evolved stars.

Individual Objects: o Cet, δ Cep, BPM 37093, FG Sge, GW Vir, XTE J1814–338

Introduction: Pulsating Stars

The first star recorded to be properly variable (rather than eruptively variable) was discovered by David Fabricius in 1596 (Wolff 1877). In 1639, Jan Fokkens Holwarda showed it to have a period of some eleven months. Johannes Hevelius (1662) was so impressed by this star, which varies by nearly 7 magnitudes in visible light, that he called it Mira, meaning "wonderful, astonishing", for it acted like no other known star (Hoffleit 1997). This is still true. Also known as o Ceti, it was the third star (after the Sun and Betelgeuse) to have its surface resolved, showing a curious prominence (Karovska et al. 1997), and was discovered to be shedding a tail some 8.10^5 astronomical units in length long (Martin et al. 2007). Mira is an asymptotic giant branch star – of which more later – which means that from time to time it undergoes a thermal pulse which radically alters the structure of its outer layers. Mira's period varies slightly from cycle-to-cycle, but other Mira variables show systematic changes in period which must be associated with changes in internal structure (Templeton et al. 2005). Such observations enable direct tests of the stellar evolution theory.

δ Cephei

Stellar pulsation science came into its own with the discovery of pulsations in δ Cephei (Goodricke 1785) and the subsequent discovery of the Cepheid period-luminosity relationship (Leavitt 1908). Providing a ruler with which to measure the universe, Goodricke's discovery ultimately changed the global human perspective. Yet understanding why Leavitt's relation should work, what the interior of a Cepheid variable should look like, and how pulsations are driven would lead to a serious discrepancy between the masses inferred from pulsation and evolution theory respectively (Cox 1980). This discrepancy would not be resolved until the physics, i.e. the opacity, of stellar material was sufficiently understood (Simon 1982, Moskalik et al. 1992). Now, with confidence that pulsations have much to tell us about physics and cosmology, and new instruments to observe individual stars over long periods of time, the science of asteroseismology has matured and been applied in a huge range of contexts.

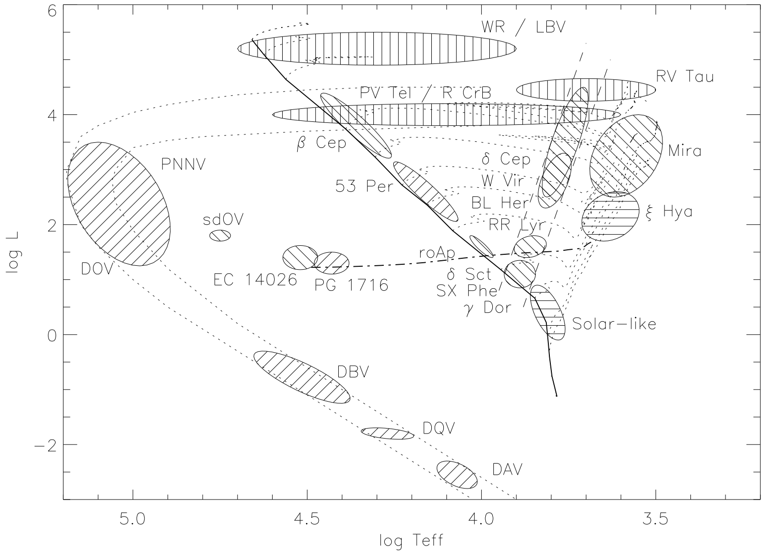

Figure 1: Schematic Hertzsprung-Russell diagram showing the locus of major classes of pulsating variable star. The zero-age main sequence shown as a heavy solid line and evolution tracks from the main sequence through helium-burning shown as dotted lines are computations by the author. The zero-age horizontal branch is shown as a heavy dot-dash line. Cooling tracks for He and and CO white dwarfs are also shown (dotted). Diagonally-shaded regions correspond to opacity-driven p- and g-mode pulsating variables. Horizontally-shaded regions show acoustically-driven (solar-like) variables. Vertically-shaded regions correspond to highly non-adiabatic pulsations, possibly strange modes of various types. The figure concept follows one by J. Christensen-Dalsgaard.

Asteroseismology

This paper reviews the impact of asteroseismology on the theory of stellar evolution. Strictly, asteroseismology is the science that “studies the internal structure of pulsating stars by the interpretation of their frequency spectra” (according to Wikipedia). Again strictly, stars which pulsate with one mode only give information about their mean density, and not about their internal structure. Even in this case, additional information may be available to infer something about their structure. Conversely, to infer the complete core-to-surface density distribution of a star from a frequency inversion requires a pulsation spectrum so rich that it may only ever be obtained for the Sun and a few bright stars. However, studies with a resolution intermediate between these extremes can tell us much about the structure and local physics within a star. Whether this can be translated to information about their evolution (as distinct from structure or physics) is not always apparent.

Consequently, this review considers how the study of stellar oscillations of all types has made an impact on our understanding of stellar evolution (Fig. 1). The emphasis leans towards cases where multiple periods have enabled some resolution of structure in the radial direction. The first half of the paper provides a brief reminder of the stellar evolution theory, including a summary of the open questions important at different stages in the life of a star and the types of pulsating stars available to test the theory. The second half reviews specific examples of where asteroseismology has helped to resolve key questions. Reflecting the author’s interest, this is biased toward stars in their later stages of evolution.

The Stellar Evolution Theory

A primary object of the stellar evolution theory is to explain the widely diverse properties and the overall distribution of stars represented in the Hertzsprung-Russell (HR) diagram. Another is to understand how stars change both their physical and chemical structure as they deplete their available energy reserves. The extent of the task can be illustrated by noting that stars exhibit oscillations with periods ranging from $\sim 10^{-3}$ s (neutron stars) to $\sim 10^{8}$ s (Mira variables), and by recalling that the fundamental pulsation period varies inversely as the root mean density, i.e. the mean densities found in stars span some 22 orders magnitude. A simplified picture of the theory of stellar evolution showing the evolution of representative stars with masses 1 and $5M_\odot$ through the HR diagram may be found at www.maths.monash.edu.au/~johnl/StellarEvolnV1/.

Main Sequence Stars

On the main sequence, where stars spend over 90% of their lives, hydrogen is converted to helium in the stellar core via the pp-chains and the CN(O) cycles. Most of the major questions about how these stars evolve revolve around the micro-physics. Thus κ, the radiative opacity, ∇, the physics of convection, ω, rotation, B, magnetic fields, and diffusion all influence the rate of energy transport, chemical transport and consequently the overall structure of the star. On the upper main sequence, stellar winds and mass loss feed into this system and all feed back to affect the overall luminosity and main sequence lifetime.

Pulsating stars associated with this phase of evolution include the Sun and solar-type, δ Sct, γ Dor, SX Phe (variable blue stragglers), ro-Ap, 53 Per (slowly-pulsating B stars), and β Cep variables.

Giant-Branch Stars

As hydrogen in the core is depleted, the core contracts and hydrogen-burning shifts to a shell, the outer layers expand and the star becomes a red giant. Convectively-driven mixing between the unprocessed surface and processed core material, and mass-loss due to a dust-driven wind, dominate the long-term evolution. Both processes are strongly mediated by the local opacity. Rotation also plays an important role; the contracting core attempts to spin up, while the expanding envelope slows down, potentially leading to strong shear forces and complex magnetic structures. Acoustically driven oscillations have been identified in sub-giants (e.g. ξ Hya), providing a possible asteroseismic probe of the convective layers.

Helium Stars

Once the helium core reaches a critical mass, core helium-burning through the 3α and $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$ reactions provides a relatively long-lived phase of evolution. Intermediate-mass stars will evolve as yellow giants and pass through the classical (δ) Cepheid instability strip.

There are several ways to consider the masses and ages of stars. For the Cepheids, it is possible to measure radii, luminosities and masses directly using Baade's method or some variant. Masses can also be estimated by matching the luminosity and radius with evolution models for helium-burning stars that pass through the instability strip, and by matching the observed luminosity and pulsation period using stellar pulsation theory. As discussed already, the mismatch between Cepheid masses predicted by these methods was one of the longest-standing failures of theory until it was proven to be due to missing opacity. Metal-poor counterparts to the classical Cepheids appear as W Vir (long period) and BL Her (short period) variables.

Low-mass core-helium burning stars form a clump near the base of the red giant branch (clump giants), unless they are either metal-poor or have very thin hydrogen envelopes. In this case they appear as horizontal-branch stars, some of which fall in the RR Lyrae instability strip. The bluest horizontal-branch stars (or subdwarf B stars) lie in the EC14026 and PG1716 instability strips. The rôle of opacity and the $^{12}\mathrm{C}\alpha$ reaction cross-section dominate uncertainties in the evolution through this phase.

