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THE STRUCTURE OF SUBDWARF B STARS AS REVEALED BY ASTEROSEISMOLOGY

S. Charpinet[1], G. Fontaine[2], P. Brassard[2], P. Chayer[3,4] and E. M. Green[5]

[1] *UMR 5572, Université Paul Sabatier et CNRS, Observatoire Midi-Pyrénées, 14 Av. Edouard Belin, F-31400 Toulouse, France*

[2] *Département de Physique, Université de Montréal, C.P. 6128, Succursale Centre-Ville, Montréal, QC, H3C 3J7, Canada*

[3] *Department of Physics and Astronomy, Johns Hopkins University, 3400 North Charles Street, Baltimore, MD 21218-2686, U.S.A.*

[4] *Primary affiliation: Department of Physics and Astronomy, University of Victoria, P.O. Box 3055, Victoria, BC V8W 3P6, Canada*

[5] *Steward Observatory, University of Arizona, 933 North Cherry Avenue, Tucson, AZ 85721, U.S.A.*

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Abstract. The rapid p-mode oscillations observed in EC 14026 stars offer interesting opportunities to constrain, with the tools of asteroseismology, the main parameters that define their internal structure. We present the structural properties of sdB stars that are emerging from our detailed asteroseismic studies. We find, in particular, that these properties seem to follow (and thus confirm) expectations from standard EHB stellar evolution. We also show that asteroseismology of EC 14026 stars should play a crucial role in solving the long-standing puzzle of the evolution mechanisms that lead to the formation of extreme horizontal branch stars.

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

1. FROM MODE DRIVING TO ASTEROSEISMOLOGY OF EC 14026 STARS

Since the first discovery of rapid oscillations in hot subdwarf B stars (these are referred to as the EC 14026 stars from the name of the prototype; Kilkenny et al. 1997) and the identification of an efficient driving mechanism to explain this phenomenon (Charpinet et al. 1996, 1997), substantial observational efforts from various groups (see the reviews of Charpinet 2001 and Kilkenny 2002) have raised significantly the number of known EC 14026 pulsators (34 at the time of this writing). The driving mechanism is a κ-effect triggered by the region of partial ionization of heavy elements, especially iron, in the envelope of the star. It can reach sufficient efficiency to destabilize modes because of the accumulation of iron in the driving region due to microscopic diffusion processes.

It was quickly recognized by us that an adequate modeling of the EC 14026

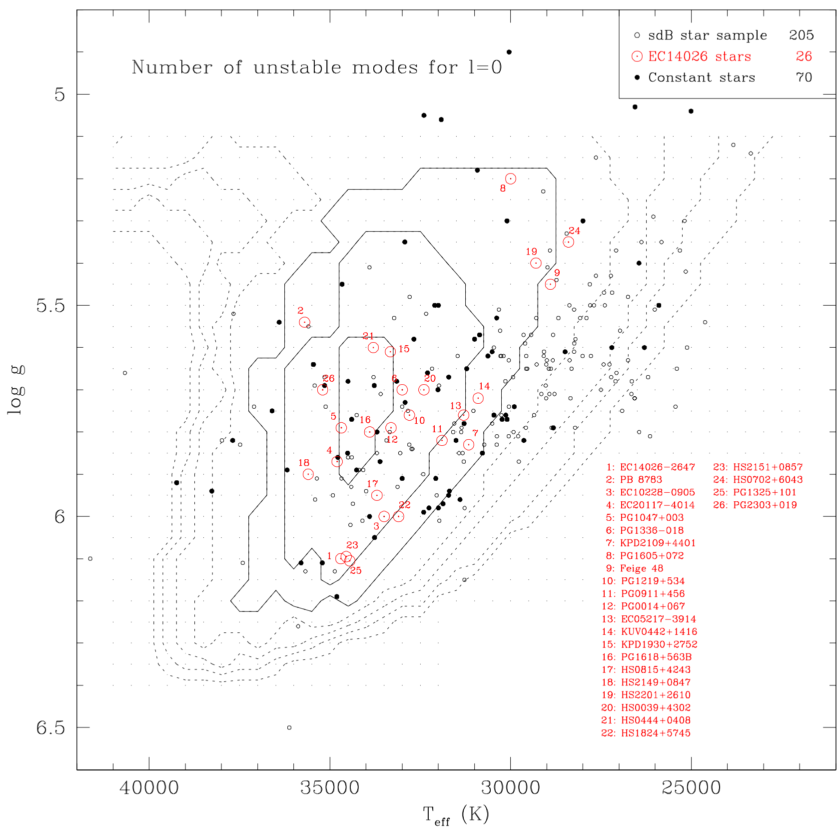

Fig. 1. Global comparison: the observed and predicted instability domain.

phenomenon would require special attention to such 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. With such models, global theoretical properties of the EC 14026 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 EC 14026 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. We illustrate below two aspects of these model/observation comparisons.

