Part 7

Chemical composition of variable stars

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Element stratification in main sequence stars and its effect on stellar oscillations

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Abstract. Element settling due to the combined effects of gravity, thermal gradient, radiative acceleration and concentration gradient may lead to important abundance variations inside the stars that cannot be neglected in the computation of stellar structure. These processes were first introduced to account for abundance anomalies in "peculiar stars", but their importance in the so-called "normal" stars is now fully acknowledged, specially after the evidence of helium settling in the Sun from helioseismology. These microscopic processes work in competition with macroscopic motions, such as rotation-induced mixing or mass loss, which increase the settling timescales. We have recently obtained clear evidence that asteroseismology of main sequence solar-type stars can give signatures of the chemical variations inside the stars and provide a better understanding of these processes.

1. Introduction

It is clearly admitted nowadays that the element abundances observed in stellar outer layers by spectroscopy do not necessarily reflect the chemical composition inside the stars. This composition may be altered by microscopic diffusion or by accretion, modulated by the macroscopic motions which may occur below the outer convective zones, namely rotation-induced mixing, internal waves or mass motions induced by stellar winds

The importance of element settling inside stars (also called "microscopic diffusion") was first recognized as an explanation for the so-called "chemically peculiar stars" (Michaud 1970; Michaud et al. 1976; Vauclair et al. 1978a,b). At that time, it was presented as "the diffusion hypothesis", which appeared as a special process added in some cases to account for stellar abundance peculiarities. The fact that element settling is a fundamental process which must occur in most stars, including the so-called "normal" stars, has been proved by helioseismic investigations (Gough et al. 1996). It has been known for a long time that helium and metals should have diffused by about 20% down from the solar convective zone since the birth of the Sun (Aller & Chapman 1960). Comparison between the sound velocity inside the Sun as computed in the models and as deduced from the inversion of seismic modes confirmed that this settling has really occurred.

Element settling is now introduced in most computations of stellar models as a "standard process". A star is a self-gravitating gaseous sphere, composed

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of a mixture of various gases with different partial pressures, masses and atomic spectra. Due to the pressure and thermal gradients and to the selective radiative transfer, individual elements diffuse with respect to each other, leading to a slow but effective restructuring. It is more difficult, in this framework, to understand why the consequences of diffusion processes are not seen in all the stars, than to explain abundance anomalies. It is also not easy to account for the fact that, in chemically peculiar stars, the observed anomalies are not as strong as predicted by the theory of pure microscopic diffusion: these questions are related to the hydrodynamical processes which occur in stellar radiative zones and compete with element settling, thereby increasing the timescale of abundance variations.

In the following sections, I will discuss the interaction between element settling and stellar oscillations in two parts: 1) element settling as a stabilizing or an exciting process for triggering stellar oscillations; 2) asteroseismology as a test of element settling inside stars.

2. Element settling as a stabilizing or an exciting process for triggering stellar oscillations

Variations of the chemical composition insides the stars, which result from element settling, can in some cases lead to the stabilization of layers which would otherwise trigger oscillations (e.g., helium depletion in Am stars). In other cases this can help destabilizing a star which would otherwise be stable against pulsations (e.g., iron accumulation in some peculiar stars, or helium diffusion in roAp stars).

2.1. Generalities about element settling and radiative accelerations

Inside the convective regions, the rapid macroscopic motions mix the gas components and force their abundance homogenization. The chemical composition observed in the external regions of cool stars is thus affected by the settling which occurs below the outer convective zones, while in hot stars diffusion occurs directly in the atmosphere, which may lead to abundance gradients or "clouds" in the spectroscopically observed region. As the settling timescales vary, to first approximation, like the inverse of the density, the expected variations are smaller for cooler stars which have deeper convective zones. While some elements can see their abundances vary by several orders of magnitude in the hottest Ap stars, the abundance variations in the Sun are not larger than a few 10%.

While gravitational settling and thermal diffusion lead to a downward motion of all the elements other than hydrogen, selective radiative transfer may push some elements upwards. This is due to the fact that the elements absorb photons which basically come from the internal layers of the star and re-emit these photons in an isotropic way, thereby gaining a net momentum upwards. This absorption may take place through the continuum (ionization) or through the lines (excitation of the ions). In practice the line process is much more significant than the continuum.

