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Atomic diffusion in stellar surfaces and interiors

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Abstract. Atomic diffusion may play a significant role for the Sun and Population I Main Sequence stars up to some 25000 K, Population II turnoff stars and cluster age determinations, horizontal branch stars (including sdOs and sdBs), white dwarfs and neutron stars. In all these cases, radiative accelerations play a significant role. A stars are, however, arguably those that show most prominently the effects of atomic diffusion. In so far as the effects of accretion, mass loss, turbulence and meridional circulation may be neglected in the evolutionary models of A stars, the effects of atomic diffusion in them have now been calculated from first principles and are presented using complete evolutionary models of 1.7 and 2.5 $M_\odot$ stars. Their abundance anomalies are not only superficial, but extend over a significant fraction of the stellar radius. Iron convection zones appear at a temperature of about 200000 K. Abundance anomalies similar to those observed in Am stars are produced. However the comparison with the observations requires linking atmospheres to interior evolution. Models that have been proposed to take into account atomic diffusion in atmospheric regions to explain observations are critically reviewed. They depend on a number of parameters. Unfortunately the atmospheric regions are imperfectly modeled, the magnetic field is not taken into account, and important hydrodynamic processes currently require arbitrary parameters for their description.

Keywords. Convection, diffusion, turbulence, stars: abundances, stars: atmospheres, stars: chemically peculiar, stars: evolution, stars: horizontal-branch, stars: interiors, stars: magnetic fields, stars: mass loss

1. Atomic diffusion in stellar evolution

As the accuracy of abundance determinations improves, atomic diffusion potentially has observational implications for more stars. In the best known case, helioseismology has confirmed the importance of gravitational settling in modifying the He concentration in the Sun's external regions (Guzik & Cox 1992, Christensen-Dalsgaard *et al.* 1993, Proffitt 1994, Guenther *et al.* 1996, Richard *et al.* 1996, Brun *et al.* 1999). In a more speculative paper, Bildsten *et al.* (2003) suggested that radiative accelerations, $g_{\rm rad}$ could be reponsible for the strength of Fe lines seen during thermonuclear flashes on neutron stars.

In Population II stars atomic diffusion is responsible, according to VandenBerg *et al.* (2002), for M 92 to have an age 2 Gyr less than determined by Grundahl *et al.* (2000) in the absence of diffusion processes. It also potentially plays a role in the surface composition of turnoff stars (Richard *et al.* 2002) where anomalies might have been observed in M 92 (King *et al.* 1998) though those observations remain to be confirmed. The Li abundance in the stars of the Spite & Spite (1982) plateau and the age of M 92 are compatible (see Richard *et al.* , submitted) with the cosmological age and the Li abundance determination of WMAP (Cyburt *et al.* 2002, 2003).

One of the most striking examples of the effects of atomic diffusion driven by $g_{\rm rad}$ has recently been confirmed in horizontal branch stars. It was originally noticed by Sargent & Searle (1967, 1968) that the field halo stars with the same $T_{\rm eff}$ and the $\log g$ as the

Main Sequence HgMn stars, also appear to have very similar abundance anomalies. This occurs where the horizontal branch crosses the Main Sequence. It was then argued that the small He abundance in those stars could not be used to suggest that some stars had a He abundance smaller than the *cosmological* abundance. The observation of a relative overabundance of ^{3}He by Hartoog (1979) confirmed the link with the Population I Main Sequence star 3 Cen A which had been strengthened by the comparison of the observations of 14 chemical species in both stars by Baschek & Sargent (1976).

Michaud *et al.* 1983) considered atomic diffusion processes in the presence of g_{rad} in horizontal branch stars. They showed that large overabundances of the metals were to be expected in the hotter HB stars, where He underabundances are observed. A limiting equatorial rotation velocity is also expected for the HB stars with anomalies when one considers the 100 km s^{-1} upper limit to the equatorial rotation velocity of the HgMn stars and the link to meridional circulation (Michaud *et al.* 2004a).

