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# THE POTENTIAL OF ASTEROSEISMOLOGY FOR HOT, SUBDWARF B STARS: A NEW CLASS OF PULSATING STARS?

S. Charpinet, G. Fontaine, and P. Brassard
Département de Physique, Université de Montréal, C.P. 6128, Succ. Centre-Ville, Montréal, Québec, Canada, H3C 3J7; charpinet@astro.umontreal.ca, fontaine@astro.umontreal.ca, brassard@astro.umontreal.ca

and

B. Dorman[1]
Laboratory for Astronomy and Solar Physics, NASA/GSFC, Greenbelt, MD 20771; ben.dorman@gsfc.nasa.gov
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## ABSTRACT

We present key sample results of a systematic survey of the pulsation properties of models of hot B subdwarfs. We use equilibrium structures taken from detailed evolutionary sequences of solar metallicity ($Z = 0.02$) supplemented by grids of static envelope models of various metallicities ($Z = 0.02$, 0.04, 0.06, 0.08, and 0.10). We consider all pulsation modes with $l = 0$, 1, 2, and 3 in the 80–1500 s period window, the interval currently most suitable for fast photometric detection techniques. We establish that significant driving is often present in hot B subdwarfs and is due to an opacity bump associated with heavy-element ionization. We find that models with $Z \geq 0.04$ show low radial order unstable modes; both radial and nonradial ($p$, $f$, and $g$) pulsations are excited. The unstable models have $T_{\rm eff} \lesssim 30{,}000$ K and $\log g \lesssim 5.7$, depending somewhat on the metallicity. We emphasize that metal enrichment need only occur locally in the driving region. On this basis, combined with the accepted view that local enrichments and depletions of metals are commonplace in the envelopes of hot B subdwarfs, we predict that some of these stars should show luminosity variations resulting from pulsational instabilities.

*Subject headings:* stars: interiors — stars: oscillations — subdwarfs

## 1. INTRODUCTION

In the last 20 years, considerable progress has been made in our understanding of the physical properties and evolutionary status of hot, hydrogen-rich, subdwarf B stars (see, e.g., Greenstein & Sargent 1974; Heber 1987; Saffer et al. 1994). Following the scenario originally proposed by Heber and collaborators (e.g., Heber et al. 1984), it is currently believed that subdwarf B stars are $\sim 0.5\ M_\odot$ objects with hydrogen envelope masses that are small enough that, after core helium exhaustion on the extended horizontal branch (EHB), they never evolve toward the asymptotic giant branch (AGB). They remain at high effective temperatures ($T_{\rm eff} \gtrsim 20{,}000$ K) throughout their core-burning evolution. In the post-HB, He-shell–burning stage of evolution the models are referred to as "AGB-manqué" objects (see Greggio & Renzini 1990) and are associated with the field subdwarf O stars (Dorman, O'Connell, & Rood 1995 and references therein). A number of post-EHB evolutionary studies have appeared in the literature in the last several years (see Dorman 1995 for a review).

While asteroseismology is proving to be an extremely powerful tool in studying other types of stars, its potential has not yet been studied for subdwarf B stars, partly because of the lack (until recently) of sufficiently realistic equilibrium structures. Furthermore, and to our knowledge, luminosity variations caused by pulsational instabilities have not been reported for these stars. However, pulsation theorists with a keen eye may have noticed for some time that the potential for driving pulsation modes appears to exist in the envelopes of subdwarf B stars. Indeed, early models of such envelopes (Wesemael et al. 1982; Groth, Kodritzki, & Heber 1985) as well as their more sophisticated modern counterparts are all characterized by the presence of a He II–He III convection zone. By analogy with other types of pulsating stars (whose instabilities are always driven by one form or another of an opacity mechanism), one might expect that the opacity bump associated with this partial ionization zone could also excite pulsation modes in hot B subdwarfs.

