Observations of compact pulsators: the subdwarf B variables

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Abstract. Following the successes of white dwarf asteroseismology made possible through the instigation of appropriate infrastructure for multi-site observational campaigns, novel kinds of multi-periodic nonradial pulsators among compact evolved objects recently have received a lot of attention. Since the discovery of the first prototype a decade ago, these subdwarf B variables have developed into a major new focus due to two reasons:

(1) Although their current evolutionary status appears to be solved (subdwarf B stars can be identified with extreme horizontal branch models), the corresponding proposed formation scenarios still await validation or falsification through decisive evidence, and in the meantime continue to raise fundamental questions related to late stellar evolution. Probing the internal structure of these objects with asteroseismological methods therefore represents a valuable potential resource, for which the observational basis must be provided.

(2) In an amusing course of matters, the theoretical interpretation of the pulsational behaviour of the variety of pulsational properties found in subdwarf B stars seems to have grown more difficult with time: From the successes of an initial simultaneous prediction of the $p$-mode pulsations by theory at the time of discovery of the first variables, to the current difficult task to reproduce the complex behaviour observed especially in the $g$-mode domain theoretically. The observed overlap area (hybrid objects with both $p$- and $g$-modes) in particular seems to constitute a major challenge to theory and has triggered vivid activity with some surprising first results.

This obviously has significant impact on how to best exploit the wealth of observational data that is currently available, which spans time-resolved photometric and spectroscopic data from the optical (ground-based) to the FUV (space-based) domain. In the course of briefly reviewing some important observational campaigns on subdwarf B pulsators conducted world-wide in the last years, as well as a subjective selection of specific targets, I will identify some key objects.

1. Compact pulsators
The group of compact pulsators comprises the variable white dwarfs (GW Vir, DBV, and ZZ Ceti stars), the two classes of pulsating subdwarf B stars, one pulsating He-subdwarf B [1] and one pulsating sdO star [2]. The evolutionary history of this collection of evolved objects is diverse, and so are the driving mechanisms responsible for their respective instability.

The various excitation mechanisms for white dwarfs and subdwarf B stars are discussed elsewhere in these proceedings [3], where the individual types of pulsating white dwarfs are also discussed in some detail. The similarities between white dwarfs and sdBs arise not simply from the fact that their evolved internal structure makes both significantly more compact than main sequence stars. White dwarfs pulsate in $g$-modes, while that group of variable sdBs that was
discovered first pulsates in $p$-modes. Due to their differing degrees of compactness, this results in periods of minutes for both the classical sdB as well as for the classical white dwarf pulsators (the ZZ Cetis), so that very similar observational strategies are required. As non-radial pulsators, they have in common their multi-periodic oscillation spectra.

This contribution focusses on pulsating subdwarf B stars. Its objective is to summarize the observational properties of pulsating subdwarf B stars, which provide the constraints to be taken into account by any modelling approach.

1.1. Necessity of coordinated campaigns
The observational strategies required to resolve the multi-mode frequency spectra of white dwarfs and sdB stars aim at a narrow window function with strongly suppressed alias peaks, i.e. a long time base for high frequency resolution and a good filling factor for low spectral leakage, and have therefore classically involved the organisation of multi-site campaigns. In the field of compact pulsators, the most famous collaboration name is certainly the WET, or Whole Earth Telescope [4] (recently placed under the roof of the newly created DARC, the Delaware Asteroseismic Research Center [5]). Changing and less formally associated collaborative initiatives are often at least partially recruited from this community, such as the MSST (Multi-Site Spectroscopic Telescope [6]).

The fact that white dwarfs and subdwarfs are faint blue stars, and that their pulsation amplitudes are small (at the percent level), implies minimum requirements in terms of telescope aperture and sensitivity in the blue spectral range. Even in the commencing era of space missions specifically designed for stellar time-domain work, ground-based networks remain of importance due to the faintness of the objects, and many general-purpose ground-based surveys fail to adequately sample the rapid pulsations which require short exposure times in an uninterrupted series.