Observationally, Glaspey *et al.* (1989) measured an underabundance of He and an overabundance of Fe by a factor of 50 in a T_{eff} =16000 K horizontal branch star of NGC 6752 but not in the cooler HB stars of the same cluster. This observation has now been strikingly confirmed by Behr *et al.* (1999, 2000a, 2000b) and Moehler *et al.* (2000) who observed many horizontal branch stars of NGC 6752, M15 and M13 and found that, whereas those cooler than about 11000 K have the same composition as giants, those hotter than 11000 K usually have larger abundances of some metals by large factors. They observed in particular Fe to be overabundant by a factor of 50 (see Fig. 1 of Behr *et al.* 1999). Since such anomalies cannot have been produced inside these stars and all HB stars must have had very similar original compositions. This is a striking confirmation of the importance of transport processes and of the role of g_{rad} in that region of the HR diagram. The link to transport processes is further strenghtened by that the higher T_{eff} HB stars rotate more slowly than the cooler ones which show no abundance anomalies (Behr *et al.* 2000a, 2000b, Recio-Blanco *et al.* 2002).

In the white dwarfs, ever since the original suggestion of Schatzman (1945), atomic diffusion has been recognized as the main process causing surface abundances. In the hotter white dwarfs ($T_{\mathrm{eff}} > 30000$ K), g_{rad} was later suggested to play a role (Vauclair *et al.* 1979, Fontaine & Michaud 1979, Chayer *et al.* 1995).

Am and Ap stars appear as the most evident manifestation of phenomena (Michaud 1970) that are very widespread.

2. Interior of A stars

The availability of large atomic data bases has made it possible to calculate stellar evolution models from first principles. Evolutionary models taking into account g_{rad} , thermal diffusion, and gravitational settling for 28 elements, including all those contributing to the OPAL stellar opacities, have been calculated for a number of Population I stars: the Sun (Turcotte *et al.* 1998), F stars (Turcotte *et al.* 1998), AmFm stars (Richer *et al.* 2000) and solar metallicity stars of 0.5 to 1.4 $M_\odot$ (Michaud *et al.* 2004b). Stellar models of 1.7 and 2.5 $M_\odot$ are used here to describe the interiors of A stars. From Figure 1 of Richard *et al.* (2001), the 2.5 $M_\odot$ star starts its Main–Sequence evolution with T_{eff} = 10500 K, has $T_{\mathrm{eff}} > 10000$ K for the first quarter of its Main–Sequence life and ends it at 8500 K, while the 1.7 $M_\odot$ one starts at 8000 K and ends its Main–Sequence life at 6500 K. These stars cross and bracket the T_{eff} range of interest.

