Precision Asteroseismology
Proceedings IAU Symposium No. 301, 2013
J. A. Guzik, W. J. Chaplin, G. Handler & A. Pigulski, eds.

doi:10.1017/S174392131301449X

Reaching the 1% accuracy level on stellar mass and radius determinations from asteroseismology

V. Van Grootel[1]†, S. Charpinet[2,3], G. Fontaine[4], P. Brassard[4], and E. M. Green[5]

[1]Institut d'Astrophysique et de Géophysique de l'Université de Liège, Allée du 6 Août 17, B-4000 Liège, Belgium
email: valerie.vangrootel@ulg.ac.be

[2]Université de Toulouse, UPS-OMP, IRAP, Toulouse, France

[3]CNRS, IRAP, 14 avenue Edouard Belin, 31400 Toulouse, France

[4]Université de Montréal, Pavillon Roger-Gaudry, Département de Physique, CP 6128, Succ. Centre-Ville, Montréal QC, H3C 3J7, Canada

[5]Steward Observatory, University of Arizona, 933 North Cherry Avenue, Tucson, AZ, 85721, USA

Abstract. Asteroseismic modeling of subdwarf B (sdB) stars provides measurements of their fundamental parameters with a very good precision; in particular, the masses and radii determined from asteroseismology are found to typically reach a precision of 1% containing various uncertainties associated with their inner structure and the underlying microphysics (composition and transition zones profiles, nuclear reaction rates, etc.). Therefore, the question of the accuracy of the stellar parameters derived by asteroseismology is legitimate. We present here the seismic modeling of the pulsating sdB star in the eclipsing binary PG 1336−018, for which the mass and the radius are independently and precisely known from the modeling of the reflection/irradiation effect and the eclipses observed in the light curve. This allows us to quantitatively evaluate the reliability of the seismic method and test the impact of uncertainties in our stellar models on the derived parameters. We conclude that the sdB star parameters inferred from asteroseismology are precise, accurate, and robust against model uncertainties.

Keywords. stars: binaries: eclipsing, stars: subdwarfs, stars: oscillations (including pulsations), stars: individual: PG 1336−018 (NY Virginis).

1. Introduction to subdwarf B stars

Subdwarf B (sdB) stars are hot and compact objects with effective temperatures $T_{\rm eff}$ between 20 000 − 40 000 K and surface gravities log g in the range 5.0 to 6.2. They occupy the so-called extreme horizontal branch (EHB), burning helium in the core and having a very thin residual H-rich envelope. This extreme thinness of the hydrogen envelope is the original feature of sdB stars, and is the main difficulty when explaining the formation of such objects. They are thought to be post-RGB (Red Giant Branch) stars that went though the He-flash and that have lost most of their envelope through binary interaction. While about half of sdB stars reside in binaries with a stellar companion, the recent discoveries of planets around single sdB stars (e.g. Charpinet *et al.* 2011) also support the idea that planets could influence the evolution of their host star, by triggering the mass loss necessary for the formation of an sdB star.

† Chargé de recherches, Fonds de la Recherche Scientifique, FNRS, rue d'Egmont 5, B-1000 Bruxelles, Belgium.

The sdB stars exhibit pulsation instabilities driving both acoustic modes of a few minutes and gravity modes with 1 − 4 h periods. To date, 15 sdB stars have been modeled by asteroseismology (Fontaine *et al.* 2012), allowing for seismic determinations of their global and structural parameters (total mass M_*, surface gravity log g, radius R_*, thickness of the H-rich envelope, mass and composition of the He-burning core, etc.). The mass distribution of sdB stars, although still based on small number statistics, is consistent with the idea that sdB stars are post-RGB stars (Van Grootel *et al.* 2013a). The masses, surface gravities and radii of sdB stars are typically determined from asteroseismology with a very good precision of ∼1%, 0.1%, and 0.6%, respectively. We demonstrate here that these numbers are reliable, and the sdB parameters inferred from asteroseismology are precise, accurate, and robust against model uncertainties. We used for this purpose PG 1336−018, one of the only two known eclipsing binaries where the sdB component is a pulsating sdB star. This allows us to compare results obtained from the two independent techniques of asteroseismology and orbital light curve and eclipse modeling.

2. PG 1336−018, the Rosetta stone of sdB asteroseismology

PG 1336−018 (NY Virginis) is an eclipsing binary made of an sdB pulsator and an M dwarf. Orbital solutions, including the mass and radius of the sdB component, are provided by Vučković *et al.* (2007) from eclipses and light curve modeling. From the pulsational point of view, the sdB component of PG 1336−018 exhibits 28 p-mode periodicities in the 96 to 205 s range (Kilkenny *et al.* 2003). The atmospheric parameters of the sdB component of PG 1336−018 are (Van Grootel *et al.* 2013b): $T_{\rm eff} = 32807 \pm 82$ K, log $g = 5.771 \pm 0.015$, and log N(He)/N(H) $= -2.918 \pm 0.089$.