1.2. What are subdwarf B stars?
Subdwarf B stars are subluminous B-type stars that are found to have effective temperatures from 20 000 K to 40 000 K, surface gravities between about 5.0 and 6.2 in log ($g$ [cm s$^{-1}$]), and luminosities roughly one to two times solar. When placing the subdwarf B stars in a Hertzsprung-Russel diagram (Fig. 2), it is immediately obvious that standard single star evolution tracks never cross the region occupied by them (or by the sdOB and sdO stars). They form a blue extension to the horizontal branch and can thus be identified with core-helium burning models [7] [8], i.e. evolved objects beyond the red giant phase. Although spectroscopically their surfaces appear particularly hydrogen-rich (due to purification from helium by gravitational settling, combined with radiative levitation of the heavier elements in varying amounts), the hydrogen shell is too thin to sustain nuclear burning, and causes the blue appearance of these objects. The existence of horizontal branch stars with such thin hydrogen shells is a puzzle, and it appears that a combination of different feeder channels is required (both single and close binary star evolution, including mergers, common envelope phases, stable or unstable mass transfer via Roche lobe overflow) to explain their origin [9].

In this light, it is surprising that the sdBs appear as a relatively homogeneous group. Different types of variability have been detected in a certain fraction of sdBs, so we are in the lucky position that asteroseismological methods can be exploited to obtain further constraints on the suggested evolutionary scenarios.

1.3. Pulsating subdwarf B stars
Only a fraction of the sdB stars with otherwise identical effective temperature, surface gravity and photospheric metallicity are pulsators; they co-exist with non-variable stars in the same region of the HRD and fall into two groups, the short-period $p$-mode and the longer-period
Table 1. Key objects.

| comments                          | analysis                        |
|----------------------------------|---------------------------------|
| EC 14026                         | $p$-mode prototype [10] (V 261 Hya) |
| PG 0014+067                      | [17]                            |
| PG 1047+003                      | [18]                            |
| PG 1219+534                      | [19]                            |
| Feige 48                         | [20]                            |
| EC 20117−4014                    | [21]                            |
| PG 1325+101                      | [22] [23]                       |
| PG 0911+456                      | [24]                            |
| PG 1336−018                      | [25]                            |
| PG 1605+072 bright, high-amplitude, multi-periodic [26] | [27] MSST |
| Bal 090100001 hybrid [28]        | bright, high-amplitude, multi-periodic [29] [30] [25] |
| HS 0702+6042 hybrid [31]         |                                  |
| HS 2201+2610 hybrid [32]         | planetary-mass companion [33]    |
| PG 1716+425 $g$-mode prototype [11] (V 1093 Her) |                      |

g-mode oscillators. The short periods of the EC 14026 stars [10] are of the order of minutes and have amplitudes of a few tens mmag, while the longer periods in the PG 1716 stars [11] range from 30 to 80 mins at even lower amplitudes of a few mmag. Typical light curves are compiled in Fig. 1 of [12].

2. Key objects: $p$-mode pulsators

Although the excitation mechanisms for both the $p$- and $g$-mode pulsations in sdB stars have been explained to result from a $\kappa$ mechanism due to a $Z$-opacity bump accumulated by radiative levitation [13] [12], the modelling of the $g$-mode pulsators turns out to be significantly more difficult than that of the $p$-mode pulsators [14]. While new developments [15] [16] suggest that the $g$-mode empirical instability region will soon be reproduced by models to a similar degree as the $p$-mode region, the majority of reliable individual asteroseismological analyses has so far been carried out for $p$-mode pulsators (see Table 1), which are also easier to study observationally due to the shorter periods and higher amplitudes associated with them.

2.1. Photometric period matching

In the approach pioneered by [34] to [35], the modes extracted from photometric time series observations are compared to large grids of non-adibatic pulsation models using a global optimization procedure. Table 1 gives a census of the objects successfully analysed so far, resulting in the first preliminary asteroseismic mass distribution [35].

The photometric period matching method relies on complementary spectroscopic information (the 'spectroscopic error box' in $T_{\text{eff}}$ and $\log g$) to narrow down the manifold of solutions in the usually very complex parameter space. This complexity can be reduced by supplying a priori mode identifications. The classical white light observations are therefore increasingly being supplemented by high precision multi-colour light curves as well as by time-resolved spectroscopy, which allow to extract aspects of the mode geometry and hence constrain the degrees $l$ and $m$ of the spherical harmonic function describing the mode associated with an observed frequency.

Multi-periodic pulsators, with several tens of frequencies observed, in principle provide...
correspondingly stronger constraints on the models, but their complex frequency spectra must first be resolved by extensive multi-site campaigns. Endeavours to organise such multi-site spectroscopic observations, supplemented by synchronous extended photometric monitoring, have so far been attempted for PG 1605+072 (see below) and for the bright high-amplitude object Balloon 090100001 [29] [28] [36] [30] (which will not be further discussed here).