1.1. The theoretical instability region

Figure 1 represents the $\log g$ vs. $T_{\rm eff}$ plane where are positioned 26 (out of the 34 known) EC 14026 stars which have spectroscopic estimates of their atmospheric parameters available (shown as red dot-circles in the figure). Filled circles represent the 70 sdB stars observed with fast-photometry and found constant by Billères et al. (2002). As an illustration of the extent of the region where sdB stars are found, the sample of Saffer et al. (1994) is also shown as open circles. In addition, contours derived from full, non-adiabatic pulsation calculations based on the 2nd generation models are superimposed to the observations. These contours indicate the number of excited, $\ell = 0$ modes found in the models – a tracer of the efficiency of the driving mechanism – as a function of $\log g$ and $T_{\rm eff}$. Remarkably, *all* the 26 EC 14026 stars represented in this diagram are found within or slightly outside the three highest contours (shown as plain lines in Figure 1), i.e., where the driving is most efficient. Of course, this is precisely where one would expect to find the pulsators based on theory. Also, a closer look at Figure 1 indicates that the theoretical instability domain is wider than observed and that non-pulsators cohabitate with pulsators in the same $\log g$ vs. $T_{\rm eff}$ region, a property not expected from the 2nd generation models as they currently stand. Some of these issues, however, may be solved with further refinements in the modeling of the diffusion processes in sdB stars (see Fontaine et al. 2006).

1.2. The driven pulsation modes

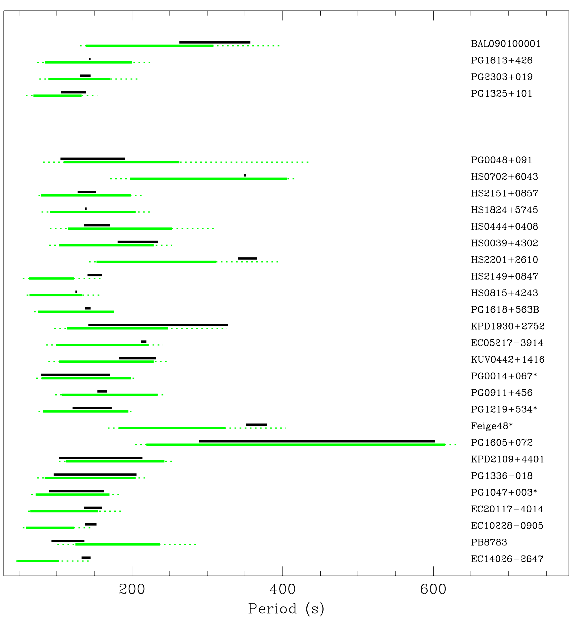

Fig. 2. Global comparison: the observed and predicted period ranges

Figure 2 provides a comparison between the observed period range (black segments) and the theoretical period range of the driven modes (green segments) for the EC 14026 stars with spectroscopic $\log g$ and $T_{\rm eff}$ measurements available. These were taken at face value to compute a representative 2nd generation model of each star from where the non-adiabatic pulsation properties could be derived. Considering the (sometimes large) uncertainties associated with the spectroscopic evaluations of the atmospheric parameters (which, in terms of the driven periods, translate into the dotted extensions of the green segments), we find that, so far, *all* EC 14026 stars, including outliers like PG 1605+072 or Feige 48 which have much lower surface gravities and longer periods than the other known pulsators, show periods that are within the expected range according to theory.

These basic observations underline the fact that a very strong overall consistency exists between the predicted properties of EC 14026 stars from the current 2nd generation models and the observed properties of the real pulsators.