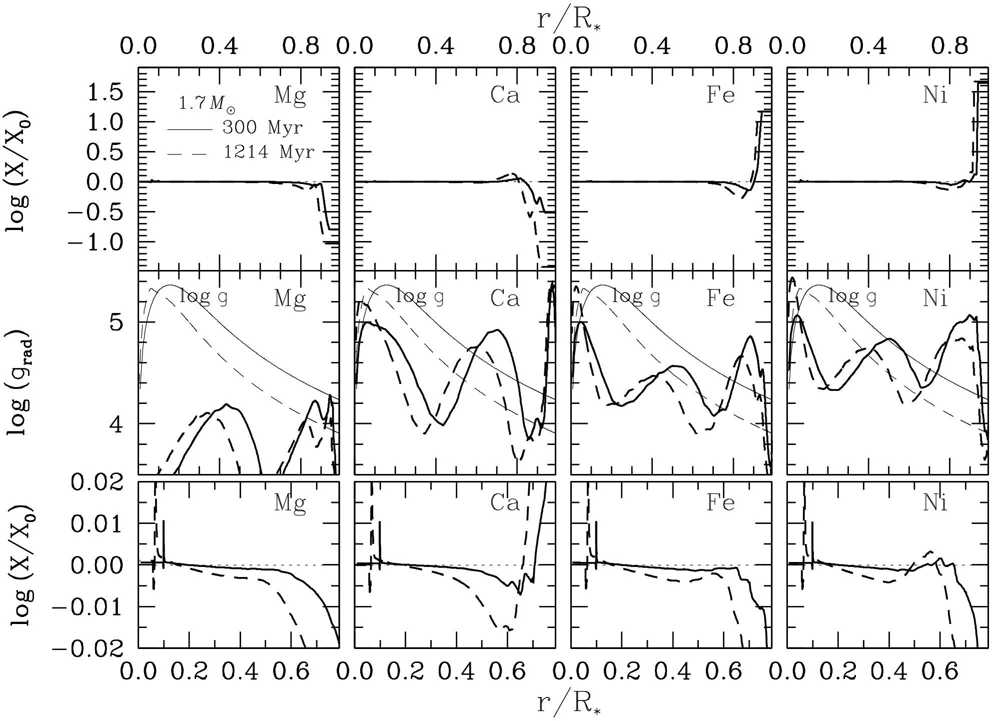

Figure 1. Abundances and $g_{\rm rad}$ as a function of radius, at 300 and 1214 Myr, in a 1.7 $M_\odot$ model for four of the 28 calculated species. For the two upper rows, the abscissa is above and covers the whole radius. The larger anomalies, by factors of more than 10, involve the outer 10% of the star. They are linked to $g_{\rm rad}$ shown on the second row. Note the vertical and horizontal scale changes for the bottom row. As may be seen on the lower row, at the 0.02 dex, or the 5%, level, anomalies cover the outer 40% of the radius. Metals are also overabundant, just outside the central convective zone, by a factor of 1.05. This is caused by interaction of inward settling metals with He diffusing outward from the central convective core (see §3.1.3 of Richard *et al.* (2001) for a more detailed discussion).

2.1. *Calculations*

The models were calculated as described by Turcotte *et al.* (1998) and Richard *et al.* (2001). They were assumed to be chemically homogeneous on the pre-Main Sequence with relative concentrations as defined in Table 1 of Turcotte *et al.* (1998) and most had a solar metallicity. The $g_{\rm rad}$ are from Richer *et al.* (1998) with a correction for redistribution from Gonzalez *et al.* (1995) and LeBlanc *et al.* (2000). The atomic diffusion coefficients were taken from Paquette *et al.* (1986) (see also Michaud & Proffitt 1993).

The $g_{\rm rad}$ calculations use the same OPAL data as was found to best reproduce the solar structure. Some questions have been raised recently after the proposed reduction of the O abundance in the Sun (Asplund *et al.* 2004). Basu & Antia (2004) concluded that such a reduction led to structural changes in clear disagreement with heliosismic measurements unless the opacity tables were revised upwards by 3.5% or that the metal abundance was very arbitrarily assumed to be larger *in* the solar convection zone than in the solar photosphere.

2.2. *Interior structure*

The concentrations of the chemical species are modified by particle transport in the interior of A stars (see Fig. 1). One notes that: 1) Overabundances of metals occur locally and are linked to the variations of $g_{\rm rad}$ and so to electronic shells. 2) These local abundance variations are superimposed on a generalized overabundance of metals at the level of up to 0.3% in the inner 40% by mass (inner 15% in radius) and a generalized underabundance in the outer region. 3) In the hotter A stars, some $g_{\rm rad}$ are larger than gravity over the outer 10% of the mass. 4) Iron convection zones occur at $T \simeq 200000$ K. The He convection zone disappears (Vauclair *et al.* 1974). The formation of Fe convection zones is described in detail in §3.1.2 of Richard *et al.* (2001). It appears in all solar metallicity stars with $M_* \geqslant 1.4\ M_\odot$ (see Fig. 2). 5) As may be seen in Fig. 1, the abundances are modified by diffusion processes in the outer 40% of the radius at the 5% level, for most species. For a few species, up to the outer 40% by radius is affected by overabundances caused by $g_{\rm rad}$. This is limited partly by the region where $g_{\rm rad} \geqslant$g but more importantly by the region where there is enough time for anomalies to develop during the stellar lifetime. The effect of atomic diffusion is not a static but a dynamic process. 6) Atomic diffusion leads to increases in the size of central convection cores. This is related to the appearance of semi-convection zones and is more important for F than A stars (see Richard *et al.* 2001, Michaud *et al.* 2004b). A peak at the 5% level also appears just outside the central convective core for some stellar masses.