For massive stars, helium-core burning may occur while the star is still hot and blue and, being associated with high luminosity, pulsations are likely to be associated with strange-mode instability.

Asymptotic Giant-Branch Stars

With core-helium exhaustion, the focus of nuclear-burning in low- and intermediate-mass stars shifts to a double-shell structure. Because of an imbalance between the burning rates of the hydrogen and helium shells, an instability known as thermal-pulsing is established. The thermal pulse is one of the most important processes in cosmology. The faster-burning hydrogen-burning shell produces an accumulation of helium-rich material above the boundary with the degenerate carbon-oxygen core. When sufficiently massive, the helium-shell ignites mildly, the intershell region is forced to expand and hydrogen-burning is extinguished. A nuclear-driven convection zone penetrates upwards and through the helium-hydrogen boundary, mixing processed material upwards and bringing protons down into hot helium-rich layers. These protons seed the nucleosynthesis of exotic elements. The helium-shell cannot sustain itself once the inter-shell mass drops below a critical value. Helium-burning reactions subside, the inter-shell contracts, the hydrogen-shell is reignited and opacity-driven envelope convection dredges freshly processed material up to the stellar surface, whence it escapes to enrich the interstellar medium.

As a consequence of the intensity of the hydrogen-burning shell, the star becomes very luminous and very large. The outer layers are increasingly unstable, exhibited first as opacity-driven pulsations of very long-period (e.g. o Cet), and then as strong stellar winds creating an extended optically thick envelope. While the evolution driver is the nuclear physics of the shells, the stellar structure is governed by opacity, dust-formation and the wind.

Planetary Nebula Formation and White Dwarf Cooling

Ultimately, the expansion results in a dynamical instability which causes the expulsion of the outer layers as a planetary nebula. Unable to sustain nuclear reactions, the remnant envelope starts to contract on a thermal timescale. When it has cooled sufficiently (the surface actually heats, but the total entropy falls), the star approaches the white dwarf cooling track. The significant physics in this phase are the chemical structure of the cooling envelope and the very high overall luminosity.

As the star reaches the white dwarf cooling track with effective temperatures $> 100\,000$ K, even the envelope becomes electron-degenerate. Opacity-driven g-mode pulsations can manifest when the internal chemical structure is right (GW Vir variables).

As the star descends the cooling track, ionization zones in the white dwarf atmosphere become convective. During subsequent cooling, the star passes through the DBV and DAV=ZZ Cet instability domains. Again, g-modes are excited, offering a possibility to explore the chemical structure of the deep interior, as well as the physics of surface convection and the white dwarf equation of state.

Binary Stars

The above description applies to those stars which evolve as single stars or as members of wide binary systems which do not interact. It is increasingly clear that a large fraction of stars are born in binary systems in which the components exchange material at some point during their evolution. Mass transfer may be slow and conservative (stable Roche Lobe overflow), rapid (dynamical mergers), or non-conservative (common-envelope ejection). The resulting stars (e.g. blue stragglers, early-R stars, subdwarf B stars, R CrB stars) have structures entirely different from those predicted by single-star theory. A vital task of asteroseismology is to probe the current structure of these stars and explain the physics of the prior interaction.

The Impact of Asteroseismology

In reviewing the impact of asteroseismology on the theory of stellar evolution, we have already touched on one major problem in stellar pulsation – the Cepheid mass discrepancy. Another was the driving mechanism for the β Cepheid variables (Moskalik & Dziembowski 1992). In both cases the solution was opacity – specifically the contribution of iron-group elements to opacity at temperatures around 10^5K. It will be seen that the rôle of opacity is a recurring theme in asteroseismology.

Time and space do not permit discussion of the recent impact of studies of the Sun and solar-like oscillations, δ Sct and γ Dor variables, ro-Ap stars and slowly-pulsating B stars, not to mention RR Lyr, BL Her, and W Vir variables, bump Cepheids and many others. The author has chosen to focus on familiar territory, i.e. asteroseismology in the late stages of stellar evolution.

Extreme Horizontal Branch Stars

Extreme horizontal-branch (EHB) stars were first discovered as faint blue stars in the Galactic halo, where they became more commonly known as subluminous B (or sdB) stars (Greenstein & Sargent 1974). Their cosmic importance is established by the contribution they make to the ultraviolet light of giant elliptical galaxies and certain galactic globular clusters (Yi & Demarque 1998, Brown et al. 2000). Straightforward studies of low-mass stellar structure and evolution demonstrates that sdB stars (a) must be helium-core burning stars with a mass of ~ 0.5 $M_\odot$ and a negligible hydrogen envelope and (b) cannot be produced by conventional single-star evolution. Fortunately, it is clear that there are at least four binary-star evolution channels that will result in the production of an EHB star, as well as at least four types of stellar system containing an sdB star. The question is whether we can compare nature and theory. Stellar population synthesis can be used to estimate the mass distribution of the EHB stars expected from each of the binary evolution channels (e.g. Han et al. 2003). While a specific mass distribution depends on certain simulation parameters (metallicity, critical mass ratio for stable mass transfer, mass transfer efficiency, etc.) it is clear that, for example, helium white dwarf mergers will result in a much broader sdB mass distribution than common-envelope evolution, or stable Roche lobe overflow. It is possible to identify which sdB star came from which evolution channel from its binary properties, but not usually to measure its mass precisely. Fortunately, the discovery of pulsations in sdB stars (EC 14026 stars: Kilkenny et al. 1997, PG 1716 stars: Green et al. 2003) has made it possible to carry out asteroseismology (e.g. Charpinet et al. 2008) and hence determine the mass distribution of different classes of sdB star (e.g. Randall et al. 2008). More systems will have to be solved by asteroseismology before this technique yields an unequivocal test of the theory – but current signs are promising. A second consequence of the pulsation discoveries was evidence of chemical stratification – iron-group elements have to be enriched in the driving zones by radiatively-driven diffusion if they are to pulsate at all (Charpinet et al. 1997).

Post-AGB Stars

Beyond the horizontal and asymptotic-giant branches, low-mass stars contract towards a fully degenerate configuration on the white-dwarf cooling sequence. Their interior properties are governed by chemical stratification, a record of previous evolution frozen in by the hard equation of state. Along the cooling sequence, white dwarfs traverse a series of instability strips where, if the composition of the driving layers is right, excited g-modes make it possible to explore this deep interior. Recent progress is reviewed amply elsewhere (Fontaine 2008). It suffices here to recall the poster child BPM 37093 (= Lucy: Metcalfe et al. 2004). Asteroseismology using data collected by the Whole Earth Telescope concluded that this star was 90% crytallized carbon – a giant diamond in the sky – and placed strong constraints on the masses of the outer hydrogen and helium layers ($-4.2 > \log M_{\rm H} > -5.6$, $2 > \log M_{\rm He} > -2.6$). While the details are not entirely uncontested (Brassard & Fontaine 2005), it is significant that twenty years ago, there was considerable debate over the value of $M_{\rm H}$ at the end of AGB evolution. Strong limits on $M_{\rm H}$ and $M_{\rm He}$ from asteroseismology now directly constrain stellar evolution theory.

Post-Post-AGB Stars

Also in the last two decades, substantial evidence has accumulated that contraction to become a white dwarf is not the final journey in the life of very low-mass star. In some stars, it appears that re-ignition of the helium-burning shell as the star is contracting (a late thermal pulse) or even after it has reached the cooling track (a very-late thermal pulse) causes the star to expand vigorously to become a yellow super-giant. Whilst cool and luminous, an increasing pulsation period may give direct evidence of expansion (cf. FG Sge, van Genderen & Gautschy 1995). The challenge for stellar evolution theory is to understand the physics of these late thermal pulses. For example, following a late thermal pulse, models suggest that flash-driven convection mixes fresh nuclear material up through the inter-shell region, but these are not dredged to the surface until the star has become a giant and has developed a deep opacity-driven surface convection zone, whereupon the surface becomes rich in helium and carbon. In the case of a very-late thermal pulse, models suggest that flash-driven convection is sufficiently energetic to penetrate the now much lower entropy barrier at the base of the hydrogen envelope and to reach all the way to the stellar surface (Schönberner 1979, Herwig et al. 1999). Prompt mixing of the entire outer layers will result, including ingestion of protons into hot helium- and carbon-rich inter-shell material with the likely production of additional s-process elements.

