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The need for radiative levitation for understanding the properties of pulsating sdB stars

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Abstract. We emphasize the central role that radiative levitation plays in accounting for the very existence of the short-period pulsating EC 14026 stars as well as of the long-period PG 1716 ("Betsy") stars. Standard models of sdB stars with uniform solar metallicity are unable to excite pulsation modes. In contrast, models which incorporate radiative levitation of iron are quite successful (especially for the EC 14026 stars) at reproducing the locations of the real pulsators in the surface gravity-effective temperature plane. In addition, radiative levitation (through its important effects on the Rosseland opacity profile) changes significantly the structure of the envelope of a sdB model, to the point where the pulsation periods are affected. We thus find that quantitative asteroseismology of pulsating sdB stars is not possible without including this key ingredient of constitutive physics.

Key words. Stars: oscillations – Stars: diffusion – Stars: hot subdwarfs

1. Introduction

Hot subdwarf B (sdB) stars are evolved, hot (20,000 K $\lesssim$ $T_{\rm eff}$ $\lesssim$ 40,000 K), and compact (5.0 $\lesssim$ log g $\lesssim$ 6.2) stars that populate the extreme horizontal branch (EHB; Saffer et al. 1994). After a few 10^8 yrs of evolution near the EHB, they ultimately collapse into low-mass white dwarfs without going through the AGB phase (Dorman et al. 1993; Bergeron et al. 1994). All of them are also chemically peculiar, and it is believed that diffusion processes (gravitational settling, ordinary diffusion, radiative levitation) competing with weak stellar winds are responsible for their observed abundance anomalies (see, e.g., Michaud et al. 1985).

Standard evolutionary models with solar and uniform metallicity are unable to explain the very existence of the two distinct classes of pulsating sdB stars uncovered recently: that of the short-period (100–200 s), p-mode pulsators of the EC14026 type (Kilkenny et al. 1997), and that of the long-period (3000–8000 s), g-mode pulsators of the Betsy star type (Green

Send offprint requests to: G. Fontaine et al. 2003). To account for their existence, it was necessary to construct improved, "second-generation" models of sdB stars by postulating the state of diffusive equilibrium between gravitational settling and radiative levitation of Fe in their envelope. This led to local accumulations of Fe in the driving region, boosting the local opacity and inducing further driving through the κ-mechanism, enough to overcome global damping and excite pulsation modes (Charpinet et al. 1997; Fontaine et al. 2003).

These more sophisticated models, with highly nonuniform envelope metallicity, have been quite successful at explaining qualitatively the ranges of observed periods and the locations of the pulsators in the log g–$T_{\rm eff}$ diagram. Quantitative agreement has also been achieved for many EC14026 pulsators (see, e.g., Charpinet et al. in these proceedings). Despite these successes, one obvious question has remained unanswered so far: How well is this equilibrium approach justified? The answer can only come from time-dependent calculations, and we provide here some results of such exercises.

2. The Approach to Diffusive Equilibrium

We carried out detailed time-dependent diffusion calculations to study the evolution of the Fe distribution in typical models of sdB stars. In this, we followed the approach discussed briefly in Chayer et al. (2004). Figure 1 shows the evolving distribution of Fe in the envelope of a representative model of a sdB star in presence of diffusion, starting with a uniform and solar abundance of Fe. This initial distribution at time t=1 yr is represented by the horizontal red line. As time goes by, and starting at the surface because the diffusion speed is largest there, the abundance of iron reaches an equilibrium value specified by the equality between the local radiative acceleration and the local effective downward gravitational acceleration. Hence, a nonuniform equilibrium profile of Fe is created from the surface downward.

This buildup with time of a truly levitating reservoir of Fe is represented by the heavy black curve in the figure. Note that the number

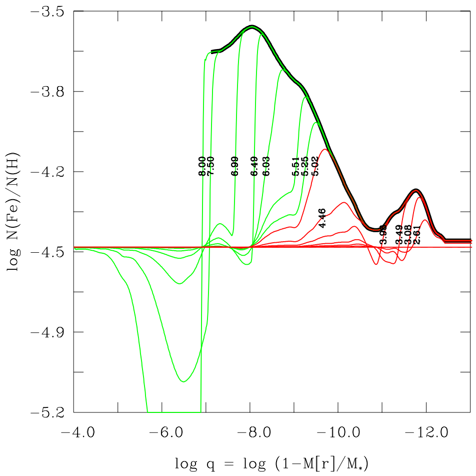

Fig. 1. The approach to diffusive equilibrium: the evolving distribution of the Fe abundance in the envelope of a typical sdB model characterized by M = 0.5 $M_\odot$, $T_{\rm eff}$ = 30,000 K, and log g = 5.5.