The limitations of these models come from the exterior regions. The transport is treated from first principles from the regions where the Fe convection zone forms, down to the center. However, in most calculations, the star is assumed mixed above the Fe convection zone all the way to the surface. In Figure 3 of this paper and Figures 4 and 16 of Richard *et al.* (2001) are shown results where this constraint is relaxed.

The Fe mass fraction, X(Fe), at which the Fe convection zone appears, depends on the Fe contribution to the opacity. Is the Fe contribution to opacity correctly calculated by OPAL? Given the remark made in §2.1, we have evaluated the uncertainty by arbitrarily decreasing the Fe contribution to the opacity by 30% for a 2.0 $M_\odot$ model and found that it increased by approximately 5% the X(Fe) at which the convection zone appears. Increasing the Fe contribution to opacity by 20% decreases by about 2% the X(Fe) at which the convection zone appears. One may find a detailed discussion of the dependence of convection on abundance variations in §3.3 of Michaud *et al.* (2004).

2.3. *Competing processes*

Competing processes include turbulence, meridional circulation, accretion and mass loss. Each of those processes, except some meridional circulation models, requires some adjustable parameter (and more generally parameters) for its description.

Turbulence has been studied in detail in conjunction with evolutionary models of A stars and is mentioned below in §3.1.2. Mass loss is mentioned below in conjunction with Am, Ap and HgMn star models. Meridional circulation has been suggested by Michaud (1982) to lead to a triggering mechanism for the Am and HgMn phenomena. No arbitrary parameter is involved and the limiting equatorial velocity of ~ 100 km s^{-1} is obtained, but the meridional circulation model assumes a boundary layer whose details have been questioned. One would like to see this model confirmed by numerical simulations from first principles (see Talon *et al.* 2003, Théado & Vauclair 2003) but no simulation has yet been done for A stars. For the results to be reliable, the simulations need to be large enough to cover many scale heights with sufficient resolution.

Accretion was first suggested by Havnes & Conti (1971) and Havnes & Goertz (1984) but, except for the λ Booti stars (Turcotte & Charbonneau 1993, Turcotte (2002)), it is