As the energy of a final flash is dissipated, the envelope cools and the star contracts for a second time to the white-dwarf cooling track, as an hydrogen-deficient star. While the times-scales of contraction (and expansion) depend on when the final-flash occurred (late or very late), both channels produce very hot (DO) white dwarfs. Several stars at the transition between contraction and cooling show multi-periodic g-mode pulsations. Asteroseismology of these GW Vir variables has provided very strong constraints on the global properties (mass, radius, effective temperature) of these stars, as well as internal properties such as the thickness of the helium envelope (Corsico et al. 2007a,b, Althaus et al. 2008). One challenge is that the best models of the best-observed star (GW Vir) predict an increasing period, whilst the observations show a decreasing period. The question is whether this is a problem with the helium envelope thickness or some other aspect of the internal structure.

Post-White-Dwarf Evolution – Is There Life After Death?

The GW Vir variables and other PG 1159–035 stars and DO white dwarfs form the hot end of a sequence of "post-post-AGB" stars with hydrogen-deficient and very carbon-rich surfaces ($\sim$ 10% by number). Another hydrogen-deficient sequence, with rather lower carbon abundance ($\sim$ 1% by number) is suggested by the R CrB variables, extreme helium stars (EHe) and other hydrogen-deficient hot subdwarfs (cf. www.arm.ac.uk/~csj/research/ehe_links/ and Jeffery 2008a). The late thermal pulse fails to account for many of the properties of this sequence; a stronger model is provided by the idea that binary systems containing two white dwarfs may merge. The ignition of helium material accreted onto the CO white dwarf surface forces the star to become a yellow super-giant, and subsequently to contract along this sequence (Saio & Jeffery 2002, Clayton et al. 2007). The most massive of these stars have luminosity-to-mass ratios that are so high that they are pulsationally unstable both while they are in the classical Cepheid instability strip (the RCrB stars) and as they evolve to higher effective temperature (Saio & Jeffery 1988, Jeffery 2008b). There have been suggestions that the hottest EHes exhibit multi-periodic pulsations, and clear evidence of strong line-profile variations, but with periods ~ 1 day and longer, and the likelihood of extreme non-adiabacity, a direct application of asteroseismology to test the white dwarf merger model for these stars remains a cherished dream.

Really Dead Stars

Most exotic of all, are the oscillations that might be exhibited by neutron stars. The clock-like radio signatures of pulsars are well-known, though possibly less well-understood. Some authors have examined the potential for generating surface Rayleigh waves in the solid crust (e.g. Yoshida & Lee 2001, 2002), while Piro & Bildsten (2004, 2005a,b) have looked at oscillations in the fluid layers above the solid crust. The question is whether any of these oscillations, if excited, would manifest to a distant observer. X-ray observations point to millisecond oscillations in a number of neutron stars (Kaaret et al. 2007, Casella et al. 2008, Strohmayer et al. 2003). XTE J1814-338 has suggested an asteroseismological application that leads to the mass-radius ratio and hence to a strong constraint on a stiff equation of state for the neutron-star interior (Bhattacharyya et al. 2005, Leahy et al. 2008).

Conclusion

The opening slide of the talk on which this paper is based showed a photograph of an asteroseismologist and a geologist (the author and daughter) sailing a small boat on Belfast Lough. There is evidence of a driving mechanism – wind acting on the sails of the boat. The motion of the boat demonstrates oscillations of the water surface; since gravity (or buoyancy) is the restoring force – these must be gravity waves. Spray from the dinghy's bow shows evidence of damping, at least to the crew. Following closer inspection of the supporting fluid (by complete immersion) – the expedition concluded that further study of such waves would tell them a lot about fluid dynamics, and perhaps about the surface gravity of the Earth, but relatively little about its global structure or evolution. The lesson is that stellar oscillations invariably inform about the physics of a stellar envelope; the extension to information about stellar evolution is not always obvious.

Our introduction emphasized caution; much of the recent impact of asteroseismology has been to reveal the structure of a pulsating star, and thereby to explore the underlying physics, such as convection, rotation, opacity and diffusion. There is no doubt that the study of stellar pulsation as a whole has had a profound impact on all of these, as well as radically reforming our theories of stellar evolution and, indeed, cosmology. Asteroseismology per se is coming of age as more sensitive experiments and more numerous targets become available. It is becoming possible to test the evolution theory by observing stellar structure at many points between the stellar nursery and the stellar graveyard. In this brief résumé, we have discussed evidence that asteroseismology has made a major impact on: understanding the physics of main sequence stars, resolving the theory of stellar evolution through He-burning phases, testing new aspects of evolution theory and physics for "exotic" stars, resolving the C/He/H structure of white dwarfs, providing tests of nuclear processes and mixing in prior phases of evolution, and, via masses and rates of period change, testing models for stars evolving on thermal and/or nuclear timescales.

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DISCUSSION

Noels: I do not understand why you completely reject the single star scenario to explain sdB stars. Are you confident enough about mass loss rates during mass loss rates during red giant phase and helium flashes to rule out such a scenario?

Jeffery: So far I have not seen any result that would lead me to believe that a single RGB star can lose its envelope early. Helium flash models do not predict enhanced mass loss. Normal red giant winds do not suggest removal of the entire H-envelope. Otherwise, I would expect to see many more sdB stars than we do – especially in globular clusters. Having said that, the sdB stars in globular and old-red-dead galaxies must have a significantly different progenitor population to those in the disk of the Galaxy. It is conceivable that RGB winds behave differently in these environments. However I think it more likely that a shift in the balance between the close-binary formation channels (merger versus common-envelope, for example) is responsible for the different sdB statistics.

Lampens: Could it be that the problem with g-mode instability strip is due to the fact that many sdB stars are close binaries and that g-modes are not intrinsically excited ?

Jeffery: Since only a fraction of g-mode sdBs are in close binaries, intrinsic excitation must operate in the remainder and therefore, most likely, in all. Now that we understand the opacities better (Jeffery, C. S., & Saio, H., 2006, MNRAS, 372, L48), I do not believe there is any problem with the fundamental physics of the g-mode instability strip, though the details must still be refined.

Audience paying attention to a talk

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Examples of seismic modelling

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Abstract

Findings of a few recent asteroseismic studies of the main sequence pulsating stars, as performed in Wojciech Dziembowski's group in Warsaw and in Michel Breger's group in Vienna, are briefly presented and discussed. The selected objects are three hybrid pulsators ν Eridani, 12 Lacertae and γ Pegasi, which show both β Cephei and SPB type modes, and the δ Scuti type star 44 Tauri.

Individual Objects: ν Eri, 12 Lac, γ Peg, 44 Tau

Introduction

Main sequence stars (including the Sun) seem to be ideal objects for the seismic modelling, i.e. for construction - or rather refinement - of the models of individual stars using data on their multiperiodic oscillations. The structure of the MS stars has been understood qualitatively quite well but some details of the structure and some physical processes still need to be explained. These problems have been specified and discussed in a very compact and informative form by Marc-Antoine Dupret (2008) in his introductory talk (these Proceedings). By fitting stellar models to observational data on oscillations, we can obtain detailed constraints on stellar parameters and on physical processes in interiors.

Most of the results, presented in this contribution, have been discussed more thoroughly by Dziembowski & Pamyatnykh (2008) and by Lenz et al. (2008). However, newest observational data (in particular, for 44 Tau) may change some conclusions of those papers.

Hybrid stars ν Eri, 12 Lac and γ Peg

Hybrid stars are main sequence pulsating variables which show two different types of oscillations: (i) low-order acoustic and gravity modes of β Cephei type with periods of about $3-6$ hours, and (ii) high-order gravity modes of the SPB type with periods of about $1.5-3$ days. Theoretically, such a behaviour was predicted for $\ell > 5$ by Dziembowski & Pamyatnykh (1993, see Figs. 5 and 6 there) and later, when using newer opacity data, also for the low-degree oscillations (Pamyatnykh 1999). In the HR diagram, the overlapped region of the β Cep and SPB type pulsations is very sensitive to the opacity data (see Figs. 3 and 4 in Pamyatnykh 1999), therefore the modelling of hybrid star pulsations will allow to test the opacity of the stellar matter - for example, to choose between two independent sets of the OPAL and OP data (Iglesias & Rogers 1996 and Seaton 2005, respectively). Theoretical β Cep and SPB instability domains and position of three confirmed hybrid stars are shown in Fig. 1. All three stars are very close to the region where hybrid pulsations are expected when using the OP opacities.

