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The effects of mass loss on the evolution of chemical abundances in Fm stars

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Abstract. Self-consistent stellar models including all effects of atomic diffusion and radiative accelerations as well as mass loss are evolved from the pre main sequence for stars of $1.35 - 1.5\,M_{\odot}$ at solar metallicity (Z=0.02). A mass loss rate similar to the solar mass loss rate is sufficient to reproduce observations of the star τ UMa. We discuss the effect of mass loss on the iron convection zone that naturally appears beneath the main hydrogen convection zone of these stars. We also find that the effects of mass loss can be distinguished from those caused by turbulence, but are nevertheless able to explain the particularities of the AmFm phenomenon.

Key words: stars: abundances – stars: evolution – stars: mass-loss – diffusion

1. Introduction

Since 1970 it is generally agreed that atomic diffusion driven by radiative accelerations plays a role in creating the anomalous surface abundances of F, A and B stars Michaud (1970). However, some 40 years later, many questions remain as to the exact behavior of many physical processes within the stable envelopes of these stars. In fact, for Fm stars, two competing scenarios which have each had their share of success are presently being confronted by observations. In the "classical" scenario, Watson (1971) suggests that separation occurs below the H-He convection zone. In this framework, models which only consider atomic diffusion without extra mixing generate predicted anomalies that are 3-5 times larger than the ones observed (Turcotte *et al.*, 1998), thus implying that there is at least one competing process that slows the effects of separation. This led to more recent models (Richer *et al.*, 2000; Richard *et al.*, 2001) in which turbulence enforces mixing down to about 200 000 K. In these models, it is implied that separation occurs deeper in the star.

Like turbulence or rotation, mass loss is another macroscopic process that can reduce inhomogeneities on the surface of these stars. However, until now, only static stellar models have included the effects of mass loss (Michaud *et al.*, 1983; Alecian, 1996 for Ca; LeBlanc *et al.*, 2007 for Sc) with the latter paper showing that the actual depth at which separation occurs is still uncertain.

With self-consistent models of Fm stars ($6500\,\mathrm{K} \leq T_{\mathrm{eff}} \leq 7000\,\mathrm{K}$) we will show that mass loss can reduce predicted abundances to the observed levels. The first aim is to see to what extent observations can constrain the importance of mass loss and if its effects can be deciphered from the ones encountered with turbulence. We will also discuss the implications of our models on the depth of chemical separation.

2. Evolutionary models

The following is a continuation of the Montreal stellar model development project (Richard *et al.*, 2001 and references therein). The evolutionary calculations take into detailed account the time-dependent variations of 28 chemical species and include all effects of atomic diffusion and radiative accelerations. These are the first fully self-consistent stellar models which include mass loss. Models were calculated for $1.35M_{\odot}$, $1.40M_{\odot}$, $1.45M_{\odot}$ and $1.50M_{\odot}$. All models have evolved from the homogeneous pre-main sequence phase with a solar metallicity (Z=0.02). The mass loss rates considered varied from $1 \times 10^{-14} M_{\odot}\mathrm{yr}^{-1}$ to $3 \times 10^{-13} M_{\odot}\mathrm{yr}^{-1}$. The mass loss is considered spherical, chemically homogeneous and weak enough not to disturb burning in the core or stellar structure. The net effect is the appearance of an outward flowing wind which is represented as an advection term in the transport equation. Due to numerical instabilities resulting from very large advection velocities in the surface convection zone, some adjustments must be made in order to avoid convergence problems. The method is well described in Charbonneau (1993). The transport equation then becomes:

$$\begin{aligned} \rho\frac{\partial c}{\partial t} &= -\nabla \cdot [\,-\rho D \nabla \ln c + \rho(\mathbf{U} + \mathbf{U}_w)c] \\ &\quad + \rho(S_{nuc} + S_w)c, \end{aligned} \tag{1}$$

with a Neumann condition (no flux) imposed at the surface and with $\mathbf{U}_w$ and S_w defined as:

$$\mathbf{U}_w = \begin{cases} w_w \hat{\mathbf{e}}_{\mathbf{r}} \text{ under the SCZ,} \\ 0 \text{ in the SCZ;} \end{cases} \tag{2}$$

$$S_w = \begin{cases} 0 \text{ under the SCZ,} \\ \frac{\dot{M}}{M_{ZC}} \text{ in the SCZ.} \end{cases} \tag{3}$$