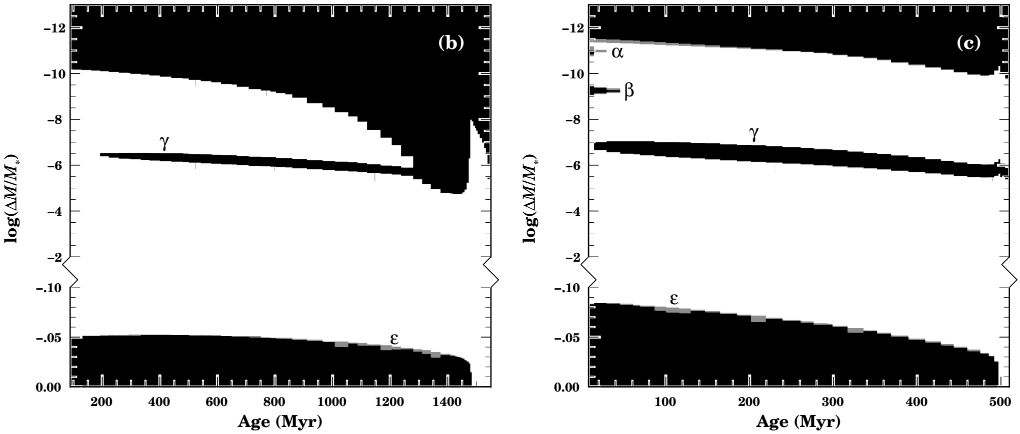

Figure 2. Convection zones in 1.7 and 2.5 $M_\odot$ models. Convection zones are in black. The ones labeled γ are the Fe convection zones, those labeled α and β are respectively He I and He II convection zones. In gray, labeled ϵ, are semi-convection zones.

unlikely to play the dominant role on a large fraction of the peculiar stars because of the relatively large fraction of M_* that needs to be accreted given the dynamical instability that heavy matter causes when accreted on lighter matter (Proffitt & Michaud 1989, see also Vauclair 2004).

3. Modelling atmospheres

To what extent can we currently explain the abundance anomalies observed on Am, Ap and HgMn stars? I will treat these in turn.

The simplest model assumes that the difference between the Ap stars and the others, comes from the presence of magnetic fields on the surface of Ap stars but not on the surface of the others. Where the magnetic field is horizontal, even ionized species whose $g_{\rm rad}$ are larger than g in the outer atmosphere are bound to the stars, since they cannot cross field lines. The magnetic field then guides diffusive transport causing patches or rings or complicated structures on Ap stars.

3.1. *Am stars*

There are currently two quite different models involving atomic diffusion that have been proposed to explain AmFm stars. One involves separation close to the surface so that only the outer 10^{-10} of M_* needs be affected. Mass loss then has to be assumed. The other occurs deeper in and involves the outer $10^{-6} - 10^{-5}$ of M_* . In this case turbulence has been suggested to play a role.

3.1.1. *Separation below the H convection zone*

Watson (1971) (see also Smith 1973) noticed that, immediately below the H-convection zone, Ca is in the Ca II (argon like) state, in which it has a small $g_{\rm rad}$. He suggested that the separation occurs there, in which case Ca would be underabundant while iron peak elements would be overabundant, in accordance with observations. This requires the disappearance of the He convection zones which occurs after He has settled gravitationally. It has been shown to explain the absence of δ Scuti pulsators (Baglin 1972) among the AmFm stars. It is also compatible with the upper limit to the rotation velocity of AmFm stars (Michaud 1982, Charbonneau & Michaud 1988, 1991).

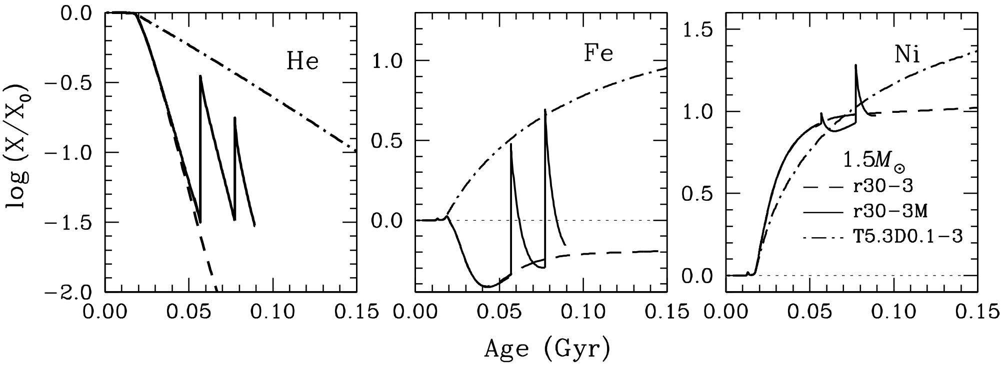

Figure 3. Effect of incomplete mixing above the Fe convection zone in 1.5 $M_{\odot}$ models. The continuous line is for a model where complete mixing is imposed above a Fe convection zone as soon as it appears. The Fe concentration is homogenized with the whole region above the Fe convection zone. It then disappears and later reappears leading to spikes in the various concentrations. The dashed line assumes no mixing above the Fe convection zone. The dot-dashed line assumes that the whole zone above *log* T = 5.3 is mixed throughout evolution, even when the Fe convection zone has not yet appeared. Observations of many species could constrain the mixing processes.

