ASTEROSEISMOLOGY OF HOT SUBDWARF STARS

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Abstract: We present a summary of the current state of the art in the study of hot subdwarf stars by using asteroseismological techniques. We first briefly describe the main physical aspects of these objects, to then analyze the different groups of hot subdwarfs from a seismological point of view.

1 Introduction

Since 1947, when Humason & Zwicky discovered *hot subdwarfs* on a survey of faint blue stars [1], and from 1960, when Greenstein established them as a spectroscopically diferentiated class of stars [2], they had been scarcely studied by the scientific community. A situation that reversed after the discovery of pulsations in some *hot subdwarfs* stars in 1997 [3].

This class of objects consists mainly of subluminous stars with a canonical mass of $0.5M_\odot$; they have blue colors and effective temperature ($T_{\rm eff}$) and logarithm of surface gravity ($\log g$) in the ranges 20 000 – 100 000 K and 4.0 – 6.5 dex, respectively. *Hot subdwarfs* reveal themselves as abundant objects in faint and blue stellar surveys [4]. Due to their high temperatures they have been considered as ionizing sources of interstellar gas at high galactic latitudes [5], and they are thought to be responsible for the UV-upturn found in elliptical galaxies and galaxy bulges [6], [7], [8].

Their evolutionary status corresponds to a lower main sequence star that has evolved through the Red Giant Branch, but that has not yet arrived at the cooling sequence of White Dwarfs (WDs). The specific details of their evolution, as well as other aspects –such as the population they belong to (they are found both in the disk and the galactic halo [9], their anomalies in metal abundances [10], their binary fraction, and the nature of the detected oscillations– are still a matter of investigation.

A definite spectroscopic classification has not yet been established either, despite various existing proposals [11], [12]. However, we can segregate *hot subdwarfs* into three main spectroscopic sequences, sdBs, sdOs and sdOBs, according to composition and effective temperatures:

- sdBs have hydrogen dominated atmospheres, with T_{eff} between 20 000 and 40 000 K, and $\log g$ between 5.2 and 6.5 dex.
- sdOs have helium rich atmospheres, with T_{eff} between about 40 000 K and 100 000K and $\log g$ between 4.0 and 6.5 dex.
- sdOBs share characteristics of the above types, both hydrogen and helium are present in their atmospheres and they have T_{eff} around 40 000K.

2 Subdwarf B-Type Stars

The physical parameters specified in the previous section place subdwarf B-type stars (the sdBs) in the area of the Hertzsprung Russell Diagram (HRD) known as the Extended Horizontal Branch ([15], EHB) a region that corresponds to the bluest part of the Horizontal Branch. This location is reproduced by theoretical models of He-core burning stars having $q \sim 0.95$, where $q = M_{\text{core}}/M_{\text{total}}$ [13], [14]. They also have a radiative He-layer plus a small ($M_{\text{H}} \simeq 0.02 M_{\odot}$) and inert hydrogen envelope, that makes the model behave almost like a helium Main Sequence star [15], [16].

Although their evolutionary path is not yet compleltely understood, they are thought to be descendents of Red Giant Branch (RGB) stars that have undergone such substantial mass loss that they have lost most of their H envelope and bypass the Asymptotic Giant Branch evolving directly into the White Dwarf cooling sequence. However, the exact mechanism that produces such mass loss at or near the tip of the RGB is unclear. Because at least 44% of the sdBs show signs of binarity, a binary origin involving common envelope phases has also been proposed [17]. Some binary scenarios of sdB formation have been studied [18] from a theoretical point of view.

Subdwarf-B stars are all chemically peculiar, with spectra dominated by the Balmer lines; they show an underabundance of He that can be very noticeable in some particular cases [19]. Other elements, such as C and Si, appear depleted in their spectra while N is aproximatly solar. The chemical abundances could result from the balance between gravity and radiative levitation, but this does not seem to be the case: the radiative and gravitatory mechanisms alone can not explain the observations [10]. Other mechanisms such as mass loss, rotation or magnetic fields, have been proposed in the attempt of reproducing observed sdB spectra [20], [21].