3. Method for asteroseismology of hot subdwarfs

The forward modeling approach developed to perform objective asteroseismic modeling of subdwarf pulsators has been described in detail by Charpinet *et al.* (2008). We fit directly and simultaneously all observed independent pulsation periods with theoretical ones calculated from sdB models, in order to minimize a merit function defined by

$$S^2 = \sum_{i=1}^{N_{\rm obs}} \left(\frac{P_{\rm obs}^i - P_{\rm th}^i}{\sigma_i}\right)^2, \tag{3.1}$$

where $N_{\rm obs}$ is the number of observed independent periodicities and σ_i a weight, here equal to σ_d, the density of theoretical modes in the considered range. The method performs a double-optimization procedure in order to find the minima of the merit function, under the external constraints from spectroscopy and from mode identification (if available). The optimal model(s) define the asteroseismic solution(s). Error estimates are provided using probability distributions defined for each input parameter of a stellar model, from a likelihood function defined by

$$\mathcal{L}(a_1, a_2, a_3, a_4) \propto e^{-\frac{1}{2}S^2}. \tag{3.2}$$

From there, the probability density function for parameter a_1 (for example the mass) is

$$\mathcal{P}(a_1){\rm d}a_1 \propto {\rm d}a_1 \iiint \mathcal{L}(a_1, a_2, a_3, a_4){\rm d}a_2{\rm d}a_3{\rm d}a_4. \tag{3.3}$$

This density of probability function is normalized assuming that the probability of the value of a_1 to be in the specified range is equal to 1. Finally, the errors associated to each parameter are defined by the 1σ range of the corresponding probability distribution.

4. Seismic modeling of PG 1336−018

The optimization procedure is launched in a vast parameter space where sdB stars are found (see Van Grootel *et al.* 2013b for details). The parameters of the optimal model are presented in Table 1. The quoted errors are the 1σ range of the corresponding probability density function, shown on Fig. 1 for the case of the stellar mass. Similar probability functions are obtained for the other model parameters. The stellar parameters inferred from asteroseismology are found to be remarkably consistent, within the 1σ errors of each method, with both the preferred orbital solution obtained from the binary light curve modeling (model II, see Vučković *et al.* 2007) and the spectroscopic estimate for the surface gravity of the star. We can therefore affirm that the stellar parameters determined from asteroseismology are accurate. We can also note that the optimal model is not an outlier of the probability distribution, but is well within the 1σ range of each distribution (see Fig. 1 for the mass). In summary, stellar models for asteroseismology of sdB stars allow for both precise and accurate determinations of the stellar parameters, in particular mass and radius. But we can wonder how the model uncertainties impact on this result. There are indeed three main sources of uncertainties in sdB models:

- The nonuniform envelope iron profile. In our sdB models, the equilibrium is assumed between radiative levitation of iron (in the H-rich envelope) and gravitational settling, ignoring competing processes such as stellar winds, thermohaline convection, etc.;
- The core/envelope transition profile, not smoothed by diffusion in our models;
- The He-burning nuclear reaction rates, from uncertainties in nuclear physics.