It has also been shown that when $g_{\rm rad}$ are included, atomic diffusion can explain the envelope of the observed abundance anomalies (Michaud *et al.* 1976). However the expected anomalies are generally much larger than those observed in individual stars, suggesting that at least one competing hydrodynamical process is strong enough to reduce the effects of atomic diffusion. Currently the most favored competing process is mass loss (Michaud *et al.* (1983). These calculations were done in static envelope models, for a limited number of species. Time dependent calculations only for Ca and Sc have been made in detail using $g_{\rm rad}$ calculated with Topbase data (Alecian 1996). It is difficult to tune such a model to reproduce the relative uniformity of anomalies observed on Am stars when the separation involves such a small mass and the time scales are as short as in this model. No calculation based on the preceding model has ever successfully reproduced the detailed abundance anomalies of individual stars, including the small anomalies of some chemical species such as Mg. This does not however prove it is impossible.

Turbulence has been investigated (Vauclair *et al.* 1978) but it does not appear to reduce sufficiently the overabundances of iron peak elements and rare earths if helium and calcium are to be underabundant.

3.1.2. *Separation at 200000 K*

As an alternative to the suggestion that separation occurs immediately below the H-convection zone, Richer *et al.* (2000) proposed that the separation occured much deeper. Detailed evolutionary models were calculated as described in §2 including the effect of atomic and turbulent diffusion for stars of 1.45 to 3.0 $M_{\odot}$. Since Richer *et al.* (2000) used turbulent diffusion coefficients that decrease rapidly as ρ increases within the star, they found their result to depend only on one parameter, the mass mixed by turbulence. The physical cause of the turbulence is not discussed. The zone mixed by turbulence is deeper than the iron convection zone, reducing the abundance anomalies to values which are too small for iron peak convection zones to develop in some models.

These authors compared the calculated surface abundances to observations of a number of AmFm stars. For Sirius A, 16 calculated abundances were compared to observations (including 4 upper limits). Of these, 12 are well reproduced by the model, while 3 are not so well reproduced and one is a very uncertain observation (see Fig. 18 of Richer *et al.* 2000).

In cluster AmFm stars, the age and initial abundances are known. There is then less arbitrariness in the calculations but fewer chemical species have been observed than in Sirius. The available observations (Hyades, Pleiades and Praesepe stars were compared) agree reasonably well with the calculated models for the five stars which they compared (see Fig. 19 to 23 of Richer *et al.* 2000). For most species, calculated abundance anomalies are within one error bar of the observed anomalies with only one fitted parameter, the mass of the mixed zone. All other quantities are from first principles. The pulsational properties of these models appear to be compatible with the observed pulsations of δ Scuti and AmFm stars (see Turcotte *et al.* 2000).

There is considerable scatter in the observations between different observers so that it is premature to conclude that hydrodynamical processes other than turbulence are needed to explain the observations. We are not ruling out that this be the case but the observations do not appear to us good enough to establish it; but neither are they good enough to establish this model. Would observations be compatible with a turbulent transport coefficient decreasing less rapidly than used by Turcotte *et al.* (2000) (see Richard *et al.* 2005)?

Even if turbulence can explain the observations, could mass loss do the same? Or at what level can mass loss be present without modifying the agreement with observations? Would such mass loss flux be chemically differentiated? To what extent are the surface abundances modified by additional separation above the Fe convection zone (see Fig. 3)?