Motivated in part by this observation, we undertook a systematic exploration of the potential of asteroseismology for subdwarf B stars. The purposes of the present Letter are (1) to report on the salient results of our investigation, (2) to call attention to the very real possibility that some subdwarf B stars may undergo stellar oscillations, and (3) to encourage searches for luminosity variations in such stars.

## 2. COMPUTATIONS AND RESULTS

The first batch of equilibrium models investigated in this study consists of full stellar models taken from five distinct evolutionary sequences. These were chosen in order to map a significant fraction of the region of the $T_{\rm eff}$–$\log g$ plane actually occupied by the known subdwarf B stars (see Saffer et al. 1994 and references therein). In this particular region, we retained about 25 models per sequence. The evolutionary models were computed with the methods described in Dorman (1992a, 1992b) and Dorman, Rood, & O'Connell (1993). The new models use the OPAL opacities described by Rogers & Iglesias (1992) computed in 1993 December, which adopted the element mix referred to as "Grevesse & Noels 1993." Where necessary (during He flashes), we used new low-temperature opacities by D. R. Alexander (1995, private

[1] NAS/NRC Resident Research Associate.

TABLE 1

PULSATION PERIODS FOR A TYPICAL SUBDWARF B STAR MODEL

| $k$ | $l = 0$ | $l = 1(p)$ | $l = 1(g)$ | $l = 2(f, p)$ | $l = 2(g)$ | $l = 3(f, p)$ | $l = 3(g)$ |
|---|---|---|---|---|---|---|---|
| 0........ | 384.13 | ... | ... | 277.45 | ... | 270.11 | ... |
| 1........ | 281.70 | 379.97 | 399.07 | 257.90 | 370.99 | 222.67 | 306.83 |
| 2........ | 226.74 | 279.72 | 669.19 | 223.56 | 407.72 | 205.82 | 355.99 |
| 3........ | 191.25 | 225.28 | 965.35 | 192.39 | 576.19 | 187.56 | 428.29 |
| 4........ | 173.54 | 188.71 | 1136.81 | 179.41 | 675.85 | 169.34 | 506.07 |
| 5........ | 157.05 | 163.60 | 1311.82 | 157.95 | 774.48 | 153.11 | 563.83 |
| 6........ | 138.66 | 147.90 | ... | 139.38 | 897.80 | 135.79 | 655.69 |
| 7........ | 114.61 | 134.07 | ... | 126.07 | 1004.21 | 121.56 | 723.91 |
| 8........ | 105.62 | 120.33 | ... | 115.90 | 1182.10 | 110.75 | 846.59 |
| 9........ | 96.96 | 108.84 | ... | 106.04 | 1361.08 | 102.54 | 975.36 |
| 10....... | 89.50 | 99.99 | ... | 97.15 | 1429.47 | 95.03 | 1030.05 |
| 11....... | 83.38 | 93.28 | ... | 89.77 | ... | 88.03 | 1130.15 |
| 12....... | ... | 87.18 | ... | 83.87 | ... | 81.88 | 1259.89 |
| 13....... | ... | 81.28 | ... | ... | ... | ... | 1337.26 |
| 14....... | ... | ... | ... | ... | ... | ... | 1425.84 |

communication, described in Alexander & Ferguson 1994), which were computed with the same element mix. These smoothly match the OPAL opacity set within the hydrogen ionization zone. The other difference in the physics was the use of the Itoh et al. conductive opacities (Itoh et al. 1983, 1993; Itoh, Hayashi, & Kohyama 1993, 1994; Itoh & Kohyama 1994).

Each sequence describes the evolution of an AGB-manqué star with a core mass of 0.4758 $M_\odot$. The sequences differ in that different envelope masses are considered: $M_{\rm env} = 0.0002$, 0.0012, 0.0022, 0.0032, and 0.0042 $M_\odot$. The composition of the envelopes is assumed to be solar ($X = 0.70388$, $Z = 0.01718$). The luminosity of each model is provided by He burning confined to a very small core. Residual H burning at the base of the H-rich envelope contributes negligibly to the luminosity until the AGB-manqué phase of the evolution.

