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Ultra-high precision white dwarf asteroseismology

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Abstract. We present a brief progress report in our quest for deriving seismic models of pulsating white dwarfs that can account simultaneously for all the observed periods at the precision of the observations. We point out that this is possible from a pratical point of view only if parametrized models are used to complement evolutionary models. We adopt a double optimization procedure that insures that the best possible model in parameter space is found objectively and automatically. Our ultimate goal is to be able to account for the exquisite period data gathered with *Kepler* and *Kepler-2* on key pulsating white dwarfs of both the DA (ZZ Ceti) and DB (V777 Her) type.

Keywords. stars — oscillations, white dwarfs

1. Astrophysical Context

The quest for credible and realistic seismic models for pulsating white dwarfs has been on for more than two decades now. Despite some remarkable early successes (e.g., Winget *et al.* 1991), progress has been slow, and conflicting results have sometimes been obtained (see, e.g., Section 8.2 of Fontaine & Brassard 2008 for a historical survey of the field through 2008). In particular, reliable and convincing seismic models of the pulsating white dwarfs have remained far and few despite the efforts of several groups. The observed periods still cannot be reproduced at a satisfactory level of accuracy, and, consequently, the inferences on the internal structure of these pulsators have remained weak, at best.

We have recently decided to revisit the problem of the seismic modeling of white dwarf stars using current and proven techniques, typical of those used highly successfully for the class of pulsating hot subdwarf B stars as reviewed and used recently in Charpinet *et al.* (2013) and Van Grootel *et al.* (2013). Our approach rests on a new detailed parametrization of white dwarf models coupled to a double optimization procedure that insures an objective search in parameter space for the best fitting model.

2. The Need for Parametrized Models

When some of us started investigating the application of the forward asteroseismological method to pulsating hot subdwarf and white dwarf stars more than a decade ago (see, e.g., Brassard *et al.* 2001 or Fontaine & Brassard 2002), we realized at the outset that the only practical way to do that would be through the use of parametrized models. It has been our assertion since that parametrized models, as compared to full evolutionary models, provide the best, if not the only way, to thoroughly search in parameter space for an optimal seismic model. In principle, state-of-the-art evolutionary models provide the best physical descriptions of stars. However, they suffer from two important drawbacks in the context of searching for the best seismic model.

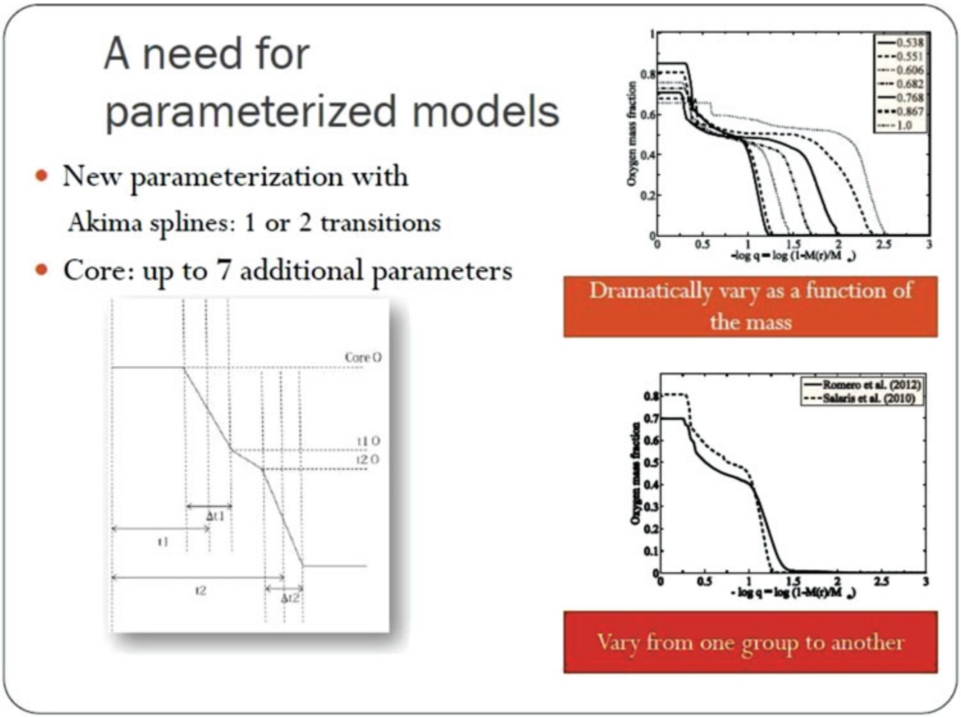

Figure 1. Our proposed scheme for parametrizing the composition profile in the C/O core of static white dwarf models and comparison with some results coming from evolutionary calculations. We note the significant differences between the results of two different studies, which should be seen as a warning against fixing the core chemical profile in a seismic search. The so-called "fully evolutionary models" of white dwarfs carry with them numerical defects that add up and may prevent, through noise, the success of an asteroseismic exercise.

The first of these shortcomings is their lack of flexibility. It is indeed nearly impossible, even with large computer clusters, to cover finely all of the relevant domains of parameter space with evolutionary sequences; it would take too much computing time. The practical consequence is that evolutionary sequences, necessarily limited in number, may actually miss the "correct" region of parameter space where resides the best seismic model.