2. DETAILED ASTEROSEISMIC STUDIES

The excellent global correspondence uncovered between theory and observation has strongly encouraged us to attempt modeling individual EC 14026 pulsators in detail. The ambition was: (1) to fully and accurately reproduce the observed pulsation period spectra based on the 2nd generation models, thus leading to a complete mode identification, and (2) to isolate the most accurate (or best-fitting) model (or family of models) that correspond to the star under study, hence bringing, for the first time, asteroseismic constraints to the stellar structure of Extreme Horizontal Branch (EHB) stars.

2.1. A global approach to asteroseismology

In the recent years, we have set up a new global approach to the problem of asteroseismology of EC 14026 pulsators. Inspired by the well known forward method, which simply consists of comparing directly theoretical periods from a model to the observed periods of a given star, our global optimization technique allows us to exhaustively and efficiently explore the vast model parameter space in order to isolate the model(s) that can best-match the period spectrum of the EC 14026 pulsator under study. Developed mainly in the context of interpreting white light fast-photometric data for which no a priori information on the mode identification exists, our procedure is a "double-optimization" scheme that simultaneously searches for the optimal combination of observed and computed periods (for a model with given parameters) and for the optimal set of model parameters. This method leads objectively to the best match of the observed periods, providing estimates of the structural parameters of the star and a complete mode identification (i.e., the ℓ and k indices) of the observed periods. More details on this method can be found in the pioneering paper of Brassard et al. (2001) and, more recently, in Charpinet et al. (2005a).

2.2. Asteroseismic analyses of EC 14026 stars

The global optimization technique has been applied to a handful of rapid pulsating sdB stars, so far. This includes the analysis of PG 0014+067 from the early work of Brassard et al. (2001), the analysis of PG 1047+003 (Charpinet et al. 2003), of PG 1219+534 (Charpinet et al. 2005a) and most recently of Feige 48 (Charpinet et al. 2005b). These studies were all based on high signal-to-noise white light photometry specifically gathered at the Canada-France-Hawaii 3.6 m telescope (CFHT) with the fast-photometer *Lapoune*. In addition, precise medium-resolution, high signal-to-noise spectroscopy from the MMT coupled with detailed atmospheric modeling has proved essential to isolate a unique best-fit model solution. In each case, it was possible to achieve a simultaneous fit of *all* the observed periods to $\sim 0.8\%$ and better. Moreover, in each case, the asteroseismic solutions appear fully consistent with expectations from non-adiabatic pulsation theory (all observed periods are assigned to modes predicted to be unstable), and the parameters derived for the best-fit model are entirely consistent with the spectroscopic values.

It is an important result that, for at least four stars analyzed in detail with asteroseismology so far, solutions could be achieved which can accommodate three different aspects of the modeling of rapid pulsating sdB stars, namely the pulsation period distribution, the excitation of the modes through the driving mechanism, and detailed model atmospheres. This was certainly not guaranteed at the outset and this provides strong additional support to the underlying ideas that explain the pulsations in EC 14026 stars, considering that we find that, so far, high consistency between models and observations is preserved even in the details.

3. LINKS TO EVOLUTION AND FORMATION THEORIES

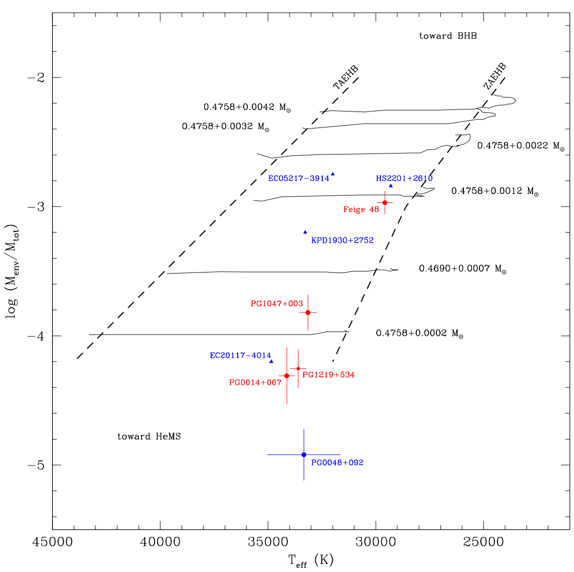

Fig. 3. $T_{\rm eff}$ vs. $\log{[M_{\rm env}/M_\star]}$ diagram. Evolutionary tracks are from Ben Dorman (1995, priv. comm.).