Radiative accelerations on individual ions strongly depend on their atomic characteristics, which have to be precisely known. They also depend on the sharing of the photon flux with the other elements. This represents the same kind of problem as those encountered for the computations of stellar opacities.

This is the reason why the most precise computations presently done on radiative accelerations are the result of collaborations between stellar physicist specialists of diffusion processes and atomic physicist specialists of opacity computations.

The importance of the radiative accelerations on individual elements increase with effective temperature (Michaud et al. 1976). While this is negligible for the Sun (Turcotte et al. 1998), it becomes larger than the gravity for most elements in hotter stars (Alecian, Michaud & Tully 1993; Turcotte, Richer & Michaud 1998; Richer et al. 1998, Turcotte et al. 2000). The Montreal models are presently the only ones which include step by step in the computations the modification of the stellar internal structure induced by the abundance variations. Approximation formulae for the general computations of radiative accelerations have been derived by Alecian & LeBlanc (2000, 2002).

The radiative accelerations on the elements vary with depth, according to their ionization stage. It may happen to be smaller than gravity at some depth and larger than gravity below. In this case there is an accumulation of the considered element at that special depth, even if it is depleted in the outer layers. This is the case, for example, for Fe inside B, A and F stars (Richard, Michaud & Richer 2001; Richard et al. 2002). It is then possible that a new convective zone, due to this Fe accumulation, takes place inside the star, thereby changing the way diffusion processes behave. Note that the same phenomenon occurs in horizontal branch stars and is supposed to be the reason for the oscillations of sdBV stars (Charpinet et al. 1997).

2.2. Am versus δ Scuti stars

Among the main sequence stars that lie inside the instability strip, many chemically peculiar stars are found. The magnetic stars will be discussed below. Here I focus on the Am stars, which are found in the HR diagram at the same place as the δ Scuti stars. Generally speaking, the former show abundance peculiarities, namely a general overabundance of metals (except calcium and scandium), but no oscillations, while the latter are pulsating, but chemically normal. As discussed by Turcotte et al. (2000), in A-type stars, almost 70% of non-chemically peculiar stars are δ Scuti variables at current levels of sensitivity, while most non-variable stars are Am stars. Furthermore, Am stars are slower rotators than δ Scuti stars. This led Baglin (1972) to suggest a dichotomy between the two kinds of stars. In this region of the HR diagram the stars display two different convective zones in their outer layers: the upper one due to H I and He I ionisation and the lower one to He II ionisation. The δ Scuti stars pulsate due to a κ-mechanism which takes place in the second convective zone. When microscopic diffusion occurs this convective zone disappears due to helium depletion and the κ-mechanism cannot take place anymore (Vauclair, Vauclair & Pamjatnikh 1974).

More recently, however, some oscillating Am stars have been discovered (Kurtz 1989; Kurtz et al. 1995; Martinez et al. 1999; Joshi et al. 2002) which challenge the previously accepted theory. Richer, Michaud & Turcotte (2000) and Turcotte et al. (2000) computed models of Am stars in the framework of the Montreal models. They found that due to the iron accumulation in the radiative zone below the H and He convective zone, a new convective region appears which increases the diffusion timescales compared to the previous models. In these new

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models helium is still substantially present in the helium convective zone at the ages of the considered stars. They claim that it is possible to account for the existence of oscillating Am stars close to the cool boundary of the instability strip. In all these computations the different convective zones are assumed to be completely connected by overshooting. This assumption, first proposed by Latour et al. (1976) and Toomre et al. (1976), is still supported by recent numerical computations (Toomre, private communication).

2.3. Rapidly oscillating Ap stars

Rapidly oscillating Ap (roAp) stars are very complex objects, due to their magnetic structure (Kurtz 2000). The models which have been proposed up to now are much too simple to be able to account for all their features. Dolez, Gough & Vauclair (1988) and Vauclair, Dolez & Gough (1991) proposed that the oscillations in roAp stars could be driven by κ-mechanism in the He II ionisation zone. As helium is always depleted by diffusion, the idea was that a wind could exist at the magnetic poles, creating a helium overabundance. This model was supposed to be the continuation for cool stars of the model proposed by Vauclair (1975) to account for helium rich stars. In cooler stars, the accumulation should not be visible in the atmosphere, but it should still occur at the place where helium becomes neutral (first ionisation zone). As the κ-mechanism is driven by the second ionisation zone, the helium accumulation could be efficient only if it was large enough so that its downward wing could appreciably extent down to this region.

