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The structure of extreme horizontal branch stars from asteroseismology

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Abstract. The rapidly pulsating subdwarf B stars (or EC 14026 stars) constitute excellent laboratories for detailed asteroseismic studies. Their relatively rich *p*-mode spectrum provides strong constraints on the main parameters that define the structure of these Extreme Horizontal Branch (EHB) stars. We present some of the structural properties of these stars that currently emerge from asteroseismology. We find, in particular, that these properties seem to follow (and thus confirm) expectations from standard evolution theory of EHB stars. Finally, we emphasize the strong potential of asteroseismology applied to EC14026 stars in solving some of the pending issues that still persist in our understanding of the evolution and formation of Extreme Horizontal Branch stars.

Key words. stars: interiors – stars: oscillations – stars: asteroseismology – stars: subdwarfs

1. Introduction

Subdwarf B stars dominate the populations of faint blue stars down to $V \sim 16$ and are found in both the old disk (field sdBs) and halo populations (globular cluster members) of our own Galaxy. They are the most likely source of the ultraviolet excess observed in elliptical galaxies (Brown et al. 1997) and have been identified with models for Extreme Horizontal Branch (EHB) stars burning He in their core and having extremely thin H-rich residual envelopes ($\lesssim 0.02\ M_{\odot}$).

A significant fraction of these stars have been discovered to pulsate (Kilkenny et al. 1997), showing multi-mode non-radial oscillations. About three dozen of the so-called EC14026 variables, with $T_{\rm eff} \sim$ 30,000–36,000 K and periods in the range 100 – 600 s, are now known. Very recently a group of longer-period sdB pulsators (the "Betsy" stars), with $T_{\rm eff} \sim$ 25,000–30,000 K and periods between 45 min and 2 h, has also been identified (Green et al. 2003). In both cases, the pulsations are

Send offprint requests to: S. Charpinet driven by an opacity peak in the sdB envelope mainly due to iron and enhanced by microscopic diffusion process (Charpinet et al. 1997, 2001; Fontaine et al. 2003) and are manifest as low-order, low degree p-modes and high order, relatively high degree ($\ell \gtrsim 3$) g-modes for EC14026 and Betsy stars, respectively.

It was quickly recognised by us that an adequate modelling of the EC14026 phenomenon would require special attention to diffusion processes. This led to the development of our so-called "2nd generation" models described in Charpinet et al. (1997, 2001) that implement the nonuniform profiles of iron (i.e., the main contributor to the opacity bump) predicted by the condition of diffusive equilibrium between gravitational settling and radiative levitation, a well justified assumption for sdB stars (see Fontaine et al., these proceedings). With such models, global theoretical properties of the EC14026 pulsators could be derived and, of course, confronted to the observed properties emerging from the evergrowing sample of known pulsators. To date, with almost three dozen known EC14026 variables, such comparisons continue to show remarkable similarities between the global properties of the modelled and observed pulsators, thus strongly suggesting that the basic ideas and physics behind the driving of pulsations in these stars are sound (Charpinet et al. 2006).

Short period hot B subdwarf pulsators have proved to be highly suitable for detailed asteroseismic studies. Illustrations of this potential has been given in Brassard et al. (2001), Charpinet et al. (2003), Charpinet et al. (2005a), and Charpinet et al. (2005b). Using our 2nd generation models, close matches of all periodicities, as well as the determination of fundamental structural parameters of the pulsating sdB stars PG 0014+067, PG 1047+003, PG 1219+534 and Feige 48 could be achieved using a new global optimization technique. Emphasis was put on the fact that microscopic diffusion, in addition of playing a fundamental role in driving the oscillations, must also be included in the models for accurate asteroseismic studies, as accumulations of iron in the envelope of the star significantly affect the pulsation periods themselves (see, again, Fontaine et al., these proceedings). In all cases, a mode identification (i.e. the radial orders k and degrees ℓ of the best matching modes) for the observed periods could also been derived.

2. EHB Stars As Seen Through Asteroseismology

Asteroseismic analyses of EC14026 stars using the global optimisation technique lead to determinations of the structural parameters of the stars under study. Four fundamental parameters are required to specify the internal structure of hot B subdwarf stars with the 2nd generation models. These are the effective temperature $T_{\rm eff}$, the surface gravity $\log g$, the total mass of the star M_*, and the logarithmic fractional mass depth of the hydrogen rich envelope $\log q(H) \equiv \log[M(H)/M_*] \simeq \log[M_{\rm env}/M_*]$, where $M_{\rm env}$ corresponds to the total mass of the H-rich envelope of the star (a more familiar parameter used in stellar evolution theory). The two latter parameters in particular, i.e., the total mass and the mass of the H-rich envelope, are quantities that cannot be measured directly with techniques other than asteroseismology (except in some rare cases for the parameter M_* in binary systems). Yet, their importance in the context of EHB stellar evolution and formation theories is crucial. Hence, systematic asteroseismic studies of EC14026 star are bound to bring new insight on these specific domains. Two interesting links with EHB stellar evolution and formation are illustrated below, based on current asteroseismic results.