2.1 Pulsations in sdBs

The discovery of pulsations in some of the sdBs allows us to improve our knowledge of these stars interior structure by making use of asteroseismological techniques.

The first pulsating sdB, EC14026-2647, was found in 1997 [3]. Several observational campaigns were then organized to search for similar objects. The intense searches performed by the South African Astronomical Observatory ([22] and references therein), University of Montreal [23], Nordic Optical Telescope [24] and recently, by Green and collaborators [25], established two subclasses of pulsating sdBs. They display the following differences:

- The objects in the "EC14026" subclass have fast pulsations, with periods that tend to cluster in the range (80-250) s. There exist, however, some particular cases (Feige 48, HS 2201+2610, HS 0702+6043 and PG 1605+072) with longer periods (up to 600 s) that are explained by a frequency dependence on the physical parameters of the star [26]. The detected frequencies are explained as p modes, both radial and non radial, of low degree and low radial order excited by the κ mechanism associated with an opacity bump due to the enhancement of the iron abundance in the sdB envelopes, probably caused by diffusion processes [27]. The $T_{\rm eff}$ and $\log g$ of EC14026 stars, between $28\,400 - 35\,700$ K and $5.25 - 6.11$ dex, respectively, place them in an area of the HRD where they coexist with constant sdBs. To date, it remains unknown what causes some stars to pulse while others, with the same physical parameters, do not. The explanation could involve weak winds that, at differents ages, would lead to differences in the amount of iron in the pulsation driving region [28].

- The subclass know as "Betsy" stars, discovered in 2002 [25], show periods of oscillation on the order of one hour, that are attributed to g modes of high radial order excited by the same mechanism acting in the EC14026 stars. We find Betsy stars in the HRD area enclosed by the values of $T_{\rm eff} \in [25\,000, 30\,000]$ K and $\log g \in [5.4, 5.7]$, respectively. In this case, it seems that all the stars lying in this region oscillate and there is no co-existence of pulsating and constant objects.

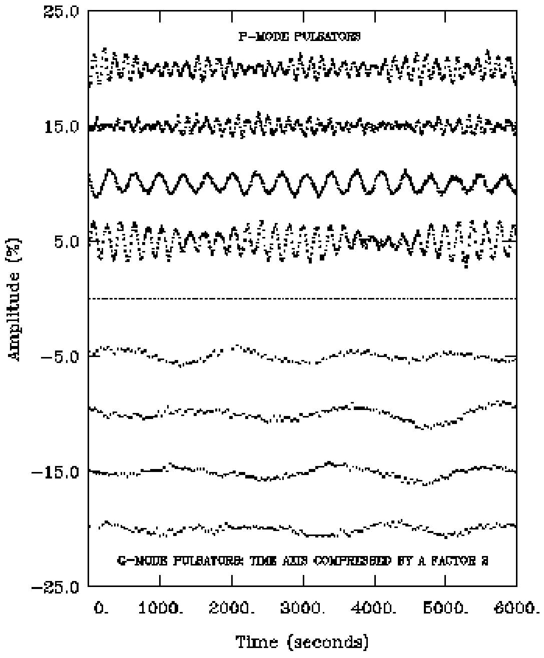

Figure 1: Some typical light curves of EC14026 (top) and Betsy stars (bottom) [29].

In Figure 1 some typical light curves of the two subclasses of pulsating sdBs are shown.

The observational discovery of the first pulsating sdB almost coincided with the theoretical prediction of the viable existence of pulsations in this class of stars. Motivated by the presence of a HeII-HeIII convection zone in the sdB envelopes that could excite pulsation modes, Charpinet *et al.* made the first theoretical study of the possible oscillating nature of sdBs [30]. Contrary to their expectations, they found a negligible contribution to driving from the HeII-HeIII region but an important contribution due to ionization of heavy elements. The same authors obtained excited pulsation modes in sdB models with enhanced Fe abundances [27]. They established that sdB models with an inhomogeneous iron distribution could present excited modes if enough of this element were present in the driving region, and proposed that the iron opacity κ mechanism is responsible for pulsations in EC14026 stars. The studies above mentioned formed the basis for an asteroseismological study of sdBs.

