Part 2.3. Chemically Peculiar Stars

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Chemical Inhomogeneities and Pulsation[1]

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Abstract. Major improvements in models of chemically peculiar stars have been achieved in the past few years. With these new models it has been possible to test quantitatively some of the processes involved in the formation of abundance anomalies and their effect on stellar structure. The models of metallic A (Am) stars have shown that a much deeper mixing has to be present to account for observed abundance anomalies. This has implications on their variability, which these models also reproduce qualitatively. These models also have implications for other chemically inhomogeneous stars such as HgMn B stars which are not known to be variable and λ Boötis stars which can be. The study of the variability of chemically inhomogeneous stars can provide unique information on the dynamic processes occurring in many types of stars in addition to modeling of the evolution of their surface composition.

1. Introduction

Chemical composition plays an important role in determining the structure of stars. Its influence comes mostly through the sensitivity of opacities on the atomic spectra and absorption features of the elements making up a star. As most variable stars are unstable precisely because of how opacity behaves in relation to perturbations (the κ-mechanism), it stands to reason that chemical composition is of fundamental interest when studying pulsating stars.

Not only does the effect of the bulk metallicity of stars need to be considered but the effect of composition gradients (*a.k.a.* chemical inhomogeneities) on stellar pulsations has to be investigated, and that has been done only crudely so far. The difficulty lies in that, in order to model chemically inhomogeneous stars properly, it is indispensable to be able to calculate opacities correctly. Standard opacity tables can follow gradients of the major constituents but not of individual elements. While valid in most cases, these tables are not adequate in stars in which substantial departures from a homogeneous composition occur and in which the total metallicity Z does not reflect accurately the opacity of the actual chemical composition everywhere in the star.

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In recent years some models have tackled those issues. For example, Charpinet et al. (1996) have used an approach in which the influence of the variation of a specific element, iron in their case, is followed. They were able to predict that sdB stars should be variable and that diffusion of iron was able to provide the necessary abundance and opacity enhancements. Another more ambitious approach is to model stars in a consistent fashion using detailed monochromatic opacities for all important elements and a full treatment of diffusion (Richer et al., 2000 and references therein). Such models allow a detailed study of chemically inhomogeneous stars, both in terms of surface abundance anomalies and in terms of stellar pulsations for a wide range of stellar types and evolutionary stages.

Simultaneously, the need for such work has been underlined by the increasing number and types of chemically peculiar stars (hereafter CP stars) which are now recognized as variable. In the past, there was an apparent dichotomy between pulsations and peculiar compositions in stars with only a few exceptions (Kurtz, 1978). Models of the time, including only the effect of hydrogen and helium abundance gradients, were mostly in agreement with the observations (Cox et al., 1979). The discovery of new classes of variable CP stars, roAp stars by Kurtz & Wegner (1979) and λ Boötis stars by Gonzalez et al. (1998), and the constant additions to the δ Delphini class of variable evolved metallic A stars (Kurtz, 2000 and references therein) showed the dichotomy to be at least partly an illusion.

2. Chemical inhomogeneities in stars

CP stars are identified and defined by their observed surface abundances. However the connection between surface abundances and internal abundance profiles depends on how and where mixing occurs in the star as well as which process or processes are causing the surface chemical peculiarities. As stellar pulsations depend on the internal profile, one must be wary of jumping to conclusions based solely on surface abundances when studying CP stars.

The most prevalent ways of modifying the surface composition in a star are: 1) differential effects of microscopic diffusion (Richer et al., 2000), 2) dredge-up of matter from the deep interior through mixing or mass loss (Fowler et al., 1965), 3) accretion of matter affected by dust formation (Venn & Lambert, 1990) or nucleosynthesis (Guthrie, 1971), 4) differential mass loss where some elements are ejected and others not (Babel, 1996). The connection between the surface abundances and internal profiles are essentially determined by whatever mixing exists in the superficial regions of the star for all these processes. Some of these processes, however, are expected to be active mostly in young stars (accretion) while others are expected to have an effect only later on (dredge-up).