This model for roAp stars has been challenged by Balmforth et al. (2001), who computed the driving of the modes with different helium profiles at the magnetic poles and equator. They found that, contrary to what was assumed before, a helium accumulation induced by diffusion in a wind does not help driving the pulsations. On the contrary, the excitation of the modes is more important when there is less helium in the atmosphere, the basic driving mechanism being induced by hydrogen ionization (this was already suggested by Dziembowski & Goode 1996). Meanwhile the magnetic equator damps the oscillations due to energy loss by turbulence in the remaining convection zone: this could explain why oscillations aligned with the magnetic axis are preferentially excited in these stars. In this respect, recent spectroscopic observations that show evidence of abundance stratification in roAp stars, which is not seen in noAp stars, may give interesting clues (Gelbmann et al. 2000; Ryabchikova et al. 2002).

3. Asteroseismology as a test of element settling inside stars

3.1. The solar case

Owing to helioseismology, the sound velocity inside the Sun is known with a precision of $\sim$0.1% and gives evidence of the occurrence of helium settling as predicted by diffusion computations. Solar models computed in the old "standard" way, in which the element settling is totally neglected, do not agree with the inversion of the seismic modes. This result has been obtained by many authors in different ways (see Gough et al. 1996 and references therein). There is a characteristic discrepancy of a few percent, just below the convective zone, between the sound velocity computed in the models and that of the seismic Sun. Introducing element settling considerably improves the consistency with the seismic Sun, but some discrepancies still remain, particularly below the convective zone where a peak appears in the sound velocity. The reason for this peak is probably due to the steepness of the μ-gradient induced by pure microscopic diffusion (Richard et al. 1996). The helium profiles directly obtained from helioseismology (Basu 1997, 1998; Antia & Chitre 1998) show indeed a helium gradient below the convective zone which is smoother than the gradient obtained with pure settling. Introduction of macroscopic motions in competition with the settling slightly smoothes down the helium gradient, and may rub out the peak, although some differences still remain between the models and the seismic inversion results (Brun, Turck-Chièze & Zahn 1999; Richard, Théado & Vauclair 2003).

Such motions are also needed to reproduce the observed abundances of light elements, namely a Li depletion by about 140 compared to the protosolar value while Be is normal (Balachandran & Bell 1998). Furthermore, observations of the ^{3}He/^{4}He ratio in the solar wind and in the lunar rocks (Geiss & Gloecker 1998) show that this ratio may not have increased by more than ~10% in the sun during the past 3 Gyr. While the occurrence of some mild mixing below the solar convective zone is needed to explain the lithium depletion and helps reconcile the models with helioseismic constraints, the ^{3}He/^{4}He observations put a strict constraint on its efficiency. The effect of μ-gradients on the mixing processes has to be invoked to explain these observations in a consistent way.

3.2. Solar-type stars

Oscillations of solar-type stars have already been observed from ground-based instruments (Bouchy & Carrier 2003). Future space missions, such as Corot and Eddington, will yield important new data. We have begun to study the oscillations of stellar models that both include and do not include diffusion or metal accretion with the aim to test special signatures of these processes. The models are iterated so that their external parameters (T_{eff}, L, $\log g$, metallicity) are the same, while their histories, and accordingly their present internal structures, are different. Complete results will be presented elsewhere (Théado et al. 2004; Bazot & Vauclair, these proceedings). Here we show some preliminary results: Fig. 1 displays evolutionary tracks for 1.2 $M_\odot$ stars, with and without diffusion, iterated so that the outer stellar parameters remain quite similar (Castro 2003). Oscillation frequencies have been computed for the models corresponding to the crossing point, which have the same luminosity and temperature: $\log(L/L_\odot) = 0.388$ and $\log(T_{eff}) = 3.8$. Fig. 2 displays for the two models the "second differences", namely $\nu_{n+1} + \nu_{n-1} - 2\nu_n$. As pointed out by Gough (1990), these second differences present characteristic oscillations due to the partial reflection of the sound waves on the regions of rapid variations of the sound velocity. Fig. 2 shows clearly that they differ in the two models. Detailed analyses of all these effects is presently underway.