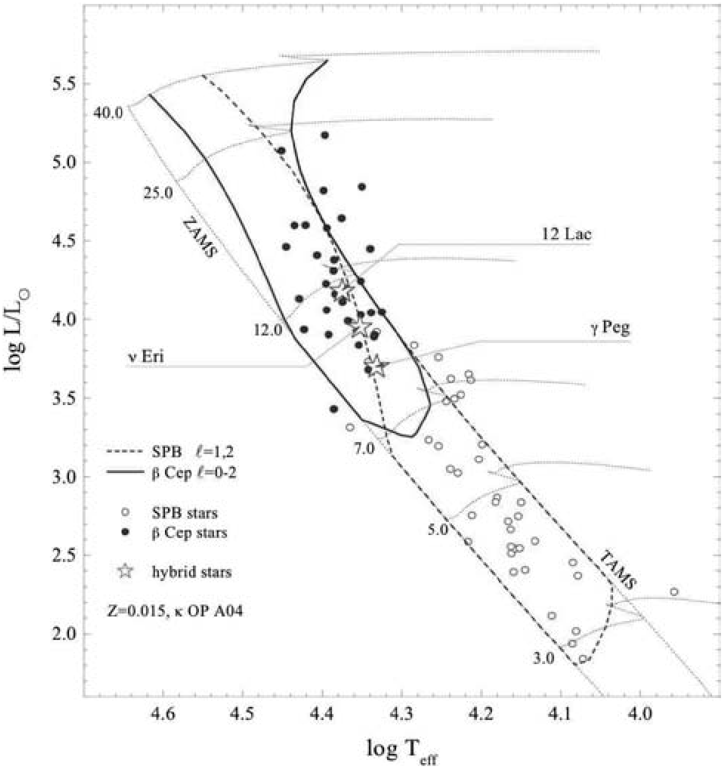

Figure 1: Pulsational instability domains in the upper part of the main sequence. In the overlapped region of the β Cep type and SPB type oscillations the hybrid pulsations are expected. OP opacity data for $Z = 0.015$ and for new solar proportions in the heavy element abundances were used (mixture A04, Asplund et al. 2005). The positions of observed stars were obtained using catalogs of Stankov & Handler (2005, β Cep) and De Cat (2007, SPB). Three hybrid stars are marked explicitly.

Fig. 2 shows the observational frequency spectra of ν Eri and 12 Lac. High-frequency modes of the β Cep type are well resolved, and their degree, ℓ, and in some cases also azimuthal order, m, are determined from photometry and spectroscopy. For very slow rotating star ν Eri, one radial mode, two $\ell = 1$ triplets (modes g_1 and p_1) and one more mode ($\ell = 1, p_2$, $\nu = 7.89$ c/d) are identified. For 12 Lac, one radial mode, two components of a $\ell = 1$ triplet and 5 other $\ell = 1$ and/or $\ell = 2$ modes are identified.

The seismic models of ν Eri which fit radial and two $\ell = 1, m = 0$ frequencies were constructed for different opacities (OP and OPAL) and different assumptions about the efficiency of the overshooting from the stellar convective core. Ausseloos et al. (2004) constructed seismic models of this star which fit one more mode, $\ell = 1, p_2$ at $\nu = 7.89$ c/d, but it was necessary to assume rather unrealistic chemical composition parameters (X and/or Z) and a quite effective overshooting. Moreover, they did not consider the low-frequency modes of the SPB type pulsations. We argued that the overshooting from the convective core is ineffective in ν Eri (seismic models with overshooting are located outside the observational error box in the HR diagram) but this result critically depends on the $T_{\rm eff}$ determination.

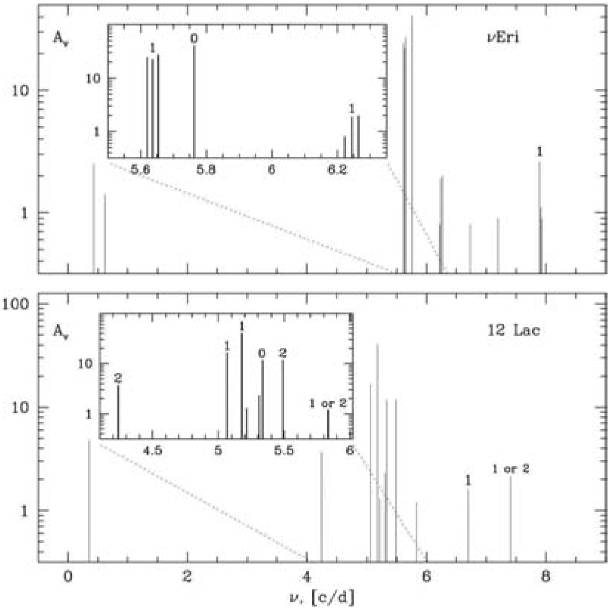

Figure 2: Observational frequency spectra of ν Eri and 12 Lac based on Jerzykiewicz et al. (2005) and Handler et al. (2006) data, respectively. The numbers above frequency bars mark mode degree values, ℓ, as inferred from multicolour photometry (according to Dziembowski & Pamyatnykh 2008).

Fig. 3 illustrates the effect of the opacity choice between the OPAL and OP data on the instability of $\ell = 1$ and $\ell = 2$ modes of ν Eri seismic model. The OPAL model was discussed by Pamyatnykh et al. (2004). Using the OP data leads to wider frequency instability range, as it has been demonstrated very clearly for whole β Cep and SPB domains by Miglio et al. (2007). They also showed that the effect of the choice between old and new solar proportions in the heavy element abundances - respectively, GN93 (Grevesse & Noels 1993) and A04 (Asplund et al. 2005) - is significantly smaller than that of the opacity choice. Only the model constructed with the OP data is unstable in low-frequency modes (high-order g modes of $\ell = 2$) and can fit the measured frequency at 0.61 c/d. The local η maximum for $\ell = 1$ nearly coincides with another measured low frequency at 0.43 c/d, but no instability was found there. There is also a problem of excitation and fitting of the observed peaks at 7.89 c/d, one of them was identified from photometry as an $\ell = 1$ mode (it must be $\ell = 1, \mathrm{p}_2$ mode). Zdravkov & Pamyatnykh (2008) demonstrated that an additional opacity enhancement by approximately 50 % around the iron bump at its slightly deeper location may lead to the instability of both high-order g modes and $\ell = 1, \mathrm{p}_2$ mode at the observed frequencies.

The two $\ell = 1$ triplets in the ν Eri frequency spectrum allow to constrain internal rotation rate. In Fig. 4, the rotational splitting kernels (weighting functions in the integral over the local rotational velocity inside the star) for two dipole modes of the seismic ν Eri model are shown. These kernels determine the sensitivity of different layers to the rotational splitting of the oscillation frequencies, therefore from the measured spacings between components of different multiplets we can obtain information about internal rotation. We showed that in ν Eri the convective core rotates approximately 5 times faster than the envelope.

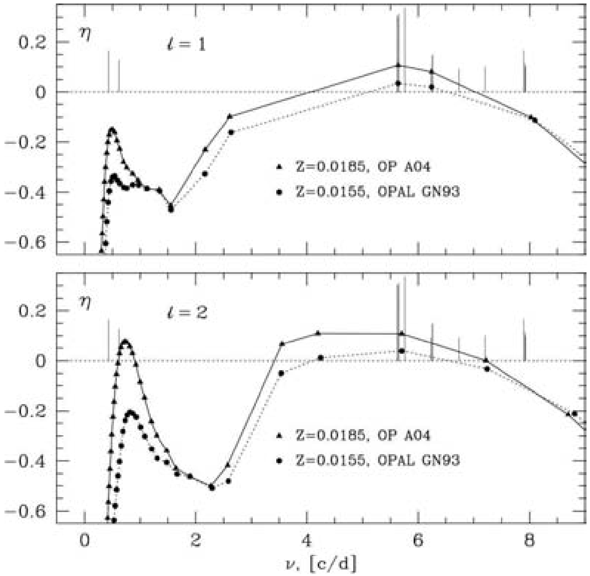

Figure 3: The normalized growth rate, η, as a function of mode frequency for ν Eri seismic model constructed both with OPAL and OP opacities ($\eta > 0$ for unstable modes). Both models fit the observational error box ($\log L, \log T_{\rm eff}$) in the HR diagram. The frequencies of radial fundamental and two dipole modes ($\ell = 1$, modes g_1 and p_1) fit the observed values at 5.763, 5.637 and 6.244 c/d, respectively. The observed frequencies are shown by vertical lines, with their lengths proportional to the mode amplitudes in a logarithmic scale. Note that in the OP case there are unstable low-frequency quadrupole ($\ell = 2$) modes, whereas in the OPAL case all low-frequency modes are stable.