Fontaine *et al.* provided a theoretical explanation for the occurrence of oscillations in the Betsy stars [29]. The same κ mechanism that excites p modes in EC14026 stars is proposed as responsible for the light curve variations on Betsy stars, but leading to excited g modes of high radial order in this case.

The discovery of an oscillatory behaviour for some sdBs has led to investing great effort in trying to remove some of their uncertainties but, above all, it has opened the possibility of using seismological techniques to probe their interiors and, hence, to gain more information about this still puzzling stellar evolutionary phase. However, this task is not lacking of problems: the low number of detected pulsation frequencies in some cases, the complexity of the amplitude spectra in others, and the low amplitudes of pulsation, of the order of a few milli-magnitudes, that prevent us from accurate mode identifications, are delaying the application of seismology techniques to studying sdBs in detail. In the near future, with the aid of space missions, like COROT [31], these problems may be overcome, but to date, the only existing complete asteroseismological analysis of a sdB can be found in [32] and [33].

On this scene, our group is working both observationally and theoretically. The use of the IAC80 telescope (Teide Observatory) has led to the discovery of the latest EC14026 star known to date: Balloon090100001 [34], which is the brightest ($B = 11.8$) and has one of the greatest pulsation amplitudes (~ 60 mmag) among its class. On the other hand, we are able to compute full stellar evolution structural models of sdB stars by using the code of one of us (JM, [35]), and their corresponding theoretical frequencies of pulsation by using the adiabatic code of Christensen-Dalsgaard [36]. These computational results are used to carry out the seismological analysis of the observational data.

3 Subdwarf O-Type Stars

Hot subdwarfs O-type (hereafter sdOs) are helium rich objects with a mean canonical mass of $M = 0.5M_\odot$. They most likely have C/O cores with a helium burning shell. Their exact evolutionary state is still uncertain, in part due to a paucity of stellar evolution calculations for these objects. Nevertheless, two possible scenarios explaining the origin of sdOs have been proposed based on their location in the HR diagram [37]:

- The post-AGB (Asymptotic Giant Branch) or “luminous” sdOs are found in a region of the HRD crossed by tracks leaving the AGB.
- The post-EHB (Extended Horizontal Branch) or “compact” sdOs sit on the HRD near the EHB region. The majority of sdOs are found in this location.

Both of these scenarios pose a number of yet unanswered questions:

The “luminous” sdOs would be the descendants of AGB objects and would evolve like central stars of planetary nebulae. However, only four sdOs are known that show signs of a surrounding nebula [38], [39]. Some explanations to why this is have been proposed by [40] and [42].

The “compact” sdOs would be the sdBs (EHB) descendants. The main question is how a hydrogen rich star (a sdB) may have evolved into a helium rich one (a sdO). There are only a few calculated tracks for the post-HB state (see [13], [43], [44], [45] and [46]). Recently, Lanz *et al.* have used “deep helium flash-mixed models” to account for helium enriched sdBs [47]. Their models yield effective temperatures on the Zero Age Horizontal Branch higher than the canonical value which may explain the helium enrichment and give subsequent evolution to the sdOs.

A binary origin of sdOs has been addressed in [41] and [48]. It is proposed that single sdOs may be the merger of a pair of low-mass helium WDs which lose angular momentum by gravitational wave radiation. There are a few studies which estimate the binary fraction of sdOs ([17], [49], [50], [51] and [52]) at between 30 and ∼64%.

The highly inhomogeneous sdOs spectra (with the common characteristic of a usually strong HeIIλ4686Å spectral line) echo the peculiarities of their atmospheres. There are to date few exhaustive spectral analyses of sdOs (see *e.g.*: [53], [54], [55]). From them, we know that the helium abundance (from 50% to a 100%) shown in their spectra is usually accompanied by nitrogen enhancement and carbon depletion, pointing to the action of the CNO cycle, while sometimes carbon is enhanced which shows the action of the 3α process. Enhancement and depletion, in various degrees, of other metals like oxygen, silicon, magnesium, neon and iron in different stages of ionization are also found [56], rendering the spectral classification into subclasses of these objects still a matter of debate [12].