It is assumed that convective motions are fast enough to mix convection zones instantaneously, thereby homogenizing its composition and diluting any influx or out flux of matter in its entirety. In addition, there is ample evidence that further mixing occurs in the stable region below the convection zone. The composition observed at the surface extends therefore to the base of this fully mixed region. In cool stars this region is very deep, in hot stars there might not be any significant mixed region at the surface. Below the mixed region

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the abundances can be very different from those observed at the surface. As a result, surface abundances are a test of the depth of the superficial mixing while seismology can potentially allow the study of mixing below this mixed region.

3. Pulsations in CP stars

As the chemical composition changes in a star so will the opacity profile. Variations of the composition will affect mainly the κ-mechanism for driving pulsations, although they may have indirect consequences for other mechanisms, such as the one proposed for γ Doradus stars (Guzik et al., 2000). I will concentrate here on stars were the κ-mechanism dominates.

There are three regions in a star where opacity gradients occur that can lead to the excitation of pulsations. There is one due to the ionization of HI at low temperatures (roughly 10 000 K), one due to the ionization of HeII (40 000 K) and the last one due to the opacity of heavy elements, mainly iron-peak elements, at around 200 000 K. Not all three contribute significantly to excitation or damping in all stars but in CP stars one can expect large variations in their relative contributions to the net excitation of pulsations compared to chemically normal stars.

3.1. Diffusion and pulsations

Diffusion has been shown to have a major effect on the composition of slowly rotating A and the cooler B stars. Of the types of stars for which diffusion has the largest effects, two are particularly interesting in the present context. Am stars are A type stars enriched in iron-peak elements and HgMn stars are their more massive (B type stars) counterparts, which feature varying composition anomalies especially in manganese and/or mercury. There is a strong dichotomy between pulsations and the CP phenomenon in those stars, except for the aforementioned δ Delphinis, which are thought to be evolved Am stars.

The A stars have been modeled by Richer et al. (2000) and their stability was investigated by Turcotte et al. (2000). The major effect of diffusion in A stars in terms of pulsations is to reduce the helium abundance in superficial regions, thereby decreasing the excitation of the modes typical of variable A stars. The models, however, show that superficial mixing must be very deep for the models to reproduce surface abundance anomalies. The consequence of this deep mixing is to preserve some helium in the driving region.

Figure 1 shows the relative contribution of major elements in a star of 1.8 $M_\odot$ as a function of temperature. Two models are plotted, one with a standard solar composition (Grevesse & Noels, 1993), and one representative of an Am star. It shows that the opacity in the driving region for δ Scuti-like pulsations (HeII) actually increases as the result of diffusion but that the contribution of helium decreases. As the driving is provided by the opacity "hump" due to helium at 40 000 K, the relative disappearance of helium levels the opacity gradient and removes much of the driving. The more helium settles out of this region, the less likely is the star to become variable. The increase in the contributions of hydrogen and metals play little role in these stars. However, there are suggestions that metals may contribute significantly to the variability of Ap stars (Michaud et al., these proceedings).

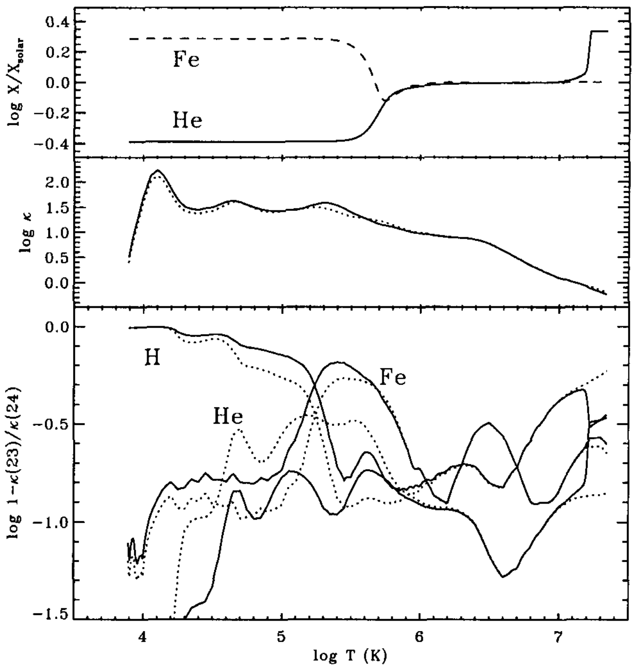

Figure 1. A model with diffusion (solid line) and one without (dotted) are compared. The top panel shows the abundance profiles of He and Fe as a result of diffusion relative to the homogeneous model. The middle panel shows the Rosseland opacity for both models. The bottom panel shows the contribution of H, He and Fe to the total opacity ($\kappa(24)$; $\kappa(23)$ is the opacity with one element removed).