We first carried out a detailed adiabatic survey of the evolutionary models with the help of the Galerkin finite-element code of Brassard et al. (1992). Specifically, for each equilibrium model considered, we computed pulsation periods in the adiabatic approximation for all modes with $l = 0$, 1, 2, and 3 in the 80–1500 s period window. This interval corresponds to the range of periods most easily detectable with present-day fast photometric techniques. Moreover, it is well known that surface cancellation effects render detection of luminosity variations excessively difficult for $l \geq 4$ in compact stars (Dziembowski 1977; Robinson, Kepler, & Nather 1982; Brassard 1987; Brassard, Fontaine, & Wesemael 1995), so such modes are not of direct observational interest. We will report elsewhere the detailed results of this extensive survey, including discussions of the effects of changing model parameters, the period evolution, the rates of period changes, and the effects of mode trapping and mode confinement caused by the composition interfaces in our doubly stratified equilibrium models. For the needs of the present Letter, in order to give an idea of the modes to be expected in the 80–1500 s period window, we simply report on some sample results.

Table 1 lists the pulsation periods for a typical model of a hot B subdwarf. This model belongs to the sequence with $M_{\rm core} = 0.4758\ M_\odot$ and $M_{\rm env} = 0.0012\ M_\odot$. It has an age of $\sim 8.4 \times 10^7$ yr (time elapsed since the zero-age HB phase), a surface gravity $\log g = 5.46$, and an effective temperature $T_{\rm eff} = 27{,}500$ K. The table gives the pulsation period (expressed in seconds) as a function of the radial order $k$. We distinguish between the radial modes ($l = 0$) and the $p$ and $g$ branches for nonradial modes with $l = 1$, 2, and 3. Our results indicate that subdwarf B stars have rich period spectra, easily accessible with present-day observational techniques (white-light fast photometry, for example). Provided that we can demonstrate that some of these modes can be excited, this should motivate observational searches for pulsational instabilities in these stars.

Therefore, in the second step of our investigation, we carried out a stability analysis of our equilibrium models with the help of the finite-element nonadiabatic pulsation code briefly described in Fontaine et al. (1994) and Brassard, Fontaine, & Bergeron (1996). In order to understand the results and be able to identify the driving regions (if any), we considered the variations with depth of the so-called work integral. Figure 1 illustrates a typical case and refers to the equilibrium model whose periods are provided in Table 1. The solid curve corresponds to the integrand of the work integral for the $l = 2, f$-mode with a period of 277.45 s. (We emphasize that, while specific to this particular mode, the results shown here are also typical of all other modes of interest.) The values of $dW/dr$ are positive in driving regions and negative in damping regions. We find that driving is negligible in the He II–He III convection zone, contrary to our initial expectation. In retrospect, it appears that the convection zone is located too high in the envelope, in a region that contains very little mass; therefore, it carries practically no weight in terms of driving (or damping). Likewise, the H-burning shell is so weak in our models that no significant contribution to driving from the $\epsilon$ mechanism is observed. The important result here is that the main driving region in hot B subdwarfs is associated with an opacity bump due to heavy-element ionization. This is shown by the dashed curve which illustrates the run of the Rosseland opacity in the unperturbed model. As expected, the opacity shows a maximum in the convection zone due to He II–He III partial ionization, but it also shows a secondary maximum around $\log q \simeq -9.2$, obviously associated with the driving region and which tends to disappear when the heavy-element content (assumed to be $Z \sim 0.02$ in this model) is decreased. The realization that driving is related to metallicity provides an important clue to the possible existence of real subdwarf B pulsators. This is similar in nature to the so-called $Z$-bump mechanism uncovered by others in different types of pulsating stars (e.g., Cox et al. 1992; Moskalik & Dziembowski 1992; Dziembowski & Pamiatnykh 1993; Gautschy & Saio 1993).