From these preliminary results, we may expect that the detailed observations and analyses of the oscillations of solar type stars will give clear signatures of diffusion processes in their interiors.

A fascinating new era is now opening in asteroseismology and stellar physics!

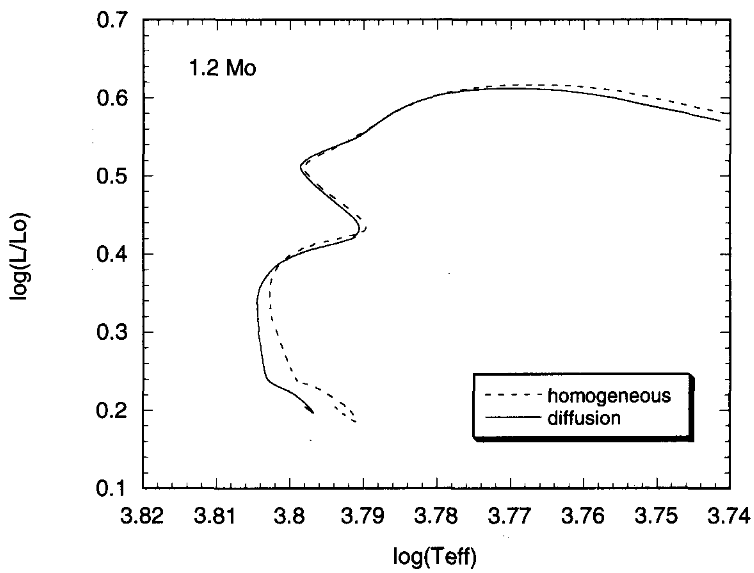

Figure 1. Evolutionary tracks of two 1.2-$M_{\odot}$ stars, with and without diffusion, iterated so that their outer (observable) parameters look the same; their internal structure is different and this difference may be tested by studying the oscillation frequencies (after Castro 2003).

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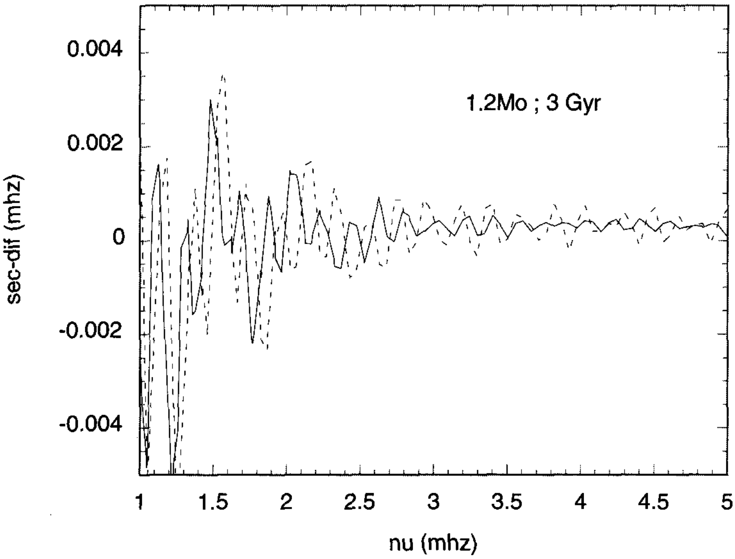

Figure 2. Second differences (see text) for the two models corresponding to the crossing of the tracks (Fig. 1); we can see that they have different variations, which is attributed to a different internal structure; such effects will be precisely analysed in a forthcoming paper

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Discussion

Aerts: What would be the timescale for settling of Fe near the driving zone around 200 000 K in 10-$M_{\odot}$ main-sequence stars with slow rotation? Is it possible at all to get an increase of iron due to radiative diffusion?

Vauclair: The computations have to be done and the time scales very much depend on the competition behaviour between selective settling and macroscopic motions (rotation-induced mixing and mass loss). But my guess is that it is quite possible that Fe abundance can be increased in a sensible way.

Shibahashi: If the roAp oscillations are induced by the hydrogen κ-mechanism associated with helium depletion, do you expect that the helium diffusion is observationally confirmed by seeing which modes are selectively excited in roAp stars?

Vauclair: Yes, we intend to do computations to check whether the induced helium gradient inside these stars could be detectable from the oscillation frequencies.

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