The stability analysis of the models showed that pulsating Am stars are restricted to fairly evolved stars, in agreement with observations, and that the blue edge of their "instability strip" is sensitive to the depth of the mixing (Fig. 2). As the blue edge shifts toward the red edge, less helium remains in the driving as a result of mixing, and the region of instability also shifts to more massive stars. The limits are far from being well defined and the models do not test whether there is an upper mass limit to the instability region.

While diffusion in A stars tends to stabilize stars to pulsations, and observations and theoretical predictions are overall in accord, the situation in the B stars is more confused. Models have shown that iron-peak elements accumulate both at the surface and in a localized region at a temperature of roughly 200 000 K, where they dominate the opacity. All the models show a significant increase in the opacity in that region, which can lead to the emergence of localized convection in some cases. Not coincidentally, pulsations in B stars are driven by the opacity of metals in that region. Diffusion should therefore lead

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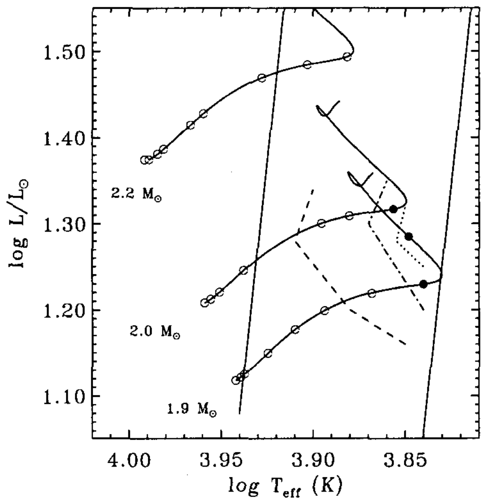

Figure 2. The approximate edges of the instability strip are shown for δ Scuti stars (solid) and Am stars (dash-dotted). The blue edge for models with deeper (dashed) and shallower (dotted) turbulence are also shown. Filled circles indicate models of variable Am stars, open circles indicate stable Am stars. The evolutionary path for models of Am stars of 1.9, 2.0 and 2.2 $M_\odot$ are shown.

to an increase in driving. HgMn stars could be expected to be variable to the same degree as Slowly Pulsating B (SPB) stars, which share the same region of the HR diagram, but the opposite is observed. No HgMn stars has been found to be variable because of pulsations.

In order to prevent pulsations in HgMn stars one would need to either introduce damping in the superficial regions or reduce the opacity of metals in the driving region. Introducing mixing would not solve the problem since normal metal abundances lead to "normal" SPB stars. No significant damping due to abundance variations of other elements, notably helium, were found in preliminary models. It remains that the HgMn phenomenon seems well correlated with slow rotation, which may well give a hint of the solution of this conflict between theory and observations.

3.2. Accretion and pulsations

Matter accreted at the surface of a star will be redistributed within the superficial mixed region and may diffuse below it. If the mass accreted is large enough the entire mixed zone will take on the chemical composition of the accreted matter (Turcotte & Charbonneau, 1993).

Accretion is the leading mechanism to explain the observed composition of λ Boötis stars (Solano et al., 2001). If accretion indeed is at the root of the λ Boötis phenomenon then one expects these stars to be young, with ongo-

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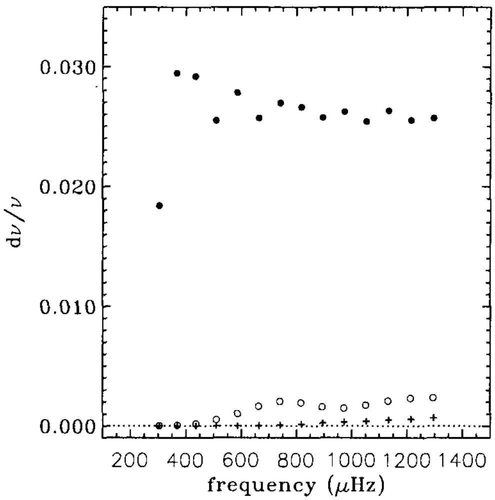