2.2. Multi-Site Spectroscopic Telescope for PG 1605+072

Following a number of feasibility studies, the first object observed in a large coordinated effort to obtain simultaneous spectroscopic, multi-colour photometric and extensive photometric data was PG 1605+072 [6], which shows a very complex pulsational behaviour. In detail, the data obtained with the MSST includes 2m spectroscopy [26] [27], 4m spectroscopy [37] and the photometric light curve [38], in combination aiming towards asteroseismology of PG 1605+072. Multi-colour light curves allowing to derive chromatic amplitudes are also available.

2.3. PG 1605+072 observed with FUSE

In addition to having been observed extensively both photometrically as well as spectroscopically, PG 1605+072 has been targeted by FUSE twice. This time-tag spectroscopic data in fact allows to derive FUV light curves, chromatic amplitudes, and radial velocities [39] [40], and hence for example also FUV light to radial velocity ratios as well as light to radial velocity phase shifts. Similar to the conclusions drawn in the analysis of the optical 2m spectroscopic data [27], the results for this latter quantity also point to non-adiabatic behaviour. There is definitely still much to be learned about PG 1605+072.

The examples of Balloon 090100001 and PG 1605+072 show that a rich frequency spectrum is an advantage if an effort is made to resolve it. A different promising approach is to exploit a set of modes that sample very different parts of a star, i.e. \( p \)- and \( g \)-modes, which actually works in very special cases.

3. Key objects: hybrid pulsators

From theoretical considerations, the \( p \)- and \( g \)-mode instability domains for sdB pulsators were initially thought to be disjoint. The discovery of hybrid objects, showing both types of pulsations, places strong constraints on the predictions for the red edge of the \( p \)-mode and the blue edge of the \( g \)-mode instability regions. Three such objects are currently known, including Balloon 090100001 [28] [36]; the other two are HS 0702+6042 and HS 2201+2610.

3.1. HS 0702+6042

Short-period frequencies in HS 0702+6042 were discovered during a survey to find new sdB variables [41], and it was found that, similarly to PG 1605+072 and Balloon 090100001 that also reside close to the cool end of the \( p \)-mode instability region, the amplitude of its main frequency is among the largest of the sdBVs. The hybrid character of HS 0702+6043 was discovered later in the form of unresolved power in the low frequency spectrum in the same data set, and confirmed by independent observations [42] [31]. This confirmation light curve, which nicely summarizes the observational characteristics displayed by the object, is shown in Fig. 1.

New HS 0702+6043 photometric data were taken at the Calar Alto 2.2 m telescope equipped with CAFOS in January 2005 through a B filter. From the whole ten day data set, the \( p \)-modes were subtracted, then only the best six nights (\( \approx 56 \) hours) were used for further analysis. To denoise this HS 0702+6043 data, a so-called \( \text{à trous} \) algorithm [43], based on wavelet transformations, was applied. The filter decomposes a light curve into different scales corresponding to different frequency bands, and transformation coefficients are compared to a simulated pure noise light curve. From all coefficients above a set threshold value, the
reconstruction then produces a noise-filtered light curve. With this procedure, three independent frequencies have been detected in the resolved gravity mode domain of the hybrid pulsator HS 0702+6043 [40] [32].

3.2. HS 2201+2610

A long-period variation was also suspected from the overall data set collected on HS 2201+2610 up to the end of 2005 (see Sect. 4.1). We therefore initiated another long, high S/N run at the Calar Alto 2.2 m telescope in September and November of 2006, with the same setup as for HS 0702+6043. Five successful nights of observation yielded a total of 26 hours of high S/N photometric data. Careful analysis indeed resulted in the detection of a single-frequency, long-period luminosity variation in HS 2201+2610 [40] [32]. The object must therefore be added to the list of hybrid pulsators.

3.3. New developments

Without having to resort to empirical determinations of the two subdwarf instability regions based on the derivation of spectroscopic parameters ($T_{\text{eff}}$ and $\log g$) using stellar atmosphere models, the existence of the hybrids directly proves their overlap. Both the correct simultaneous prediction of the extent of both instability regions as well as the simultaneous reproduction of the hybrid mode spectra of individual objects put pulsation models to a critical test.