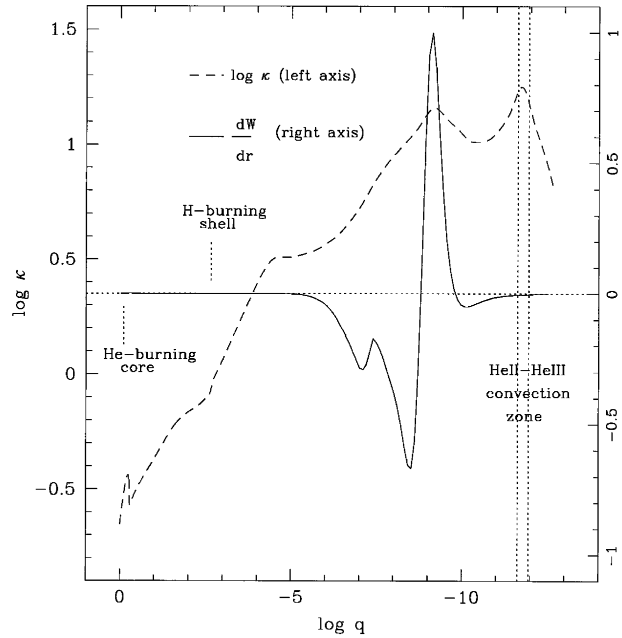


FIG. 1.—Run of the integrand of the work integral for the $f$-mode with $l = 2$ (*solid curve*) and of the Rosseland opacity (*dashed curve*) vs. fractional mass depth in a typical subdwarf B model. The locations of the He-burning core, the residual H-burning shell, and the He II–He III convection zone are indicated. The driving region (positive values of $dW/dr$) is clearly associated with an opacity bump, itself caused by heavy-element ionization.

The specific mode considered in Figure 1 turns out to be stable, the damping region below the driving region contributing somewhat more to the overall work integral. This result is quite typical of all of the evolutionary models computed with $Z \sim 0.02$. Indeed, in our detailed nonadiabatic survey of those equilibrium models, we found no unstable mode. However, in many cases, we found that the overall damping rates were very small, suggesting to us that such modes could perhaps still be excited in real stars (whose detailed structure might, of course, be different from that of the particular models we considered). In view of the correlation we uncovered between driving and metallicity, and the fact that local variations of metallicity *are* expected in subdwarf B stars (see below), it seemed natural to investigate the effects of changing the metallicity.

In the final step of our analysis, we constructed a second batch of equilibrium models taking into account variations of $Z$ in the H-rich envelope. Contrary to our previous models, these are static (i.e., nonevolving) structures. The models were built with a version of the stellar code described by Brassard & Fontaine (1994) and Brassard et al. (1996), suitably modified to produce envelope structures extending as deep as $\log q = -0.05$. The constitutive physics used is nearly identical to that used previously in the construction of our full evolutionary models, apart from the use of slightly newer OPAL opacities computed in 1995. Tests indicate that our ignoring of the small He-burning core increases somewhat the values of the periods of the $g$-modes (by 10%–20%, typically) but does not affect those of the $p$-modes which, contrary to the former, are formed essentially in the envelope region. We will provide more details on these models elsewhere.

We constructed five different model grids, one each for a fixed metal content $Z = 0.02$, 0.04, 0.06, 0.08, and 0.10 in the H-rich envelope ($X = 0.70$). Each grid consists of 72 unperturbed models covering a rectangular region in the $T_{\rm eff}$–$\log g$ plane overlapping with the region where hot B subdwarfs are actually found ($4.34 \leq \log T_{\rm eff} \leq 4.62$ in steps of 0.04, and $4.8 \leq \log g \leq 6.4$ in steps of 0.2). In these exploratory calculations, we fixed the total mass of each model to 0.48 $M_\odot$ and the H-rich envelope mass to $\log q(H) = -4$. Tests indicate that stability does not depend on the value of $\log q(H)$.