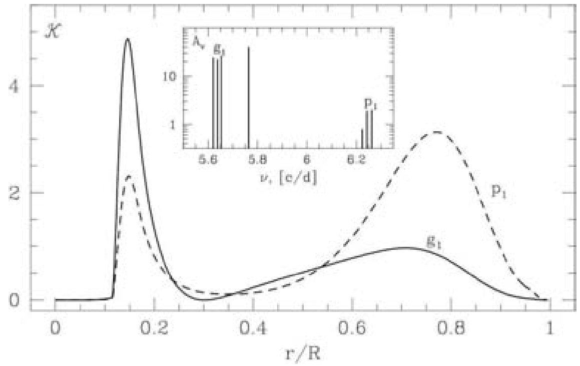

Figure 4: The rotational splitting kernels, $\mathcal{K}$, for the two dipole ($\ell = 1$) modes in the seismic model of ν Eri. The corresponding part of the frequency spectrum is shown in the small box. The inner maxima extend over the chemically nonuniform zone above the convective core.

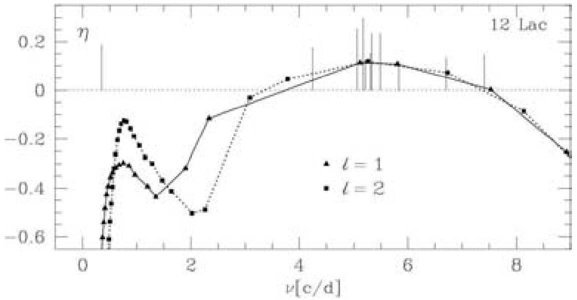

Figure 5: The normalized growth rates, η, of $\ell = 1$ and $\ell = 2$ modes as a function of mode frequency in seismic model of 12 Lac computed with the OP opacities for $Z = 0.015$ and heavy element mixture A04. Vertical lines mark the observed frequencies, with amplitudes given in a logarithmic scale.

In Fig. 5, the observed frequency spectrum of 12 Lac is compared with results for a seismic model which was constructed to fit four dominant peaks at 5.0-5.5 c/d: the radial fundamental mode, two components of $\ell = 1$ triplet and one component of the $\ell = 2$ quintuplet. Most of remaining peaks also have their counterparts among theoretical frequencies. The $\eta(\nu)$ dependence is similar to that for the ν Eri model in Fig. 3. The theoretical frequency range of unstable β Cep type modes fits the observed peaks very well. However, the high-order g modes of $\ell = 1$ and $\ell = 2$ are stable, in contrast to the $\ell = 2$ case of ν Eri. Again, the solution of the problem may require an opacity enhancement in the driving zones in deep envelope. From the frequencies of two components of rotationally splitted $\ell = 1$ triplet (and taking into account a necessity to fit the observed $\ell = 2$ peak at 4.2 c/d) we estimated that the convective core rotates approximately 4.6 times faster than the envelope, this result is similar to that for ν Eri. The calculated surface equatorial velocity of 47 km/s agrees very well with the spectroscopic estimation of about 50 km/s.

γ Peg is also a hybrid star (Chapellier et al. 2006 and private communication by G. Handler) with two oscillation frequencies of the β Cep type (6.01 and 6.59 c/d), and two - of the SPB type (0.686 and 0.866 c/d). Fig. 6 illustrates preliminary results of the modelling. The models were constructed by fitting the frequency of the radial fundamental mode to the observed frequency at 6.59 c/d. As it is easy to see from Fig. 6, the frequency of dipole mode $\ell = 1, g_1$ can fit the observed value 6.01 c/d in a model with Z value in between 0.015 and 0.02. Two observed low-frequency modes are well inside the frequency range of unstable high-order gravity modes of $\ell = 2$. The identification of the mode degree for observed peaks will allow to check these preliminary assessments. Now, an intensive campaign of ground-based and satellite observations (with the MOST satellite) is on the way (G. Handler, private communication).

44 Tau

The δ Sct type variable 44 Tau is an extremely slowly rotating star in which 15 oscillation frequencies have been measured (Antoci et al. 2007, Breger & Lenz 2008). Two of them are identified as radial modes. Moreover, 7 other modes have been identified as $\ell = 1$ and $\ell = 2$ oscillations. The $\log g$ value as determined from photometry and spectroscopy does not allow to choose between the main sequence and post-MS model for this star. Lenz et al. (2008) gave asteroseismic arguments in favor of the post-MS model. In particular, only post-MS model can fit both observational error box in the HR diagram and frequencies of two radial modes. In Fig. 7 the observed and theoretical frequency ranges are compared for two 44 Tau

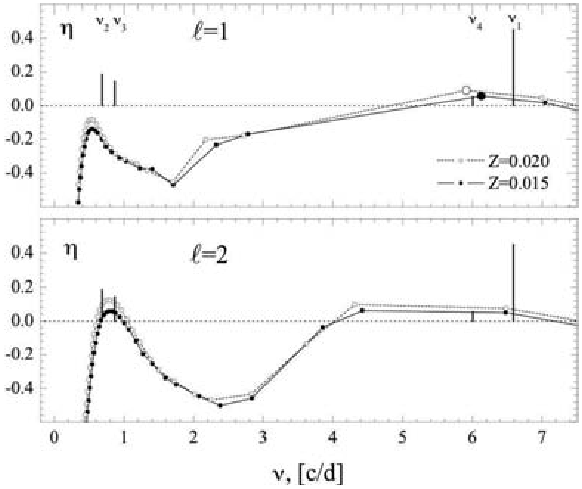

Figure 6: The normalized growth rates of $\ell = 1$ and 2 modes in two γ Peg models constructed with the OP opacities for the heavy element mixture A04. Both models have mass of 8.7 $M_{\odot}$ but differ in the heavy element mass fraction, Z. Two larger points close to the ν_4 mark mode $\ell = 1, \mathrm{g}_1$.

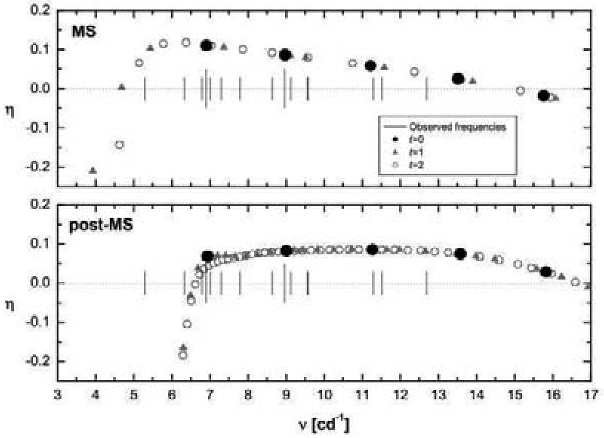

Figure 7: The normalized growth rates of $\ell = 0 - 2$ modes in the main sequence and post-MS models of 44 Tau. Vertical lines mark the observed frequencies, with longer lines for two identified radial modes. Both models fit these radial frequencies.

star models. In contrast to a similar plot given by Lenz et al. (2008), this figure also includes the previously unknown lowest frequency mode at 5.30 c/d which has been detected very recently (Breger & Lenz 2008). This finding may be an argument against the post-MS models for 44 Tau which have no unstable modes at these low frequencies.

Acknowledgments. A partial financial support from the Polish MNSiW grant No. 1 P03D 021 28 and from the HELAS project is acknowledged. I am grateful to Tomasz Zdravkov for Figs. 1 and 6, and to Patrick Lenz for Fig. 7 and useful comments.

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DISCUSSION

Noels: I fully agree with you that there probably is a missing opacity not only in β Cep stars but all along the MS. I am however surprised by your results for ν Eri on the comparison between OP and OPAL opacities. The "best" models you obtain are very different which means that the change is not only due to changes in the iron bump but also to changes in the whole star. Do you agree with that? This is very different from an increase of opacity limited to the iron bump which will only affect the excitation of the modes.