2.1. EHB stellar structure and evolution

Figure 1 shows representative evolutionary tracks of extreme horizontal branch stars with various H-rich envelope masses (see figure for details) in a $T_{\rm eff} - \log[M_{\rm env}/M_*]$ diagram. The ZAEHB and TAEHB are indicated by dashed-lines (at low and high $T_{\rm eff}$, respectively). These sequences illustrate a well known property of evolutionary models near the ZAEHB which tend to have higher (lower) effective temperatures with thinner (thicker) H-rich envelopes, as the mostly inert envelope acts as an iso-

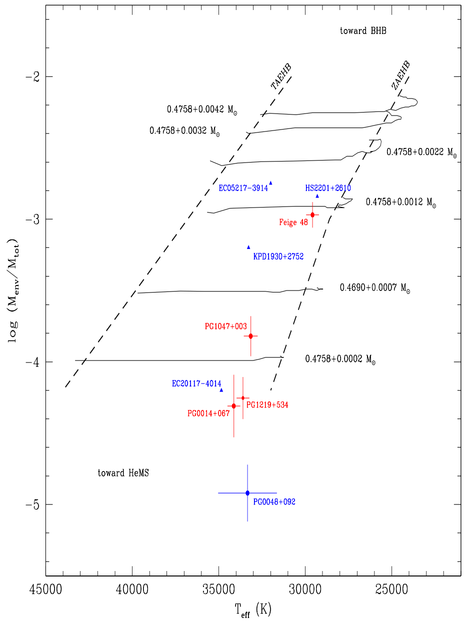

Fig. 1. $T_{\rm eff} - \log[M_{\rm env}/M_*]$ diagram. Evolutionary tracks are from Ben Dorman 1995, priv. comm.

lating layer between the helium core and the stellar surface. Asteroseismic measurements of the envelope mass should now allow us to check if this property, indeed, exists in real subdwarf B stars. Remarkably, this trend seems to be confirmed by the four EC14026 pulsators analysed in detail (PG0014+067, PG1047+003, PG1219+534, Feige 48; shown as red circles with error bars in Fig. 3). Preliminary (and thus still insecure) analyses of additional EC14026 stars (HS2201+2610, EC05217-3914, KPD1930+2752, EC20117-4014, and PG0048+092; blue triangles and circle with error bars) tend to confirm this conclusion. Nonetheless, more precise and additional asteroseismic measurements will be necessary to allow for a definitive conclusion on this issue.

2.2. EHB stellar formation scenarios

Figure 2 shows the distribution of the asteroseismic masses (with uncertainties) obtained

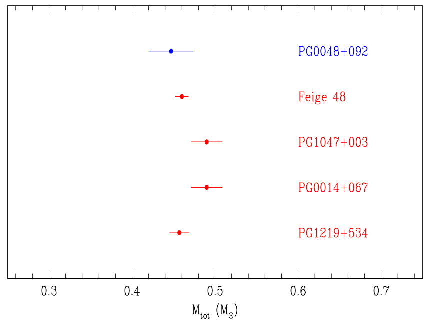

Fig. 2. Distribution of EC14026 star masses measured by asteroseismology.

for the four well studied EC14026 stars. A value derived for PG0048+092 is also given, although it should be considered as preliminary at this stage. The formation of Extreme Horizontal Branch stars remains one of the most acute issues that plague our understanding of this phase of stellar evolution. The main difficulty resides in understanding how such stars manage to loose all but a very small fraction of their H-rich envelope before reaching the quiet core He-burning phase typical of Horizontal Branch stars. Among the various channels proposed (from single and binary stellar evolution) to form extreme horizontal branch stars, some are expected to produce broader mass distributions than originally believed, with masses that could be as low as $\sim 0.30\ M_\odot$ and as high as $0.7\ M_\odot$ (see, e.g., Han et al. 2002, 2003). Quite interestingly, all the asteroseismically measured masses, so far, have values in the range $\sim 0.45 - 0.49\ M_\odot$, i.e., close to the canonical mass for extreme horizontal branch stars ($\sim 0.47\ M_\odot$; derived from standard single star evolution) with a very small dispersion.

Also of interest, one of the channels likely to form "low-mass" or "high-mass" EHB stars is the merger of two helium white dwarfs, which would also contribute to produce isolated sdB stars (as opposed to sdB's in binary systems). Three of the four EC14026 stars analysed in detail (namely, PG1047+003, PG0014+067, PG1219+534), indeed, are very likely single sdB stars. Their masses remain, however, close to the canonical value. This result might suggest that the merger scenario is not the dominant channel that forms single sdB stars. However, the mass distribution from the merger channel, although it spans a broader range, still has a dominant peak close to the canonical value. Hence, considering that the statistics are still very uncertain due to the small number involved, it is not yet possible to draw firm conclusions on this particular topic. Nonetheless, the potential of asteroseismology in solving such issues is obviously very high and asteroseismic mass measurements for more EC14026 stars will certainly bring interesting insight in this field.

3. Conclusions

For more than two decades, major efforts have been pursued in the community of stellar pulsations in order to reach the ultimate goal of asteroseismology, which is to exploit the information that is contained in the vibrations of pulsating stars to extract new information on the inner structure, physics, and evolution of stellar objects. This goal is close to be achieved for EHB stars, as the detailed study of rapid sdB pulsators has begun to reveal new fundamental elements of the structure of these objects that, so far, were known only through modelling based on standard stellar evolution theory.

As illustrated in this paper, systematic asteroseismic analyses of EC14026 stars, among other applications, open new opportunities to test the validity of stellar evolution theory applied to the helium core burning phase, and propose new ways of constraining the various scenarios that are envisioned to form extreme horizontal branch objects (a problem of stellar evolution theory that still needs to be solved). Hence, asteroseismology of EC14026 stars will constitute an essential instrument to improve further our knowledge of EHB stars in the future.

The technique of asteroseismology applied to rapid sdB pulsators is still in its infancy and more work is certainly needed to improve and check the models, the method and its predictions (the mode identification, for instance). Clearly, however, the high consistency of the solutions that could be achieved in the seismic analyses conducted so far indicate that the most basic ingredients of the models are correct and that the asteroseismic results obtained should be robust.

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