3.1 Search for pulsations in sdOs

Tracing back the history of pulsations in sdOs, as early as 1957 (only ten years after the discovery of *hot subdwarfs*) J. L. Greenstein in his paper “Evidence for instability among sub-luminous stars” [57] recommended observations to detect possible short-period pulsations among sdOs and WDs.

Bartolini *et al.* were the next to consider variability among sdOs [58]. They carried out a photometric study searching for variability in 6 hydrogen-poor stars, 3 of them being sdOs. They claimed to have found microvariability in all of them, although they were only able to estimate periodicities qualitatively.

The same authors stated the pulsational behavior of a binary system composed of the sdO star HD 128220 and a subgiant type-G companion [59]. However, it was not clear if the observed small amplitude variations were due to the sdO star or to its companion, or to fluctuations in atmospheric transparency [60]. Some non-pulsating episodes in the system, attributed to destructive interference of nearby frequencies, were also reported.

Motivated by the exciting discovery of pulsations in sdBs, and taking into consideration the related studies above [59], we have begun a photometric study of a sample of about 60 sdOs. Our objective is to search for possible pulsations among them, with the final aim of shedding some light on their evolutionary state.

11 sdOs and one sdOB have been observed in three observational campaigns: one at the Sierra Nevada Observatory (OSN) in December 1999, where 4 channel simultaneous Strömgren photoelectric photometry was performed with a 90 cm telescope, and two in April and August-September 2003 at the IAC80 telescope (Teide Observatory; OT) where fast photoelectric photometry was made with the 3 channel Tromsø-Texas photometer in white light. On the latter occasion, B Johnson CCD photometry was also acquired with the Tromsø-Texas CCD photometer.

From our spectral analysis, the star HIP 52181 stands out with a frequency of 1,04 mHz and with an amplitude over 2,5σ times the mean noise, which makes it a good candidate for pulsations. The amplitude spectrum is plotted in Figure 2. The horizontal dotted line is 2,5σ times the mean value of the amplitude, and the solid line is 3 times this value which yields roughly a 99% confidence level.

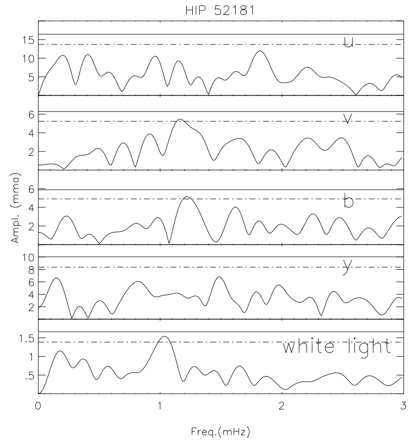

Figure 2: Amplitud spectra for HIP 52181.

For this candidate star a preliminary asteroseismological study was implemented. Two sdO models with atmospheric parameters roughly reproducing those of HIP 52181, were computed with the stellar evolution code of JM [35] by evolving Z=0.02, 1.0M$_\odot$ stars from the main sequence with enhanced mass loss. These were then used as input to the stellar evolution code to produce 19 more evolved structural models. The evolution was stopped at log $g{\sim}7$, when the star is entering the WD phase. The two evolutionary tracks are plotted in the HRD (Figure 3).

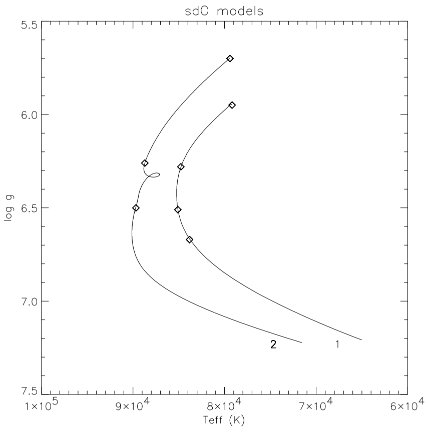

Figure 3: Traks in the HRD computed after evolving two sdOs structural models to the WDs phase.