The second drawback is that, by construction, it is implicitly assumed that the constitutive physics used in the construction of state-of-the-art evolutionary models is "perfect". Of course, this cannot be the case, especially in domains of the phase diagram corresponding to extreme physical conditions, such as those, for example, encountered in white dwarf stars. It may very well be the case in these circumstances that the input constitutive physics is not realistic enough and, consequently, that the observed pulsation periods cannot be accounted for at an acceptable level of accuracy on the basis of such evolutionary models.

In contrast, parametrized models offer maximum flexibility and speed for searching in parameter space. They can also compensate partly for uncertain input physics, and are most useful at that level for identifying the part of the input physics that needs improvement. They thus are most useful for providing feedback on the constitutive physics itself. Ultimately, they must of course be validated by improved evolutionary models.

Figure 1 illustrates the scheme that we adopted to parametrize the variable chemical composition in the C/O core of a white dwarf model. We point out in this context that evolutionary models are subject to major uncertainties, especially in late stages of

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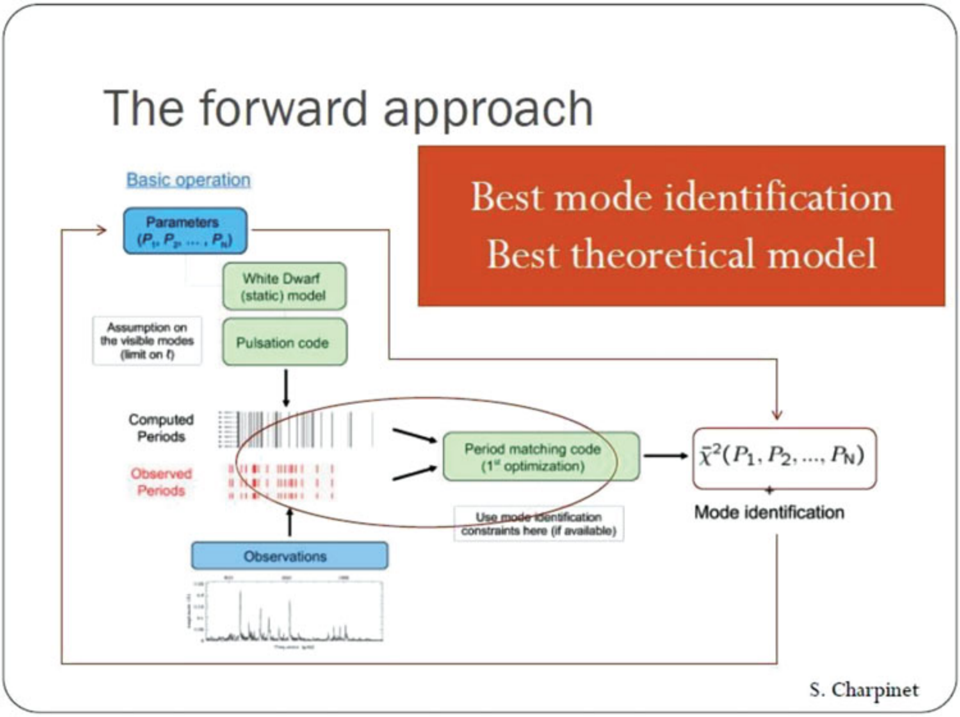

Figure 2. Schematic view of the basic operation in the double optimization procedure. The observed pulsation periods are optimally matched (first optimization) with periods computed for a model of given parameters. The fit is quantified using a χ^2-type merit function. This quantity is then further minimized as a function of the model parameters through the second optimization.

stellar evolution, that usually pile up by the time the modeled star becomes a white dwarf. Relying on such models for accurate seismic analyses of individual white dwarfs is therefore dangerous. Instead, we prefer more flexible parametrized static models that can provide seismic measurements that do not depend on these uncertainties.

3. Objective Search in Parameter Space

Our strategy is based on the forward modeling approach that consists of finding the best possible match between a set of oscillation periods detected in a given star and the periods computed from stellar models. However, in order to provide trustable results, this global search has to be *objective* in the following sense: 1) A thorough exploration of the usually vast model parameter space has to be carried out, 2) the optimal solution best matching the pulsation properties has to be robustly found, 3) the uniqueness of the solution must be evaluated and other eventual secondary solutions must also be found, and 4) consistency with available external constraints (e.g., from spectroscopy or, ultimately, with improved evolutionary models) must be achieved. These requirements are fulfilled by a double optimization scheme and the associated optimization tools that we developed for that purpose.

The basic operation in the double optimization procedure is schematically illustrated in Figure 2 (see also Van Grootel *et al.* 2013 and references therein). The second optimization then takes place in the N-dimensional parameter space where the best fit model(s) is (are) searched. This optimization can be difficult depending on the complexity of the χ^2-type merit function and is dealt with LUCY (genetic evolLUtion Code for asteroseismologY), a powerful optimizer specifically developped for that purpose. This code is a massively parallel hybrid genetic algorithm capable of multimodal optimization which provides several advantages: 1) It does not rely on model grids (the parameter space is explored continuously), leading to a much higher computational efficiency and avoiding grid resolution problems, and 2) It is very robust at finding the global optimum (best solution) as well as all potentially interesting secondary optima. More details on this technique, as adapted to white dwarfs, can be found in Charpinet *et al.* (2015).

At the time of the conference, we reported on some preliminary results that were extremely encouraging. That trend has been confirmed since then, although we have not yet completely finished our investigations. We will report elsewhere the final results of our ongoing effort, which is part of the Ph.D. thesis of the lead author.

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