Pamyatnykh: You are correct in that our best seismic models computed with the OPAL and OP data differ in a some extent not only in the iron bump region but also in the whole star. The most important difference between the OP and OPAL opacities is that in the OP case the iron bump is located slightly deeper in the star (at slightly higher temperatures) compared with the OPAL case. Our seismic models of ν Eri fit the observed frequencies of the radial fundamental mode and two dipole modes (g_1 and p_1) very nicely, with an accuracy better than 10^{-3}. The opacity changes around the iron bump even by about 20 percent (which is a systematic difference between OP and OPAL at fixed temperature in this region) lead to a change of the stellar structure and consequently to a change of the oscillation frequency spectrum, so to fit the observed frequencies we must adjust global stellar parameters - such as mass, heavy element abundance and effective temperature. Therefore, the structure of the seismic model constructed with the OP data will differ in some extent from that of the model constructed with OPAL. Again, an additional similar opacity change around the iron bump will also affect the oscillation frequencies (not only the mode excitation) and thereby the corresponding seismic model. Such a test with artificially enhanced opacity in a vicinity of the iron bump (more exactly, slightly deeper than the iron bump!) has been performed by T. Zdravkov and myself (these Proceedings).

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Asteroseismology of pre-main sequence stars

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Abstract

More than 30 years ago the first pulsating pre-main sequence (PMS) stars have been discovered. Since then, pulsations in 18 Herbig Ae stars and 18 members of young open clusters were detected and detailed asteroseismic investigations were conducted for some of them. We describe our latest results in this field.

Using ground-based observations of NGC 6530 278, it was possible for the first time to show that the star's observed frequency spectrum can only be explained by a PMS model. Observations obtained with the MOST space telescope allowed to study the pulsations of the enigmatic Herbig Ae star HD 142666, which is also surrounded by a dense circumstellar disk. In addition, 4 new pulsating PMS stars were discovered in the young open cluster NGC 2264 based on time-series photometry with the MOST satellite.

Individual Objects: HD 142666, NGC 6530, NGC 2264

Introduction

Pre-main sequence (PMS) stars are on their way from the birthline to the zero-age main sequence (ZAMS) in the Hertzsprung-Russell (HR) diagram. They derive most of their energy, half of which heats the star and half of which radiates away, from the release of gravitational potential energy as the star collapses. As hydrogen has not ignited in their cores, their interiors are mostly chemically homogeneous and lack regions of already processed nuclear material, which is the main difference to their (post-)main sequence counterparts. One can distinguish between two groups of young stars: (i) the low-mass ($M \leq 1 M_\odot$) T Tauri stars with spectral types from late F to M which are not the main candidates to search for pulsation; (ii) the intermediate-mass ($1 M_\odot \leq M_\star \leq 10 M_\odot$) Herbig Ae/Be stars with spectral types B to early F that can become pulsationally unstable. But the evolutionary stages of these stars are ambiguous: stars with masses higher than $\sim 6 M_\odot$ do not have a visible PMS phase as their birthline intersects with the ZAMS (Palla & Stahler 1993), while stars below $\sim 6 M_\odot$ have an observable PMS phase. Furthermore, the evolutionary tracks of pre- and post-main sequence stars of same mass, effective temperature and luminosity intersect several times close to the ZAMS (Breger & Pamyatnykh 1998) prohibiting a clear determination of the evolutionary phase of a field star. The reason is that young stars and their more evolved counterparts show similar envelope properties and only differ in their interiors (Marconi & Palla 1998).

As the cores of post-main sequence stars are much denser than those of PMS objects, the small frequency spacings are different in the two evolutionary phases (Suran et al. 2001). If the observed oscillation spectrum of a star is complete enough, it should be possible to determine the age of a pulsating star from asteroseismology. To test this hypothesis pulsating PMS stars for which the evolutionary phase is known from an independent source need to be investigated.

Pulsating PMS stars

The 36 known PMS pulsators (Zwintz 2008) are either Herbig Ae field stars (with masses $\leq 4M_\odot$) or members of young open clusters. The latter have to be younger than 10 Myr to ensure that their A and F type members are in their PMS phase. These 36 stars pulsate like the classical δ Scuti stars with periods between 20 minutes and 6 hours and with amplitudes at the millimagnitude level. Their pulsation is also driven by the κ and γ mechanisms in the H and He ionization zones (Marconi & Palla 1998).

NGC 6530 278[1]

For stars in the young open cluster NGC 6530, CCD time-series photometry was obtained using the CTIO 0.9m telescope and Johnson V & B filters. 6 PMS cluster members were discovered to pulsate (Zwintz & Weiss 2006); among those is NGC 6530 278 ($V = 12.16$ mag) which has a membership probability of 68% (van Altena & Jones 1972). The identified 9 pulsation frequencies of NGC 6530 278 were subject of an asteroseismic analysis using a dense and extensive grid of model spectra to find the best match to the observed frequency spectrum. This method was originally developed by Guenther & Brown (2004) for modelling stars in advanced evolutionary stages. All frequencies - except one - could be fit as $l = 0$, 1 and 2 modes providing clear evidence of the existence of nonradial pulsations in PMS stars (Guenther et al. 2007).

The model was fit under the assumption that the star is indeed in its PMS evolutionary phase. As the observed frequency spectrum of NGC 6530 278 is complete enough, it was possible to check whether the oscillations could also be reproduced by a post-main sequence model. So, we then tried to fit post-main sequence models to the observed p-mode frequencies the same way as we did for the PMS models using the same chemical composition and mixing-length parameter (i.e., calibrated to the solar model). No post-main sequence model could be found to fit the observed frequencies (Guenther et al. 2007). Therefore, we conclude that, in this case, it is possible to distinguish between a pre- and a post-main sequence star only from the observed frequencies. Based on this, we are able to confirm that NGC 6530 278 is indeed a PMS object.

HD 142666

A single pulsation period of ∼1.12 hours was discovered in the Herbig Ae star HD 142666 ($V = 8.81$ mag) by Kurtz & Müller in 2001. The pulsational variations were known to lie on top of larger irregular variations caused by a dense circumstellar dust disk seen edge-on (Meeus et al. 1998). For a detailed asteroseismic study of the pulsations of the star, additional, longer time-series of higher quality were needed. Hence, HD 142666 was proposed as target for the MOST satellite (Walker et al. 2003) to the MOST Science Team.

MOST observations of HD 142666 were conducted for 11.5 days in 2006 and for nearly 39 days in 2007. The light curves show the typical "UX-Ori type" irregular variations caused by the circumstellar dust disk with a peak-to-peak amplitude of ∼1 magnitude (see Figure 1: upper panel: 2006 data, middle panel: 2007 data). The pulsational variations at the millimagnitude level are shown in the bottom layer in Figure 1. A detailed frequency analysis of the data sets from both years was performed (for more details see Zwintz et al. 2008). 12 frequencies could be identified to originate from pulsation and were subject to an asteroseismic analysis.

The location of HD 142666 in the HR-diagram is quite uncertain, since the star is surrounded by a dense circumstellar disk which affects the determination of effective temperature and luminosity. The values for the star's effective temperature given in the literature vary

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[1] Numbering according to Zwintz & Weiss (2006)

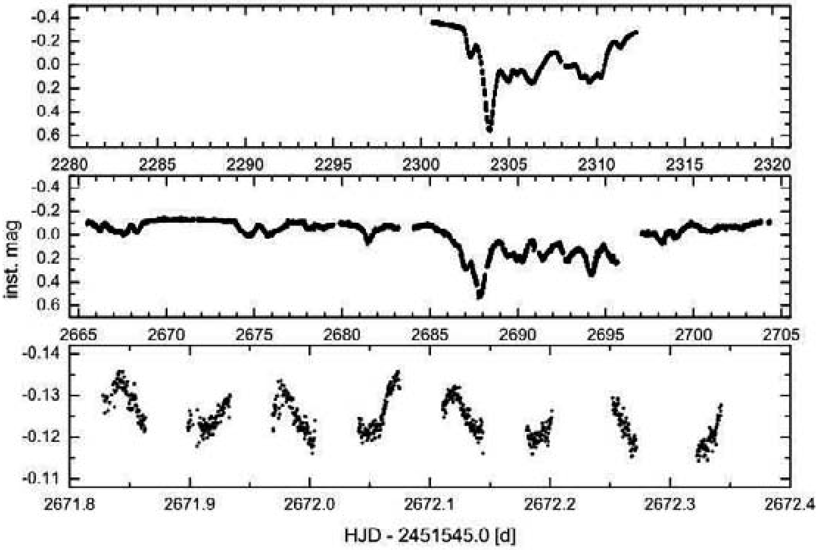

Figure 1: MOST observations of HD 142666: The typical "UX-Ori type" irregular light variations are clearly visible both in the 2006 data (top panel) and in the 2007 data (middle panel). The pulsations are seen in the lower panel which shows a zoom into the 2007 observations.

between 7200 K (Vieira et al. 2003) and 8500 K (Dominik et al. 2003). The only estimate for the luminosity is given by Monnier et al. (2005) who obtain $L = 8.8 \pm 2.5\ L_{\odot}$ derived from a relation between the circumstellar disk radius and the stellar luminosity. As the input parameters of the disk itself are uncertain, the result is quite ambiguous.