3.2. *Ap stars*

The magnetic Ap stars are the most difficult to model. In the simplest model, Babel & Michaud (1991a) followed the diffusion of half a dozen chemical species, taking the magnetic structure as observed. They assumed mass loss and turbulence to be negligible. There is then no arbitrary parameter but it is still required to make an assumption about the state of convection in the presence of magnetic fields. Is all convection suppressed by the magnetic field or is convection suppressed only where magnetic field lines are vertical?

Using relatively detailed but LTE calculations of $g_{\rm rad}$ (Ca), $g_{\rm rad}$ (Sc), $g_{\rm rad}$ (Ti), $g_{\rm rad}$ (Mn), $g_{\rm rad}$ (Cr) and $g_{\rm rad}$ (Sr), Babel & Michaud (1991a) concluded that the simple model explained the *average* abundance anomalies of those species on 53 Cam, assuming that convection was partially suppressed. However the geographic distribution of the anomalies could not be explained in the measured magnetic field configuration (Landstreet 1988). This result was not changed when the effects of polarization are introduced as described in Babel & Michaud (1991b). Mass loss guided by the magnetic field needs to be introduced Babel (1994, 1995). These calculations should be redone with more accurate $g_{\rm rad}$ (Alecian & Stift 2004) and better magnetic field determinations and abundance maps (Kochukhov *et al.* 2004). It appears likely that mass loss and chemical separation in the wind will also need to be included though that remains to be shown.

3.3. *HgMn stars*

An attempt was made to determine what abundance anomalies would be expected from a parameter free model for HgMn stars (Michaud 1981). It involved detailed calculations of $g_{\rm rad}$ (He) (Michaud *et al.* 1979), $g_{\rm rad}$ (Be), $g_{\rm rad}$ (Mg), $g_{\rm rad}$ (Ba) (Borsenberger *et al.* 1981, 1984), $g_{\rm rad}$ (B) (Borsenberger *et al.* 1979), $g_{\rm rad}$ (Ca), $g_{\rm rad}$ (Sr) ((Borsenberger *et al.* 1981) and $g_{\rm rad}$ (Mn) (Alecian & Michaud 1981) in NLTE model atmospheres.

Once one can calculate $g_{\rm rad}$, one determines the concentration of each species that can be supported by $g_{\rm rad}$ in the atmosphere. One checks that $g_{\rm rad}$ decreases as the species leaves the atmosphere, so that it is trapped there and finally one checks that the $g_{\rm rad}$ is larger than gravity deep enough into the star for the required amount of the species to be pushed into the atmosphere. All this is determined from first principles. The envelope of the abundance anomalies of He, B, Mg, Ca, Mn, Sr and Ba are explained by this model but the model fails for Be. The triggering of the HgMn phenomenom may be done by meridional circulation as mentioned in §2.3. This may be viewed as reasonnable success given the absence of any arbitrary parameter. However this does not lead to a detailed understanding of the spectrum of individual stars. No star has been found to have all those anomalies at the level calculated and no attempt was made to have a calculated spectrum completely consistent with observations.

Proffitt *et al.* (1999) carried out the more demanding task of calculating $g_{\rm rad}$ (Hg) and the abundances of Hg that could be supported by $g_{\rm rad}$ in the atmospheres of two HgMn stars. They determined atomic data (transition rates and collision rates) of Hg for that study (Brage *et al.* 1999) since their NLTE calculation required a large amount of atomic data that was poorly known but needed for abundance determinations, $g_{\rm rad}$ and isotope shift calculations. They used atmospheric models that reproduced the atmosphere as possible although these models did not include stratified concentrations. They found that the $g_{\rm rad}$ (Hg) were too weak to lead to Hg lines as strong as observed and suggested that a stellar wind of some 10^{-14} $M_\odot$ y^{-1} was needed. They did not study in detail the possibility that Hg be pushed out of the atmosphere by $g_{\rm rad}$ (Hg).

One problem with such parameter free calculations is that they produce the same abundance anomalies for all stars of a given $T_{\rm eff}$ and $\log g$. According to, for instance, Woolf & Lambert (1999) there is considerable variation from star to star even at a given $T_{\rm eff}$ and $\log g$.