We chose the 7 models marked with diamonds on Figure 3 and used them as input for the adiabatic pulsation code of Christensen-Dalsgaard [36]. Only for one of the models were two theoretical frequencies obtained that consistent with our observational data. Both frequencies are identified with high order g modes. Further observational and theoretical work is required to asses the eventual meaning of these preliminary results. In particular, one of our immediate goals is to construct more accurate structural models of sdOs and to use them with a non-adiabatic pulsation code [61] that includes the interaction between pulsation and the atmosphere to determine the unstable oscillation modes.

About 20 more sdOs of the ongoing study were observed from 1-14 December 2003 at OSN with a 1.5 m telescope with a B Johnson filter. The data obtained are under analysis. If the pulsating/non-pulsating rate is similar to that found for the sdBs, at least 1 or 2 new sdO pulsators are expected on the completion of the photometric study.

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References

[1] Humason, M.L., Zwicky, F. 1947, ApJ, 105, 85

[2] Greenstein, J.L. 1960 in *Stellar atmospheres*, University of Chicago Press

[3] Kilkenny, D., Koen, C., O'Donoghue, D., Stobie, R. S. 1997, MNRAS, 285, 640

[4] Green, R. F., Schmidt, M., Liebert, J. 1986, ApJSS, 61, 305

[5] de Boer, K.S. 1985, A&A, 142, 321

[6] Bica, E., Bonatto, C., Pastoriza, M. G., Alloin, D. 1996, A&A, 313, 405

[7] Brown, T. M., Ferguson, H. C., Davidsen, A. F., Dorman, B. 1997, ApJ, 482, 685

[8] Yi, S. 1997, Bull. of the American Astron. Soc., 29, 1407, 19112402

[9] Colin, J., et al. 1994, A&A, 287, 38

[10] Michaud, G., Bergeron, P., Wesemael, F., Fontaine, G. 1985, ApJ, 299, 741

[11] Moehler, S., Ritchtler, T., de Boer, K.S., Dettmar, R.J., Heber, U. 1990, A&A Sup. Ser., 86, 53

[12] Jeffery, C.S., Drilling, J.S., Harrison, P.M., Heber, U., Moehler, S. 1997, A&A Sup. Ser., 125, 501

[13] Dorman, B., Rood, R.T., O'Connell, R.W. 1993, ApJ, 419, 596

[14] Oreiro, R., Ulla, A., Pérez Hernández, F., MacDonald, J., García, R., Zapatero, M.R. 2004, in preparation

[15] Heber, U. 1986, A&A, 155, 33

[16] Saffer, R., Bergeron, P., Koester, D., Liebert, J. 1994, ApJ, 432, 351

[17] Ulla, A., Thejll, P. 1998, A&A Sup. Ser., 132, 1

[18] Han, Z., Podsiadlowski, Ph., Maxted, P.F.L., Marsh, T.R., Ivanova, N. 2002, MNRAS, 336, 449

[19] Heber, U., Reid, I.N., Werner, K. 2000, A&A, 363, 198

[20] Unglaub, K., Bues, I. 1998, A&A, 338, 75

[21] Elkin, V.G. 1996, A&A, 312, L5

[22] Koen, C., O'Donoghue, D., Kilkenny, D., Stobie, R. S., Saffer, R. A. 1999, MNRAS, 306, 213

[23] Billères, M., Fontaine, G., Brassard, P., Liebert, J. 2002, ApJ, 578, 515

[24] Oestensen, R., Solheim, J.-E., Heber, U., Silvotti, R., Dreizler, S., Edelmann, H. 2001, A&A, 368, 175

[25] Green, E. et al. 2003, ApJ, 583, L31

[26] Charpinet, S., Fontaine, G., Brassard, P., Dorman, B. 2002, ApJSS, 139, 487

[27] Charpinet, S., Fontaine, G., Brassard, P., Chayer, P., Rogers, F. J., Iglesias, C. A., Dorman, B. 1997, ApJ, 483, L123