We again used the dense and extensive grid of model spectra to find the best match to the observed frequency spectrum. However, in the case of HD 142666, it was not possible to find a fit to all 12 identified pulsation frequencies simultaneously. Therefore, the analysis focused on the five most dominant modes, for which good model fits were determined (Zwintz et al. 2008).

The asteroseismologically derived values lie significantly out of the uncertainty box of the values for effective temperature and luminosity taken from the literature. Therefore, additional studies of the fundamental parameters of HD 142666 together with its pulsations have to be carried out to be able to give a definite solution.

NGC 2264

Recently, MOST observed the young open cluster NGC 2264 (age ~3 Myr) to search for PMS pulsators apart from the two already known oscillators, V 588 Mon and V 589 Mon (Breger 1972; Kallinger et al. 2008). As the diameter of the cluster was larger than the field-of-view of MOST, the observations were performed using two alternating fields. High-precision time-series photometry for in total 69 stars between 7.5^{th} and 12^{th} magnitude and with spectral types from early B to K was obtained from space.

MOST revealed 4 new pulsating PMS stars in NGC 2264, one example is shown in Figure 2. The star pulsates with frequencies at 58.1 and $61.5\,d^{-1}$ and with amplitudes of 11 and 15 mmag, respectively. A detailed asteroseismic analysis of all four newly identified stars is ongoing.

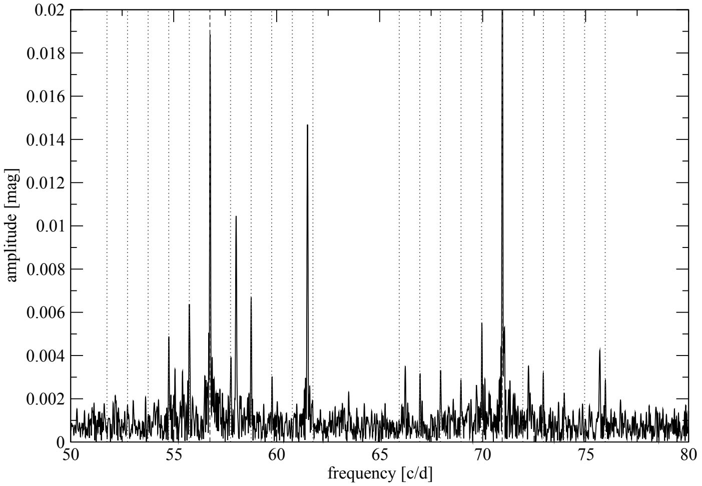

Figure 2: Amplitude spectrum of a new PMS pulsator in NGC 2264 discovered using MOST observations: the dashed lines at ~ 56.7 and 71 d^{-1} mark 4 and 5 times the orbit frequency of MOST, respectively, and the dotted lines are the corresponding 1 d^{-1} sidelobes. The two frequencies at 61.5 and 58.1 d^{-1} are due to pulsations.

Acknowledgments. KZ and TK acknowledge support from the Austrian Science Funds (FWF; KZ: project T335-N16; TK: project P17580). The Natural Sciences and Engineering Research Council of Canada supports the research of D.B.G.

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DISCUSSION

Dziembowski: Did you take into account rotational splitting?
Zwintz: No.
Weiss: There is a paper recently published by the Italian group which tries to take rotation into account and they determine very similar frequencies.

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Internal dynamics from asteroseismology for two sdB pulsators in close binary systems

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Abstract

Since their discovery eleven years ago, short-period pulsating sdB stars have proved their potential for quantitative asteroseismological studies. We have recently updated our asteroseismic diagnostic tools in order to incorporate the effects of stellar rotation on pulsations, assuming various internal rotation laws. It is possible, with these new tools, to determine the internal rotation profile of two short-period pulsating sdB stars residing in close binary systems, namely Feige 48 and PG 1336−018. They exhibit orbital periods of 9.024 h and 2.424 h respectively, as measured from spectroscopy. For the two stars, we show that spin-orbit synchronism is reached from the surface down to $\sim 0.22\ R_*$ and $0.55\ R_*$, respectively. The rotation of deeper layers cannot be inferred with the type of modes – p-modes – observed in short-period pulsating sdB stars. These results can potentially provide new elements to test tidal friction theories, particularly the angular momentum transport, in close binary systems.

Individual Objects: Feige 48, PG 1336−018 (NY Virginis).

Introduction

Subdwarf B (sdB) stars are hot ($T_{\rm eff}$ = 20,000−40,000 K) and compact ($\log g = 5.2 - 6.2$) evolved Extreme Horizontal Branch stars (EHB). They are composed of a partly convective helium-burning core, surrounded by a radiative helium mantle and a very thin radiative hydrogen-rich envelope ($M_{\rm env} < 0.02\ M_\odot$, while the total mass is around $0.5\ M_\odot$). They spend about 1.5×10^8 yr on the EHB and then evolve, after core-helium exhaustion, directly toward the white dwarf cooling sequence (Dorman et al. 1993). Subdwarf B stars host two groups of nonradial, multiperiodic pulsators. Rapid oscillations (80 − 600 s) in the so-called EC 14026 stars, discovered by Kilkenny et al. (1997), are usually identified with low-degree, low-order p-modes. The longer periods (0.75 − 3 h) of the PG 1716 stars, discovered more recently by Green et al. (2003), are due to low-degree, mid-order g-modes. The presence of excited pulsation modes in both types of pulsators is caused by a classic κ-effect associated with an opacity bump due to partial ionization of heavy metals, especially iron, locally enhanced by radiative levitation at work in the envelope of these stars (Charpinet et al. 2001, 2008).

A significant fraction of sdB stars reside in close binaries, with orbital periods from hours to days and white dwarfs or M dwarf companions (see, e.g., Maxted et al. 2001 or Green et al. 2001). The Feige 48 system is made of a short-period pulsating sdB star and an unseen companion (most likely a white dwarf), with an orbital period of 9.024 ± 0.072 h

(O'Toole et al. 2004). PG 1336−018 ($P_{\rm orb} = 2.42438$ h; Kilkenny et al. 2000) is one of the very few *HW Vir*-type sdB + dwarf M close eclipsing binaries, and the only known – to date – that exhibits short-period pulsations for its sdB component.

Tidal forces in binary systems, among other long-term effects such as circularization and alignment of the rotation axis to the normal of the orbit, tend to synchronize the rotation of the two stars with the orbital motion. Theoretical frameworks on tidal interaction have been developed in the last decades essentially by Zahn (1975, 1977, and references therein), where turbulent dissipative processes and radiative damping are invoked. Another model based on large-scale hydrodynamical currents was proposed by Tassoul & Tassoul (1992, and references therein). The question of the basic validity of these competing models is still under debate. The theoretical synchronization times can differ by orders of magnitude depending on the physical mechanism invoked, especially in the case of hot stars with radiative envelopes (such as sdB stars), where tidal forces are less efficient for synchronization. In any case, the confrontation of the theory with the observations, through the traditional photometric or spectroscopic techniques, only deals with the surface layers. The synchronization level reached in the inner parts, by transport of the angular momentum from the surface (Goldreich & Nicholson 1989), is only accessible by asteroseismology. It therefore constitutes a unique opportunity to test the theory of stellar synchronization and angular momentum transport as a function of depth.

The forward modeling approach for asteroseismology

The group of rapidly pulsating sdB stars has proved its potential for performing objective asteroseismic analyses (see Fontaine et al. 2008 for a recent review). The method implements the so-called forward modeling approach, built on the requirement of global optimization: theoretical pulsation spectra computed from sdB models must match *all* the observed periods simultaneaously. The goodness of the fit is evaluated through a merit function defined as

$$S^2 = \sum_{i=1}^{N_{\rm obs}} \left(\frac{P^i_{\rm obs} - P^i_{\rm th}}{\sigma_i}\right)^2 \tag{1}$$

where $N_{\rm obs}$ is the number of observed periodicities. The method performs a double-optimization procedure in order to find the minima of the merit function, which constitutes the potential asteroseismic solutions (see details in Charpinet et al. 2005b). The codes have been recently improved to incorporate the effect of the rotation of the star, which lifts the $(2l+1)$- fold degeneracy of eigenfrequencies of a perfectly spherically symmetric star (Van Grootel al. 2008). Assuming an internal rotation law $\Omega(r)$, the rotational multiplets are calculated, with the perturbative method to first order, by

$$\sigma_{klm} = \sigma_{kl} - m \int_0^R \Omega(r) K_{kl}(r) dr \quad ; \quad K_{kl} = \frac{\xi_r^2 - [l(l+1) - 1]\xi_h^2 - 2\xi_r\xi_h}{\int_0^R [\xi_r^2 + l(l+1)\xi_h^2]\rho r^2 dr}\rho r^2 \tag{2}$$

where K_{kl} is the rotational kernel. The optimal solution gives the structural parameters of the star ($T_{\rm eff}$, $\log g$, M_*, $\log q({\rm H})$) and, of utmost interest here, the internal dynamics $\Omega(r)$ as a function of the radius of the star.

