ASTEROSEISMOLOGY OF BINARY STARS AND A
COMPILATION OF CORE OVERSHOOT AND ROTATIONAL
FREQUENCY VALUES OF OB STARS

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Abstract. After a brief introduction into the asteroseismic modelling
of stars, we provide a compilation of the current seismic estimates of
the core overshooting parameter and of the rotational frequency of sin-
gle and binary massive stars. These important stellar parameters have
meanwhile become available for eleven OB-type stars, among which
three spectroscopic pulsating binaries and one magnetic pulsator. We
highlight the potential of ongoing and future analyses of eclipsing bi-
nary pulsators as essential laboratories to test stellar structure and evo-
lution models of single and binary stars.

1 The Asteroseismic Modelling of Stars

Asteroseismology is undergoing a revolution since the operation of space missions
dedicated (partly) to this subject, such as MOST, CoRoT, and Kepler launched
in 2003, 2006, and 2009, respectively. The past decade has seen the assembly of
uninterrupted white-light space photometry with μmag-precision for thousands of
stars that turn out to be pulsating. A thorough introduction into the field of aster-
oseismology was recently presented in the monograph by Aerts et al. (2010) and is
thus omitted here. The basic principle of asteroseismic modelling is summarized
in one snapshot in the context diagram shown in Fig.1

Following a too simplistic point of view, one could say that current research in
asteroseismology is done with two major aims:

1. To deliver high-precision stellar parameters resulting from the scheme in
Fig.1 for exoplanet host stars and for thousands of stars covering large ranges
of mass, age, metallicity, and populations in the Milky Way, as input for
further stellar and galactic studies. Hereby, it is assumed that the input
physics of the stellar structure models is sufficiently appropriate, just as
2. To improve the theory of stellar structure and evolution, both for single and binary stars, by focusing on the shortcomings of the input physics reflected by too high $\chi^2$-values with respect to the measurement errors.

Even the most basic seismic analysis, based on the frequency of maximum power as well as on the large frequency separation for solar-like pulsators (e.g., Chaplin et al. 2011), or on the average period spacing and the periodic deviations thereof for high-order gravity-mode pulsators (e.g., Degroote et al. 2010), leads to values of the global stellar parameters, such as the mass, radius, and age, with a relative precision of only a few percent, i.e., far better than what can be deduced from photometric colour indices, spectral analysis, interferometric data or present-day astrometry. As a keynote recent illustration of this, the combination of frequency and period spacings of the dipole mixed modes detected in evolved low-mass stars allowed to distinguish between red giants with only hydrogen-shell burning while climbing up the red giant branch or with core helium burning in addition after the helium flash (Bedding et al. 2011), a probing that cannot be done from classical data.

So far, the main focus of asteroseismology has been put on item 1. above, i.e., on the derivation of basic stellar parameters, assuming that the input physics of the theoretical stellar models, as indicated in the left part of Fig. 1 is correct. This was of course the first thing to do after high-precision data came in. The
Table 1. Summary of observed ($v_{\sin i}$, $T_{\text{eff}}$, log $g$, $f_{\text{rot}}$) and seismically modelled ($M$, $X_c$, $\alpha_{ov}$) stellar parameters of 11 OB-type pulsators. The star indicated in bold has a magnetic field while the three spectroscopic binaries are indicated in italic. The data sources of the observed table entries are listed in Aerts et al. (2014) and are omitted here for brevity, the references for the seismic modelling results are listed in the last column as a number according to the footnote.

| HD number | $v_{\sin i}$ (km s$^{-1}$) | $f_{\text{rot}}$ (d$^{-1}$) | $T_{\text{eff}}$ (K) | log $g$ (dex) | $\alpha_{ov}$ (H$_p$) | Mass ($M_\odot$) | $X_c$ (%) | Ref. |
|-----------|------------------|------------------|-------------------|----------------|-------------------|----------------|---------|-----|
| 16582     | 1                | 0.075            | 4.327             | 3.80           | 0.20 ± 0.05      | 10.2           | 0.25    | (1) |
| 29248     | 6                | 0.017            | 4.342             | 3.85           | <0.12            | 9.5            | 0.26    | (2) |
| 44743     | 23               | 0.054            | 4.380             | 3.50           | 0.20 ± 0.05      | 13.6           | 0.12    | (3) |
| 46202     | 25               | —                | 4.525             | 4.10           | 0.10 ± 0.05      | 24.0           | 0.58    | (4) |
| 129929    | 2                | 0.012            | 4.389             | 3.95           | 0.10 ± 0.05      | 9.4            | 0.35    | (5) |
| **163472**| 63               | 0.275            | 4.352             | 3.95           | <0.15            | 8.9            | 0.29    | (6) |
| 180642    | 25               | 0.075            | 4.389             | 3.45           | <0.05            | 11.6           | 0.23    | (7) |
| 214993    | 36               | 0.120            | 4.389             | 3.65           | <0.40            | 12.2           | 0.28(8) |     |

50230      | 7                | 0.044            | 4.255             | 3.80           | 0.25 ± 0.05      | 7.5            | 0.28    | (9) |
| 74560     | 13               | 0.010            | 4.210             | 4.15           | <0.10            | —              | —       | (10) |
| 157056    | 31               | 0.107            | 4.398             | 4.10           | 0.44 ± 0.07      | 8.2            | 0.38    | (11) |

(1) Aerts et al. (2006); (2) Pamyatnykh et al. (2004); (3) Mazumdar et al. (2006); (4) Briquet et al. (2011); (5) Dupret et al. (2004); (6) Briquet et al. (2012); (7) Aerts et al. (2011); (8) Desmet et al. (2009); (9) Degroote et al. (2010); (10) Walczak et al. (2013); (11) Briquet et al. (2007).