While the former problem now seems in principle to be resolvable since it has become clear how the driving in models changes as a function of the element mix (improvement when Ni is considered in addition to Fe) and of the opacity tables used (improvement when OP data is used instead of OPAL) [15] [16], the latter task of describing individual objects has yet to be tackled. The issue of opacity is of crucial importance also for at least two further types of variables, namely, the main sequence analogues to the subdwarf B pulsators: the $\beta$ Cephei and [SPB] stars (where recently hybrids have also been shown to exist).
4. Pulsations as tools

While their most obvious application is to probe the inner structure of stars, and to give clues on the objects’ stellar evolutionary history through information on its current global and internal parameters, pulsations can also be used to track evolutionary effects directly. Slow changes in the resonating cavity can translate into subtle but measurable period changes. Using stable periods in subdwarf B stars, such results can be obtained within about a decade of observations. A further interesting utilisation is that of pulsations as a stable clock, a method which has recently led to the discovery of the first ‘asteroseismic’ planet candidate.

4.1. Timing method: a planet around HS 2201+2610

After luminosity variations were first detected in HS 2201+2610 (also known as V 391 Pegasi) [44], an ensuing extensive time-series photometry campaign resulted in the discovery of five p-modes in this object, and a first upper limit for \( \dot{P} \) [45]. In order to measure the secular variation due to evolutionary effects in the pulsation frequencies of HS 2201+2610, this monitoring has since been continued regularly for more than seven years. A large number of observers at various telescopes has contributed to the overall data set.

In addition to measurements of the \( \dot{P} \) values for the two strongest frequencies (and clues to the hybrid nature of the object, see above), this data has provided evidence for a planetary companion [33]. Using the clock provided by the star itself through its stable stellar pulsations (comparable to the regular pulses which have made possible the detection of the pulsar planets) constitutes a new detection method which is sensitive to planets on relatively large orbits. The existence of V 391 Pegasi b has been revealed by the observation that the arrival times of the signal are periodically delayed and advanced, with a period of 3.2 years, according to the displacement of the star due to the gravitational influence of its companion.

This planet around a core helium burning extreme horizontal branch star may in fact well be one of the oldest planets known so far. The detection of a planet around a star that has undergone red giant expansion, at an orbital distance smaller than 2 AU, also proves observationally for the first time that planets at AU distances can survive this evolutionary phase.

5. Summary

Subdwarf B stars are faint blue stars, a fraction of which shows multi-periodic pulsations. The fact that models are well established for the p-mode pulsators in conjunction with an increasing number of existing analyses has allowed to construct the first asteroseismological mass distribution for sdB stars. The modelling of g-mode pulsations is also making rapid progress, triggered in part by the discovery of hybrids (showing p- and g-modes simultaneously).

Despite their intrinsic faintness, extended observational campaigns on 2m- and 4m-class telescopes to obtain simultaneous (multi-colour-)photometry and spectroscopy are now possible for the brightest targets. This allows to supplement and go beyond the photometric period matching with methods routinely applied to other pulsators (such as line profile variation analysis in \( \beta \) Cephei stars).

Both observationally and from a modelling point of view, the field of sdB asteroseismology is now mature enough to start exploiting chromatic amplitude, radial velocity, and various spectroscopic parameter variations in addition to photometric period information.

Among the diversity of results touched upon in this paper, it has been emphasized that the stable pulsations in a subdwarf B star have successfully been used as a tool to discover planets.

Acknowledgments

Thanks to the MSST core team (Stefan Dreizler, Uli Heber, Simon Jeffery, Simon O’Ttoole), the MSST team including Sigi Falter, Oliver Cordes, and Alfred Tillich, and the WET team for fruitful collaboration on PG 1605+072, as well as to Thorsten Stahn and Ronny Lutz. Thanks to
**Figure 2.** Hertzsprung-Russel diagram showing the location of classes of pulsating stars across the luminosity-effective temperature parameter space. Regions with rising lines indicate $p$-modes driven by a heat engine, those with falling lines indicate $g$-modes driven by a heat engine, and horizontal lines indicate solar-like oscillations. Overlap of instability regions is in fact not only observed for the $p$- and $g$-mode pulsating subdwarf B stars, but also for the $\beta$ Cep and [SPB] as well as for the $\delta$ Sct and $\gamma$ Dor pulsators. Graphics courtesy of Jørgen Christensen-Dalsgaard.
many of the above and in particular also to Betsy Green, Gilles Fontaine, Suzanna Randall, Jörg Huber, and Simon Hıgelmeyer for productive work done together on the hybrids HS 0702+6042 and HS 2201+2610, and especially to Roberto Silvotti for a continued pleasant collaboration on HS2201+2610. The community owes Stéphane Charpinet a large share of the theoretical results very briefly cited here.

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