[28] Chayer, P. 2003, ApJSS, in press

[29] Fontaine, G., Brassard, P., Charpinet, S., Green, E. M., Chayer, P., Billr̀es, M., Randall, S. K. 2003, ApJ, 597, 518

[30] Charpinet, S., Fontaine, G., Brassard, P., Dorman, B. 1996, ApJ, 471, 103

[31] Baglin, A., Vauclair, G. & The COROT team 2000, JApA, 21, 319

[32] Brassard, P., Fontaine, G., Billères, M., Charpinet, S., Liebert, J., Saffer, R. A. 2001, ApJ, 563, 1013

[33] Charpinet, S., Fontaine, G., Brassard, P. 2001, ASP, 113, 775

[34] Oreiro, R., Ulla, A., Pérez Hernández, F., Oestensen, R., Rodríguez López, C., MacDonald, J. 2004, ApJ, accepted

[35] Jimenez, R., MacDonald, J. 1996, MNRAS, 283, 721

[36] Christensen-Dalsgaard, J., Berthomieu, G. 1991, *Solar interiors and atmospheres*, ed., A: N: Cox, W. C. Livingston & M. Mathews (Univ. Arizona Press), 401

[37] Husfeld, D. 1987, *Proc. of the 2nd Conference on Faint Blue Stars*, Schenectady, NY, L. Davis Press, p.237

[38] Pritchet, C. 1984, A&A, 139, 230

[39] Kwitter, K. B., Congdon, C. W., Pasachoff, J. M., Massey, P. 1989, AJ, 97, 1423

[40] Schönberner, D. 1983, ApJ, 272, 708

[41] Iben, I. Jr., Tutukov, A.V. 1986, ApJ, 311, 753

[42] Brocato, E., Matteuci, F., Mazzitelli, I., Tornambẽ, A. 1990, ApJ, 349, 458

[43] Sweigart, A. V., Mengel, J. G., Demarque, P. 1974, A&A, 30, 13

[44] Gingold, R. A. 1976, ApJ, 204, 116

[45] Caloi, V., 1989, A&A, 221, 27

[46] MacDonald, J., Arrieta, S. 1994 *Hot Stars in the Galactic Halo*, Cambridge University Press, p. 238

[47] Lanz, T., Brown, T. M., Sweigart, A. V., Hubeny, I., Landsman, W. B. 2004, ApJ, 602, 342

[48] Webbink, R. F. 1984, ApJ, 277, 355

[49] Thejll, P., Ulla, A., MacDonald, J. 1995, A&A, 303, 773

[50] Williams, T., McGraw, J.T., Grashuis, R. 2001, PASP, 113, 490

[51] Williams, T., McGraw, J.T. 2001, PASP, 113, 94

[52] Stark, M. A., Wade R. A. 2003, ApJ, 126, 1455

[53] Dreizler, S., Heber, U., Werner, K., Moehler, S., de Boer, K. S. 1990, A&A, 235, 234

[54] Thejll, P., Bauer, F., Saffer, R. et al 1994, ApJ, 433, 819

[55] Bauer, F., Husfeld, D. 1995, A&A, 300, 481

[56] Heber, U. 1998, *Proc. of the conference UV Astrophysics. Beyond the IUE Final Archive'*, ESA, SP-413

[57] Greenstein, J.L. 1957, *Proc. of the 4th IAU Sym.*, Cambridge University Press, p. 179

[58] Bartolini, C., Bonifazi, A., D'Antona, F. et al. 1982, ApJSS, 83, 287

[59] Bartolini, C., Bernabei, S., Bruni, I. et al. 2001, Mem.S.A.It, 72, 4

[60] Piccioni, A., Bartolini, C., Bernabei, S. et al. 2002, *Proc. of the 1st Eddington Workshop*, ESA SP-485, p. 305

[61] Moya, A., Garrido, R., Dupret, M. A. 2004, A&A, 414, 1081