*In agreement with our expectations concerning the effects of metallicity, we found unstable pulsation modes for models with* $Z \geq 0.04$. For these models, there is a blue-edge temperature located somewhere between $\log T_{\rm eff} = 4.46$ and 4.50, which shows a weak sensitivity to metallicity. We tentatively interpret this as the consequence of the fact that metallicity primarily affects the size of the opacity bump (and, hence, the magnitude of the driving), rather than its location in a star of a given effective temperature. The blue edge itself must be due to the outward displacement of the driving region to the outermost layers (which carry little weight in the overall stability of a mode) as the effective temperature increases. Note that our actual value of the blue-edge temperature ($T_{\rm eff} \sim 30{,}000$ K) may also depend on the assumption of *uniform* metallicity as well as on the assumed mass of the models (currently 0.48 $M_\odot$), but this remains to be investigated. We find also that stability does depend on the assumed surface gravity. Unstable models have $\log g \lesssim 5.7$, with a weak dependence on metallicity, but this also remains to be investigated in more detail. As expected, the driving is more efficient in the high-metallicity models; a wider band of modes are excited in such models. In all unstable models, the excited modes have low values of the radial order $k$, and radial as well as nonradial pulsations are predicted. The most strongly driven modes have typical $e$-folding times of $\sim 8 \times 10^{-2}$ yr, much shorter than the typical evolutionary time of a hot B subdwarf ($\sim 10^8$ yr). These linear instabilities would normally develop into observable amplitudes.

## 3. DISCUSSION AND CONCLUSION

The results presented in this paper pave the way to the exciting possibility of being able to use asteroseismology to probe the internal constitution of subdwarf B stars. A subgroup of these stars may indeed constitute a new class of pulsating stars. Of course, this possibility hinges here on the question of metal enrichment in the driving region. We emphasize the fact that this enrichment need only occur in the driving region *itself* and not necessarily everywhere in the envelope (as we assumed in the relatively crude envelope models used in the present study). That heavy elements can show local enrichments in certain regions of a hot B subdwarf envelope, and local depletions in others, is not only plausible but is also *expected*. Indeed, subdwarf B stars all show peculiar surface abundances whose study constitutes a most active and interesting subfield of stellar physics in its own right. It is currently believed that the abundance anomalies observed in the atmospheres of these stars result from the competition between gravitational settling, radiative levitation, and weak stellar winds (Michaud et al. 1985, 1989; Heber 1987; Bergeron et al. 1988; Chayer et al. 1996). In the most recent investigation, Chayer et al. (1996) have carried out new computations of radiative levitation on metals in models of hot B subdwarfs using the same tools considered previously in the white dwarf context by Chayer et al. (1995) and Chayer, Fontaine, & Wesemael (1995). Of high relevance here, they found that metals, in particular iron (a major contributor to opacity), do levitate in the envelopes of these stars. Local overabundances of more than an order of magnitude can be built through this process. In the case of iron, the maximum overabundance occurs near $\log q \simeq -9, -10$. This result greatly enhances the possibility that driving occurs as a result of a local enhancement of the metal content.[2] Of course, a detailed study of the driving process in hot B subdwarfs will ultimately require the use of more detailed envelope structures taking into account diffusion processes. *In the meantime, we feel confident enough to risk the prediction that some subdwarf B stars should show luminosity variations resulting from pulsational instabilities*. We believe that the material presented in this paper warrants further theoretical investigations of the pulsation properties of these stars and, above all, searches for luminosity variations. We have undertaken both.[3]

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[2] A similar phenomenon may be responsible for mode excitation in rapidly oscillating Ap stars.

[3] After this paper was completed and submitted, we learned of the exciting discovery of pulsating sdB stars at the South African Astronomical Observatory. This was reported by O'Donoghue at the 10th European Workshop on White Dwarfs held in Blanes (Spain) on 1996 June 17–21. Thus, there *is* indeed a new class of pulsating stars out there!

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