Mass loss is bound to play a role for HgMn stars. It is observed in slightly hotter stars than HgMn. It has been suggested by Michaud *et al.* (1974) to play a role in the creation of isotope anomalies. These authors suggested that, in so far as $g_{\rm rad}$ (Hg) is close to equilibrium with gravity, the lighter isotopes may be pushed out of the star while the heavier ones would remain bound. This would be further emphasized by the shading of the lines of the heavier isotopes as they tried to acquire an outward velocity to leave the star in a wind. Only the lighter isotopes would then leave. One would expect isotope anomalies mainly for atomic species who become noble gases after only few ionizations†, such as Hg, Pt and now Ca (Castelli & Hubrig 2004). This process depends on the details of the wind structure and it has never been calculated in detail. To go beyond the suggestion that was made, one needs a detailed wind model calculated from first principles and taking differentiation in the wind into account along with the detailed NLTE $g_{\rm rad}$ (Hg) calculations. This was never attempted.

Light induced drift (Atukov & Shalagin 1988) could play a role. It is likely to be small but a better evaluation of the scattering crosssections of the excited states of ionized species appears needed to include it in calculations (LeBlanc & Michaud 1993).

Seaton (1999) attempted time dependent calculations of the anomalies of Fe group species on HgMn stars in presence of mass loss using $g_{\rm rad}$ calculated with OP project data (Seaton 1995, 1997). He does envelope calculations similar to those of Richer *et al.* (2000) except that he extends them to $\tau \simeq 1$. He does not include the effect of other species on the opacities except for the one he is considering nor does he include evolutionary effects.

† So that their $g_{\rm rad}$ decrease below gravity before they leave the star.

4. Prospects

In §3.1.2, it was seen possible, using current computing power, to calculate stellar evolution models that include the abundance variations of 28 species. Our poor understanding of stellar hydrodynamics is the main source of uncertainty of these models. On the other hand, comparison of the results of the models to observations becomes a source of information on stellar hydrodynamics. Am star observations of up to 16 of those species have been made and it is certainly possible to observe more by observing the whole visible and far UV spectrum. That would also allow improving the accuracy of observations. On the modeling side, it would be very important to have $g_{\rm rad}$ for more species, for instance Sr, some Rare Earth Elements, and Hg. These would add important observational constraints on the models.

It would be in principle possible to do similar calculations for HgMn and Ap stars. It would mainly involve the atmospheric regions. The computing power is there to do the calculations, but a large amount of code development is needed.

Acknowledgements

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Discussion

CORBALLY: In Population II horizontal branch stars, do you find relative underabundances (besides the overabundances you mentioned)?

MICHAUD: The most conspicuous underabundance is that of He. When it occurs in hot HB stars, there is also an overabundance of Fe. CNO are generally overabundant according to Behr *et al.* (1999). This is also expected from the calculations (Michaud *et al.* 1983).

NOELS: Do you think that the Fe accumulation zone that you find in A stars could also be present in more massive stars, let us say about 9 or 10 $M_\odot$ stars? I ask you this because when analyzing the stability of ν Eri, a β Cep star, it seems that Fe should be overabundant in the Fe opacity bump to excite the observed modes of pulsation.

MICHAUD: If there were no mass loss in 9 or 10 $M_\odot$ stars, a similar accumulation of Fe would occur in them as in A stars. Because of the large mass loss rate expected, however, no large Fe overabundance is expected in such stars. We are planning to introduce mass loss in our evolutionary code and determine quantitatively how abundance anomalies vary with mass loss rate. This has not yet been done.

LANDSTREET: The comparison you have shown between your computation for Sirius and observed abundances highlights a major problem in abundance analyses. Individual investigators can determine abundances with precisions of better than 0.1 dex, but different investigators often differ by far more than the uncertainties suggest. This problem needs much more attention from stellar spectroscopists.