Asteroseismic analyses of EC 14026 stars using the global optimization 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 $M_\star$, and the logarithmic fractional mass depth of the hydrogen rich envelope $\log q(H) \equiv \log{[M(H)/M_\star]} \simeq \log{[M_{\rm env}/M_\star]}$, 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 EC 14026 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.

3.1. A link to extreme horizontal branch stellar evolution

Figure 3 shows representative evolutionary tracks of extreme horizontal branch stars with various H-rich envelope masses (see figure for details) in a $T_{\rm eff}$ vs. $\log{[M_{\rm env}/M_\star]}$ 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 isolating 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 EC 14026 pulsators analyzed in detail

(PG 0014+067, PG 1047+003, PG 1219+534, Feige 48; shown as red circles with error bars in Figure 3). Preliminary (and thus still insecure) analyses of additional EC 14026 stars (HS 2201+2610, EC 05217-3914, KPD 1930+2752, EC 20117-4014, and PG 0048+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.

3.2. A link to subdwarf B star formation scenarios

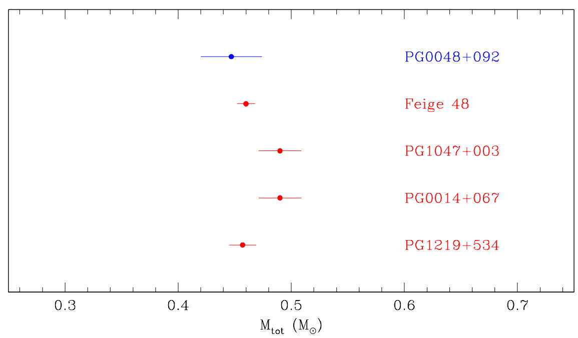

Fig. 4. Distribution of EC 14026 star masses measured by asteroseismology.

Figure 4 shows the distribution of the asteroseismic masses (with uncertainties) obtained for the four well studied EC 14026 stars. A value derived for PG 0048+092 is also given, although it should be considered as preliminary at this stage. Among the various channels (from single and binary stellar evolution) proposed 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, 2006). Quite interestingly, all the asteroseismically measured masses, so far, have values in the range 0.45–0.49 $M_\odot$, i.e., close to the canonical mass for extreme horizontal branch stars ($\sim 0.47\ M_\odot$; see, e.g., Dorman et al. 1993) 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 EC 14026 stars analyzed in detail (namely, PG 1047+003, PG 0014+067, PG 1219+534), indeed, are very likely single sdB stars. Their masses remain, however, close to the canonical mass. 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 EC 14026 stars will certainly bring interesting insight in this field.

4. CONCLUSIONS AND PROSPECTS

4.1. The future of asteroseismology of EC 14026 stars

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 about 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 modeling based on standard stellar evolution theory. As illustrated in this paper, systematic asteroseismic analyses of EC 14026 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, as surely as, yesterday, the advent of precise spectroscopy and model atmospheres have revolutionized our understanding of subdwarf B stars and have become, nowadays, essential tools to study the properties of these stars, asteroseismology of EC 14026 stars will, tomorrow, constitute an essential instrument to improve further our knowledge of EHB stars. 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.

4.2. The prospect of multicolor fast-photometry

One of the most promising avenues for future independent tests of the asteroseismic predictions resides in multicolor fast-photometry from which one has, in principle, the ability to identify the ℓ index of the pulsation modes from their amplitude ratios at different wavelengths. Theoretical efforts have been pursued recently (see Ramachandran et al. 2004; Randall et al. 2005) to accurately interpret multicolor data in the context of sdB pulsators. In parallel, a growing amount of effort is being devoted to multicolor observations (see, e.g., Jeffery et al. 2004). Such partial identification of the geometry of the modes would, of course, be extremely valuable to check, and possibly improve, the complete mode identification derived from the global optimization techniques. Along this line, we initiated several projects to carry out high S/N ratio UBV photometry of EC 14026 pulsators using the Canada-France-Hawaii Telescope in conjunction with the fast-photometer *Lapoune*. In addition, a project is underway to use the Far UV Spectroscopic Explorer (FUSE) as a fast photometer (a possibility offered by the so-called "Time-Tag" mode of the instrument) that would provide a light curve of the sdB pulsator PG 1219+534 in the FUV (~ 1000 Å) passband. Combined with nearly simultaneous ground based observations in the optical, this project should lead to strong independent constraints on the ℓ value of the modes seen in PG 1219+534, from which the predicted mode identification will be checked.

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