The effects of higher orders due to rotation have been estimated from polytropic ($N = 3$) models, using a full (nonperturbative) treatment of stellar rotation developed by one of us (Reese et al. 2006). The main results show that these higher-order perturbation effects due to rotation and tidal deformation of the star cannot affect in any significant way the asteroseismic solution proposed for Feige 48 and PG 1336−018 at the present level of accuracy (further details are given in Charpinet et al. 2008).

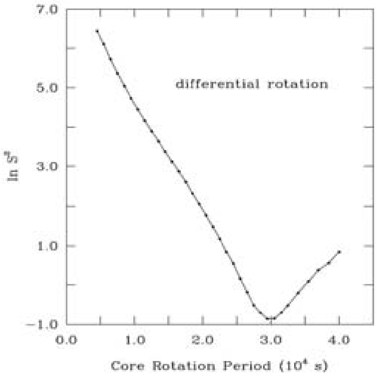

Figure 1: Merit function S^2 (in logarithmic units) as a function of the core rotation period of the sdB star in Feige 48 system. The surface rotation is fixed at the optimal value of 32,500 s (9.028 h) found for solid-body rotation. The transition between the two layers is fixed to 0.3 R_*.

Test of spin-orbit synchronism with asteroseismology

The pulsating sdB star in the Feige 48 system exhibits nine pulsation periods in the range 343 − 383 s, as observed in white light photometry at the 3.6-m CFHT during six nights in June 1998 (Charpinet et al. 2005a). Three groups of modes can naturally be constructed from this pulsation spectrum, as components of rotational multiplets approximately evenly distributed in frequency with a mean spacing of about ~ 28 μHz. These nine pulsation periods are used in the optimization procedure in order to find the minima of the merit function, assuming several internal rotation laws. First, the hypothesis of a solid-body rotation ($\Omega(r) = \Omega =$ constant) is tested, and the star rotation period $P_{\rm rot} = 2\pi/\Omega$ therefore constitutes a free parameter in the optimization procedure. This leads to the determination of the structural parameters of the star and to a rotation period $P_{\rm rot} = 9.028 \pm 0.48$ h (details can be found in Van Grootel al. 2008), in excellent agreement with the orbital period of the system $P_{\rm orb} = 9.024 \pm 0.072$ h measured from RV variations. This result strongly suggests that the sdB star is tidally locked in the Feige 48 system.

To investigate this question further, the hypothesis of differential rotation is tested by dividing the star in two regions that each rotate independently as solid structures. In a first step, the transition between the two layers is fixed to 0.3 R_*, following the suggestion of Kawaler & Hostler (2005). The surface rotation is fixed to its optimal value of 32,500 s (9.028 h), when the core rotation is varied from a period of 4,500 s to 40,000 s. The optimization procedure on structural parameters is carried out for each configuration of differential rotation. The best merit function S^2 for each configuration is plotted in Fig. 1.

A very fast core rotation can be rejected from Fig. 1, as it leads to much poorer merit functions; while S^2 again increases for longer core rotation periods. Taking the uncertainties into account, this result indicates that the sdB rotates as a solid-body in the Feige 48 system.

In a second step, the transition between the two layers can vary from 0.1 to 1.0 R_*, while the structural parameters are fixed to their optimal values. The surface rotation is fixed to the value of 32,500 s, and the core rotation period $P_{\rm core}$ can vary, as shown in Fig. 2 (left), from 5,000 to 45,000 s. All the merit functions are shown in Fig. 2, with a color scale in logarithmic units. The optimal core rotation period $P_{\rm core}$ (continuous white line) is not

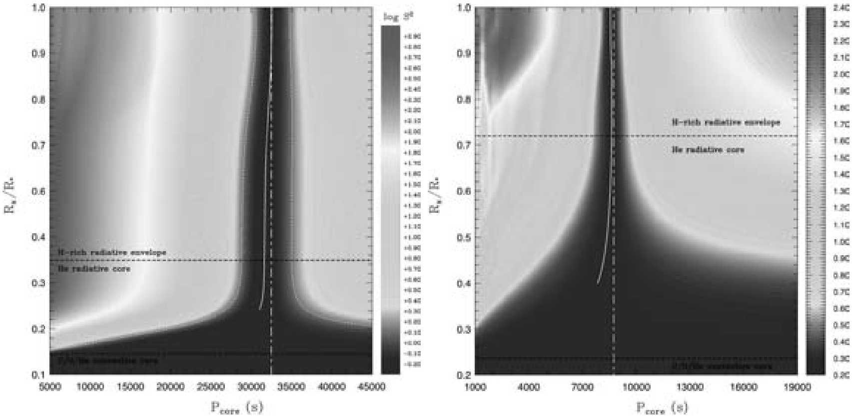

Figure 2: Seismic internal rotation profile of the sdB star in Feige 48 (left; $P_{\rm orb} = 9.024$ h) and PG 1336−018 (right; $P_{\rm orb} = 2.424$ h). This S^2 map (on a logarithmic scale) shows the quality of fit to the observed pulsation periods as a function of the parameters $P_{\rm core}$ and R_S/R_*. The continuous white line indicates the minima of the merit function. The white dot-dashed vertical lines indicates the orbital period. White dotted-line contours indicates the 1-σ, 2-σ et 3-σ confidence level relative to the best-fit solution. The transitions between the H-rich envelope and the radiative He core; and between the radiative He core and the convective C-O-He core are also indicated.

significantly different from the surface rotation period (equals to the orbital period, vertical dot-dashed line) in the most part of the star: the sdB component in the Feige 48 system is tidally locked, from the surface down to $\sim 0.22\ R_*$ at least. The blue valley enlarges significantly under this limit, which translates the insensitivity of the *p*-modes to these deep regions.

The same exercise is carried out with the 25 pulsation periods in the frequency spectrum of the sdB star in the PG 1336−018 system (Kilkenny et al. 2003). Details on the asteroseismic analysis is reported in Charpinet et al. (2008), and the internal rotation profile is shown in Fig. 2 (right). The sdB star is also tidally locked, down to $\sim 0.55\ R_*$ at least. Again, the dynamics of deeper regions (under the H-rich envelope much thinner in this case compared to the envelope of Feige 48), cannot be probed by the p-modes in action here.

Conclusion

We have demonstrated, for the first time by asteroseismic means, that spin-orbit synchronism is reached in the most part of two short-period pulsating sdB stars residing in close binary systems, namely Feige 48 and PG 1336−018. Both stars rotate as solid bodies with periods equal to their orbital periods from the surface down to at least $\sim$ 0.22 and 0.55 of their radius, respectively. The rotation of deeper layers cannot be inferred with the type of modes observed in short-period pulsating sdB stars. This observed synchronization as a function of depth, achieved within $\sim 1.5\times10^8$ yr (the lifetime of a sdB star on the EHB), could provide constraints for tidal evolution theories, concerning particularly the angular momentum transport from the surface to the center. In a next step, the dynamics of deeper regions in sdB stars residing in binaries could be probed, in principle, by the g-modes observed in long-period pulsating sdB stars.

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DISCUSSION

Shibahashi: I am wondering how one can distinguish clearly intrinsic pulsation signal of a star from influence coming from its companion, such as the reflection effect? Is there any possibility of such contamination?

Van Grootel: A reflection effect can only possibly be detected with a main sequence companion, and it is indeed observed in the light curve of PG 1336−018 (see Kilkenny et al. 2003). One can also possibly observe an ellipsoidal deformation of the sdB star in the case of very close systems with massive companions. Such contamination effects have very different timescales than the pulsations in short-period sdB stars (80 − 600 s), and therefore it is easy to separate them. In the case of PG 1336−018, the reflection effect has been removed from the light curve before the Fourier analysis to extract pulsation frequencies (Kilkenny et al. 2003).