The largest benefit of asteroseismic modelling is, however, yet to come. It requires the detailed modelling of all the individual detected and identified oscillation modes in carefully selected stars of various kinds, in terms of the assumed input physics, with the aim to improve the latter (item 2. above). Intensive future efforts on the left part of Fig. 1 are necessary to achieve this, based on joint collaborations between asteroseismologists and experts in the theory of stellar structure. Progress will be made in the next few years by studying the impact of changes in various aspects of the input physics on the oscillation properties, just as it was done in helioseismology to get a better model of the Sun (e.g., Christensen-Dalsgaard 2002 for a thorough review). For the moment, we are not yet at that stage for stars, given the focus on the observational aspects of asteroseismology during the past few years.

2 Compilation of Seismic Analysis Results of OB-type Stars

In an attempt to offer new tools to evaluate theoretical stellar models of massive stars in terms of interior mixing processes, Aerts et al. (2014) made a compilation of 68 OB-type nearby stars undergoing the CNO cycle in their convective core and studied their observational properties, including oscillations, rotation, magnetic
Setting a New Standard in the Analysis of Binary Stars

Fig. 2. The core overshoot parameter of OB pulsators as a function of the observed values for the rotational frequency and effective temperature. Open symbols are single pulsators and filled symbols represent spectroscopic binaries with a pulsating component. The cross indicates a magnetic pulsator.

field, and nitrogen abundance, from careful multivariate statistical analysis. This led to the conclusion that the effective temperature and the frequency of the dominant acoustic mode are significant predictors for the nitrogen abundance, while the rotation diagnostics are not. This result implies that the oscillation properties should not be ignored in the evaluation of stellar evolution models.

To trigger further asteroseismic studies of massive stars, including eclipsing binaries, we assembled the eleven stars in the sample by Aerts et al. (2014) for which seismic modelling according to the scheme in Fig. 1 has been successful and led to a derivation of either a value or an upper limit for the core overshoot parameter $\alpha_{ov}$, based on the Schwarzschild criterion of convection and assuming a fully mixed overshoot region. The spectroscopic and seismic properties of those stars, which are all slow rotators, are listed in Table 1.

Their seismically derived core overshoot parameters are plotted as a function of two observables, $\log T_{\text{eff}}$ and $f_{\text{rot}}$, in Fig. 2 where the three spectroscopic binaries are indicated with full symbols and the one magnetic pulsator has an additional cross indication. By itself, the rotational frequency, which was deduced from Fourier analysis of the seismic data without any model assumption, is not an obvious predictor for the amount of core overshooting. A similar conclusion holds for the mass and the central hydrogen fraction (which is a proxy for the evolutionary
state of the star), as can be seen from Fig. 3, although the sample is still limited, particularly at high masses. Earlier studies suggested that the core overshoot parameter increases with increasing stellar mass for stars with $M \in [1.1, 1.7] \, M_\odot$ (Clausen et al. 2010; Torres, these proceedings). Asteroseismology shows that this conclusion is too simplistic for stars with masses above 10 $M_\odot$, in line with the results of Claret (2007) based on massive eclipsing binaries. Staritsin (2013) considered nine of the stars in Table 1 to make three-dimensional hydrodynamical simulations of the extra mixing at the boundary of the convective core, based on the physical model of turbulent entrainment proposed by Meakin & Arnett (2007). He found that the overshoot parameter deduced from the simulations decreases as the star moves along its evolutionary track (cf. his Fig. 3). Our findings represented in Fig. 3 are not in contradiction with this conclusion, as can be deduced from e.g., the three stars with seismic mass between 8.9 and 9.5 $M_\odot$, but the sample is not yet suitable to test this result in detail. Such a test would require several seismic estimates of $\alpha_{ov}$ for a particular value of the stellar mass, as a function of $X_c$.

Unfortunately, we have only two seismic values of $\alpha_{ov}$ for pulsating B stars in close binaries (Table 1), but several new case studies are on the way, such as two SB2 pulsators discovered from Kepler data (Pápics et al. 2013). Although the current sample is too small to be statistically meaningful, this is one of the...
important and promising ways towards improving the implementation of the input physics of massive stars.