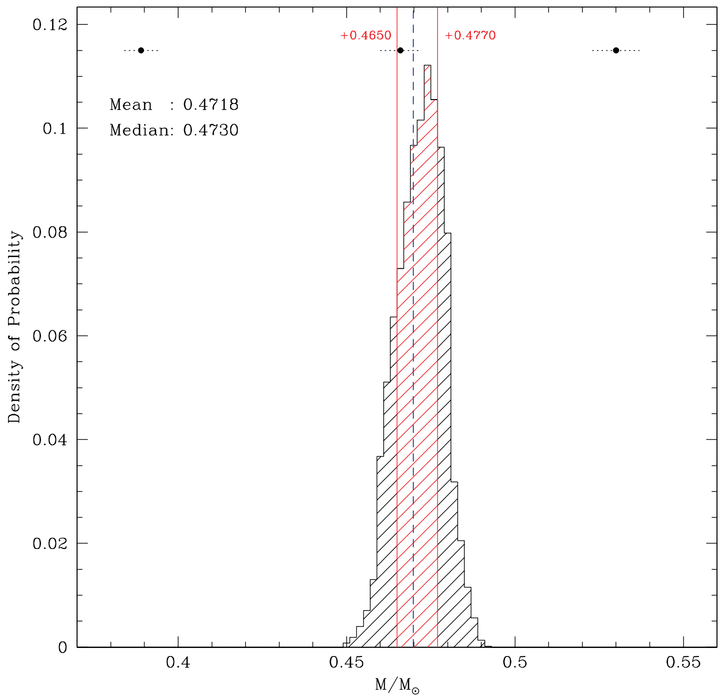

Figure 1. Probability density function for the stellar mass from asteroseismology. The filled circles with the dotted lines are the three orbital solutions for the mass of the sdB component proposed by Vučković *et al.* (2007) with their 1σ uncertainties. The red hatched part between the two vertical solid red lines defines the 1σ range, containing 68.3% of the mass distribution. The blue vertical dashed line indicates the mass of the optimal model solution of lowest S^2-value.

https://doi.org/10.1017/S174392131301449X Published online by Cambridge University Press

Table 1. Structural parameters of PG 1336−018 derived from asteroseismology, spectroscopy, and orbital light curve analysis.

Quantity	Asteroseismology	Spectroscopy	Orbital light curve modeling		
	This study		Vučković *et al.* (2007)		
			Model I	Model II	Model III
$M_*/M_\odot$	0.471 ± 0.006 (1.3%)	...	0.389 ± 0.005	0.466 ± 0.006	0.530 ± 0.007
$R_*/R_\odot$	0.1474 ± 0.0009 (0.6%)	...	0.14 ± 0.01	0.15 ± 0.01	0.15 ± 0.01
$\log g$	5.775 ± 0.007 (0.1%)	5.771 ± 0.015	5.74 ± 0.05	5.77 ± 0.06	5.79 ± 0.07
$T_{\rm eff}$ (K)	32850 ± 175 (0.5%)	$32\,807 \pm 82$	...	...	...
$\log(M_{\rm env}/M_*)$	-3.83 ± 0.06 (1.6%)	...	...	...	...
$\log(1 - M_{\rm core}/M_*)$	unconstrained	...	...	...	...
$X_{\rm core}$(C+O)	0.58 ± 0.06 (10%)	...	...	...	...
$\log(L/L_\odot)$	22.9 ± 0.6 (2.6%)	23.3 ± 1.5	...	...	...

In order to quantitatively appreciate the impact of these uncertainties on the stellar parameters, we built new stellar models with modified physics and carried out again seismic analyses of PG 1336−018 following the same procedure as before. First, we built stellar models with our standard equilibrium envelope iron profile divided by two and by four, and we also built models with a uniform solar abundance. We therefore re-did three seismic analyses of PG 1336–018 with the modified models. As a result, despite significant changes in the iron abundance profiles, the derived parameters are mostly unaffected (e.g. the mass) or only subject to very small systematic drifts compared to the standard seismic solution. Secondly, for the core/envelope transition profile, we built modified models with smoothed transition profiles, and carried out again a seismic analysis. No significant drift on stellar mass, radius and log g was observed. Finally, we multiplied by two the ^{12}C(α,γ)^{16}O rate and increased by 10% the triple-α rate. The seismic analysis with these modified models led to almost unchanged stellar parameters. Details on these experiments and on sdB models can be found in Van Grootel *et al.* (2013b).

5. Conclusion

We presented here the seismic modeling of the p-mode sdB pulsator in the eclipsing system PG 1336−018. This very rare configuration allowed us to test some of the stellar parameters inferred from asteroseismology with the values obtained independently from the orbital light curve analysis of Vučković *et al.* (2007). We also tested the impact of the uncertainties of the input physics in the stellar models. We conclude that seismic parameters determined from asteroseismology for sdB stars are both precise, accurate, and robust against model uncertainties. We can indeed achieve ∼1% accuracy for mass and radius determinations from asteroseismology. We also demonstrated that the best-fit (optimal) model is not an outlier of the statistical distribution of potential solutions, and can therefore safely be considered as the most representative model of the star.

References

Charpinet, S., Van Grootel, V., Reese, D., *et al.* 2008, *A&A*, 489, 377
Charpinet, S., Fontaine, G., Brassard, P. *et al.* 2011, *Nature*, 480, 496
Fontaine, G., Brassard, P., Charpinet, S., *et al.* 2012, *A&A*, 539, 12
Kilkenny, D., Reed, M. D., O'Donoghue, D., *et al.* 2003, *MNRAS*, 345, 834
Van Grootel, V., Fontaine, G., Charpinet, S., *et al.* 2013a, *EPJ Web of Conferences*, 43, 04007
Van Grootel, V., Charpinet, S., Fontaine, G., *et al.* 2013b, *A&A*, 553, 97
Vučković, M., Aerts, C., Østensen, R., *et al.* 2007, *A&A*, 471, 605