Figure 3. Predicted frequency differences of radial modes in models of a 1.80 $M_\odot$ star with λ Boötis-like superficial abundances relative to a normal star. The crosses are for a model where the chemical anomalies attain a depth of $\log T = 4.4$ (just below the SCZ in standard models of A stars), the open circles for $\log T = 5.0$ (1000 times more massive), and the filled circles for $\log T = 5.8$ (10^6 times more massive).

ing accretion (Charbonneau, 1993; Turcotte & Charbonneau, 1993). Although some observations play in favor of the accretion scenario, such as evidence of circumstellar matter and even infall in some cases as well as their δ Scuti-type variability, there remain some problems. The most troublesome problem is that the λ Boötis stars can be ZAMS or TAMS stars or anywhere in between.

The Richer et al. (2000) models for A stars have shown that deep mixing can be expected in slowly rotating stars. That mixing is expected to be at least partially driven by rotation. It follows that one may expect that faster rotating stars such as λ Boötis stars have mixing below the convection zone extending as deep or even deeper than in Am stars. Deep mixing in λ Boötis stars has a few repercussions on the mechanics of accretion and on the modeling of the stars.

As accreted material must be diluted in the entire mixed region, the mass which needs to be accreted for surface abundances to reflect those of the accreted matter must be proportionally larger. It also means that the time scale for the establishment of the characteristic surface composition increase as well which might imply that accretion rates are higher than previously thought. The peculiar surface composition will persist longer after accretion is halted than the few Myr obtained by Turcotte & Charbonneau (1993). Finally, and perhaps more importantly in the context of pulsations, the star will have a peculiar composition to a much greater depth than in anterior models. Such large abundance anomalies to such large depths can have non-negligible effects on stellar structure.

If one recalls the models of Am stars, the chemically homogeneous region extends from the surface to points beyond the region where iron-peak elements dominate the opacity (at roughly 200 000 K). As λ Boötis stars are superficially metal-poor, the opacity in the metal bump will be significantly lowered. Although this has some effect on driving, the driving is still dominated by helium, as in Am stars. The structure of the star is changed somewhat and the frequencies of the modes of oscillation in the star are changed by a significant amount, as shown in Fig. 3. The effect is not significant if mixing is shallower.

If mixing is indeed as deep as the models of Am stars suggest, then models including opacities adequate for the peculiar chemical composition may be necessary if one hopes to constrains the models or analyze the seismology of these stars in more details.

4. What can we learn from variable CP stars ?

The evolution of the chemical composition in a star is very sensitive to mixing processes occurring within it. As there is an obvious signature of separation processes likely modified by mixing in chemically peculiar stars, it follows that they are objects through which one stands to learn a great deal about those mixing processes. In so-called normal stars, one does not have the same tools to study those processes.

We have shown here that detailed modeling of A stars has lead to a radical change in the paradigm for their structure, pointing to much deeper mixing than was expected from anterior models. These models also reproduce qualitatively the observed variability in metallic A stars. Detailed models of specific stars will be able to confirm whether the predicted pulsations agree with observations as well as predicted surface composition agrees with what can be measured in Am stars.

In B stars, there is an apparent contradiction between theoretical expectations for pulsation driving and observed non-variability in HgMn stars. Solving this problem is likely to bring about a better understanding of mass loss and mixing in B stars. Better models of CP B stars will be possible when new opacity data better suited to calculating radiative pressure on individual elements in superficial regions are released by the OPAL group.

As models of CP stars improve, models of other variable stars will be achieved, such as roAp stars for which preliminary models are now being attempted (see Richard et al., and Michaud et al., these proceedings).

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Discussion

C. Aerts : Some of SPBs studied by De Cat (2001) have deviating chemical abundance (mostly in Si). They all have low $v \sin i$. How does that compare to your excitation models ?

S. Turcotte : Surface abundance anomalies in B stars are very difficult to interpret in terms of internal abundance profiles because the structure and mixing or separation processes occurring in the external regions are essentially unknown. However low $v \sin i$ in SPB stars is an intriguing problem if the stars are really slow rotators because one would then have to introduce another parameter in addition to rotation to understand the non-variability of HgMn stars.

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