3 Eclipsing Binaries: Complications and Opportunities

Given that both the modelling of eclipsing binaries and the seismic modelling of stars are two independent methods to deduce interior physics constraints, among which the overshoot parameter and the age, it is obvious to try and combine them. This idea is not new but good data to bring it into practice with predictive power for the improvement of stellar physics had to await uninterrupted high-precision photometry from space. These data have shown that asteroseismology of pulsating eclipsing binaries turns out to be far from trivial, in part because the binary modelling tools were not up to the precision of the Kepler data (e.g., Degroote, these proceedings). Effects like Doppler beaming and gravitational lensing occur at measurable amplitudes reaching several 100µmag and thus have to be taken into account in the binary modelling to achieve valid interpretations (e.g., van Kerkwijk et al. 2010; Bloemen et al. 2011, 2012). Conversely, the high quality of the photometric data allows to discover and interpret binarity from careful pulsational analyses thanks to the detection of the Romer delay, even without having spectroscopic data at hand (Shibahashi & Kurtz 2012, Telting et al. 2012).

Both the CoRoT and Kepler missions led to the discovery of numerous eclipsing binary pulsators, with a variety of flavours in terms of masses and evolutionary stages of the components (Prša, these proceedings). An extensive overview of pulsating binaries with high-precision photometry by Kepler will become available in Huber (2014) while several case studies are discussed elsewhere in the current proceedings. Here, we limit ourselves to highlight a few remarkable case studies of pulsating eclipsing binaries, without any effort of being exhaustive and referring to the original papers for details.

The unravelling of pulsational and binary variability, which is a prerequisite for seismic modelling, necessitates rather complex iterative data-analysis schemes when the intrinsic and extrinsic variations have about equal amplitude, such as in the case of the double-lined eclipsing binary KIC11285625 analysed by Debosscher et al. (2013). Even if the data analysis can be successfully accomplished, challenges are faced with the physical interpretation, particularly in the cases where tidally excited g-mode oscillations occur amidst (unidentified) free oscillations of (one of) the components in eccentric systems or when reflection effects are so strong that asymmetrically heated atmosphere models must be used before seismic interpretations can be attempted. Examples of eclipsing binaries with a main-sequence pulsator are, e.g., HD 174884 (Maceroni et al. 2009), CoRoT 102918586 (Maceroni et al. 2013), KIC 10661783 (Southworth et al. 2012, Lehmann et al. 2013), and KIC 4544587 (Hambleton et al. 2013). The compact subdwarf pulsator 2M1938+4603 requires a new generation of atmosphere models before a solid interpretation can be made (Østensen et al. 2010). These case studies represent a variety of situations where the pulsational information was too limited, or was compatible with current-day evolutionary models of single stars, or requires new
theoretical developments in atmosphere and interior physics. The latter was the case for the extremely eccentric F-type binary KOI-42 (Welsh et al. 2011), where strong forces due to dynamical tides trigger nonlinear resonant locking of pulsation modes (Fuller et al. 2012).

Easier cases to analyse and interpret were also found, e.g., KIC 8410637 which is a 408-day period eclipsing binary containing a red giant with solar-like oscillations discovered shortly after the launch of Kepler (Hekker et al. 2010). This object is ideally suited as a test laboratory to evaluate the scaling relations of solar-like oscillations (e.g., Huber et al. 2011) as well as to assess isochrone fitting in eclipsing binaries and in open clusters (Frandsen et al. 2013). Many other much more complicated red giant binaries with shorter eccentric orbits have recently been found and are being analysed on the basis of Kepler photometry combined with long-term follow-up spectroscopy (Gaulme et al. 2013, Beck et al. 2014).

4 Future Studies of Massive Binary Pulsators

While various studies of pulsating eclipsing binaries based on Kepler and spectroscopic data are ongoing (e.g., Schmid et al., these proceedings), we are not aware of any such new case studies with OB-type primaries. Unfortunately, pulsating OB-type stars in eclipsing binaries are scarce and the few known ones have insufficient seismic data to tune stellar physics. This is why a Kepler guest observer proposal focused on the massive binary V380 Cyg, the brightest star observed by the Kepler satellite by means of a dedicated mask. Tkachenko et al. (2012) discovered low-amplitude photometric and spectroscopic variability in a preliminary analysis of Kepler photometry and high-resolution spectroscopy. Further data gathering and analysis delivered radii and masses of a relative precision near 1%, but pointed out that the line-profile variations are connected with spots of Si while the photometric variability is of stochastic nature with unknown cause (Tkachenko et al. 2014). Even without a good explanation of the intrinsic variability of the primary, it was re-emphasized that single-star models cannot explain the components of the V380 Cyg system, not even if we include a high value for the core overshooting.

Interesting ongoing case studies of double-lined spectroscopic binaries with at least one pulsating OB component concern Spica (see also Königsberger, these proceedings) and σ Scorpii, the latter binary’s primary being a large-amplitude radial-mode pulsator for which we recently discovered additional low-amplitude modes in an extensive data set of high-resolution spectroscopy (Tkachenko et al., in preparation). So given that the majority of massive stars are in binaries (de Koter, Sana, these proceedings), we are in need of new dedicated observing campaigns to improve their modelling via asteroseismology.

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