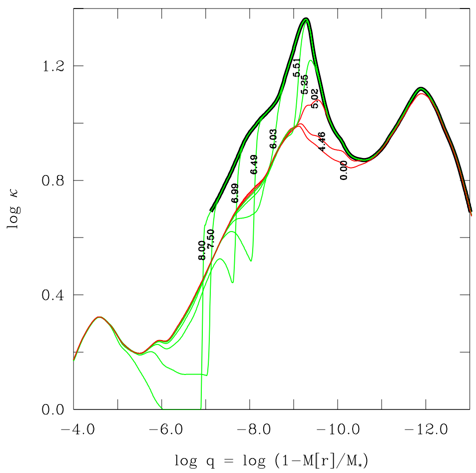

Fig. 2. The approach to diffusive equilibrium: the evolving distribution of the Rosseland opacity in the envelope of the same model as in Fig. 1.

associated with each profile gives the logarithmic value of the age of that distribution. For example, the profile labelled 8.00 gives the actual distribution of iron after 10^8 years of evolution. Note also that radiative levitation can only occur in those regions of the star where the radiative acceleration exceeds the local effective gravity. In the deeper layers illustrated here, Fe cannot levitate and sinks with time, thus creating a gap below the reservoir of levitating Fe atoms. Note furthermore that there is a color code in the figure: models in red cannot excite pulsation modes, while models in green have accumulated enough extra Fe in the driving region to excite such modes. After a little more than 10^5 yrs only, which is quite short compared to a typical sdB lifetime of a few 10^8 yrs, many pulsation modes can be excited.

Figure 2 shows the associated temporal evolution of the opacity profile. We plotted a smaller number of profiles here than in the previous graph in order not to clutter too much the diagram. The driving mechanism in pulsating sdB stars is a κ-mechanism associated with the partial ionization of the K-shell electrons in Fe. This corresponds to the 2nd bump in opacity from the surface, sometimes also called the Z bump. Notice that at time t=1 yr (the red profile labelled 0.00), this iron opacity bump is not large enough to excite pulsation modes. It is only with the accumulation of enough Fe atoms in the driving region that the opacity can exceed a critical value for exciting pulsation modes. The heavy black curve gives the equilibrium distribution of the opacity.

It is also quite enlightening to follow the evolution of the period spectrum itself as a function of time. Hence, in Figure 3, we show the low-order segment of the p-mode pulsation spectrum of the model for modes with values of the degree l = 0, 1, and 2. This is particularly of interest for the EC14026 stars. The bottom spectrum corresponds to that of the initial model at time t=1 yr with a uniform and solar Fe abundance. None of these modes are excited as indicated by the red color. With passing time, and rather quickly at that relative to the typical lifetime of a sdB star, some modes (in green) and then more modes can be driven through the buildup of Fe in the driving region.

It is very interesting to note that the evolving iron profile changes the structure of the envelope significantly enough so that, as can be seen, the periods also change significantly. In particular, it should be clear that, for quantitative asteroseismology, models with uniform and standard solar abundances are totally inadequate. The shifts in periods between the initial spectrum and the one at 10^8 years are simply too large. At the same time, one can notice that there is a convergence to some sort of "equilibrium" period spectrum in the last phases of the evolution (and remember the logarithmic scale of the ages listed here). This is easily explained by the fact that the p-modes are essentially envelope modes in sdB stars, and what is happening in the very deep envelope, in the Fe gap in particular, seems immaterial for those modes.

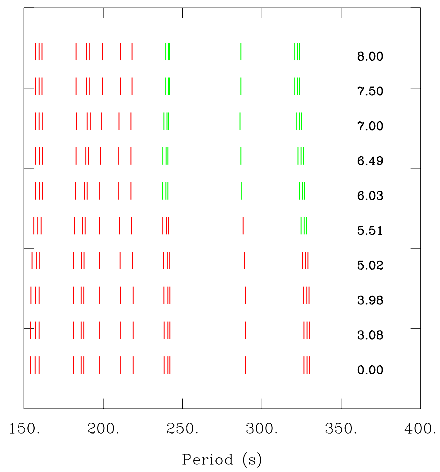

Fig. 3. The approach to diffusive equilibrium: the evolving period spectrum for modes with l = 0, 1, and 2 in the period range 150–400 s ($k \geq 0$).

Finally, Figure 4 shows the evolution of the surface abundance of Fe. This illustrates the often-forgotten fact that, in presence of diffusion, the observable abundance of a given element may not tell us much about what is happening inside. Note that the equilibrium surface abundance of Fe is very very quickly reached and, in this particular model and by accident, the equilibrium abundance is close to solar.

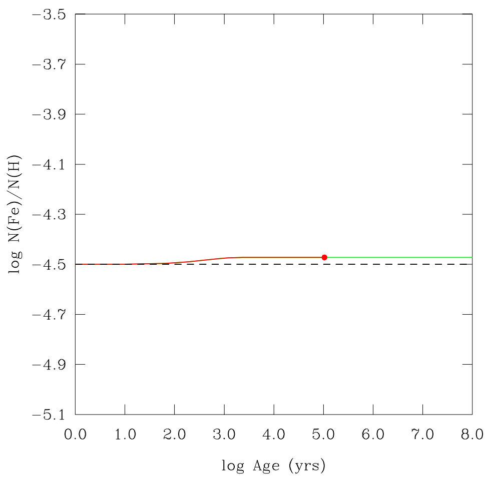

Fig. 4. The approach to diffusive equilibrium: the evolving surface (observable) abundance of Fe.

3. Conclusions

1) Radiative levitation is an essential ingredient in the mechanism responsible for exciting pulsation modes in sdB stars. Standard equilibrium models with uniform and solar metallicity are unable to drive pulsation modes.
2) The "equilibrium approach", whereby one assumes a Fe profile obtained by the equality between the radiative acceleration and the local effective gravity in the driving region, is generally valid. The timescale for reaching this equilibrium state is very short compared to the lifetimes of sdB stars on and near the EHB.
3) Quantitative asteroseismology of sdB stars cannot be seriously attempted with models that ignore radiative levitation since the latter also has a significant impact on the values of the periods themselves.

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