Here, c is the time and depth dependent concentration, ρ is density, D is the total diffusion coefficient, U is the total velocity field, U_w is wind velocity, M_{CZ} is the mass of the SCZ, $\dot{M}$ is the mass loss rate, S_{nuc} is a source/destruction term linked to nuclear reactions and S_w is a destruction term linked to mass loss.

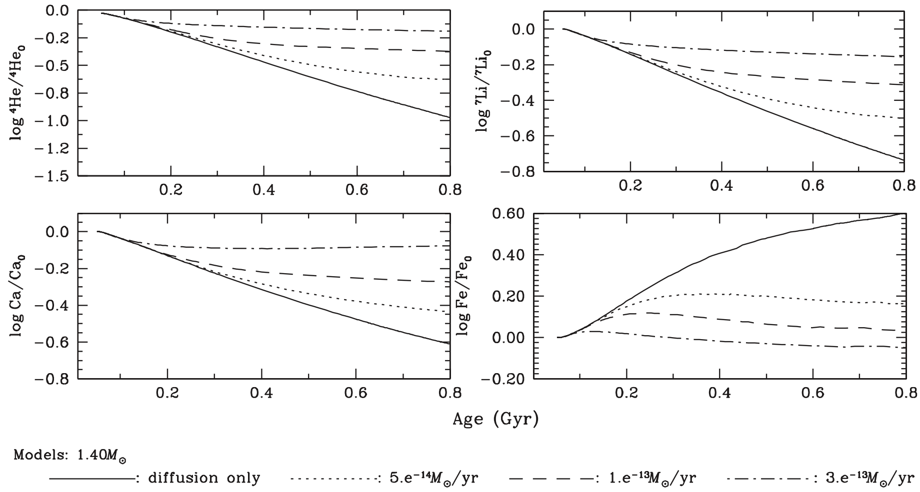

Figure 1. Evolution of surface abundances (^{4}He, Li, Ca and Fe) for $1.4M_\odot$ models with different mass loss rates as well as with atomic diffusion only. It is clear that a slight change in the mass loss rate can have an important effect on abundance anomalies.

3. The effects of mass loss on surface abundances

One of the effects of mass loss is to drag elements which tend to sink. Because the diffusion velocity must be greater than the wind velocity for separation to occur, the greater the mass loss the deeper we have to look to see any effects of separation. On the other hand, elements which are naturally supported by the radiation field will be pushed into the surface convection zone and evacuated through the stellar surface. As seen in Figure 1, models in which only atomic diffusion is included lead to larger surface abundances anomalies than in the presence of mass loss. For instance, after 0.8 Gyr of evolution predicted anomalies (in terms of the original abundance) for the plotted elements are respectively, without mass loss and with a mass loss rate of $5 \times 10^{-14} M_\odot \mathrm{yr}^{-1}$, $\times 0.2$ and $\times 0.3$ for Li, $\times 0.25$ and $\times 0.3$ for Ca, $\times 4$ and $\times 1.5$ for Fe. We also see that for the given stellar mass, a mass loss rate of $5 \times 10^{-14} M_\odot \mathrm{yr}^{-1}$ is sufficient to reduce anomalies by a factor of 1.5 to 3, and a mass loss rate of $3 \times 10^{-13} M_\odot \mathrm{yr}^{-1}$ practically flattens the surface abundances.

3.1. The $1.5M_\odot$ models

The $1.5M_\odot$ model is particularly interesting because it corresponds to the minimum mass at which iron accumulation due to the spatial distribution of its radiative acceleration causes the appearance of a convection zone (Figure 3, left

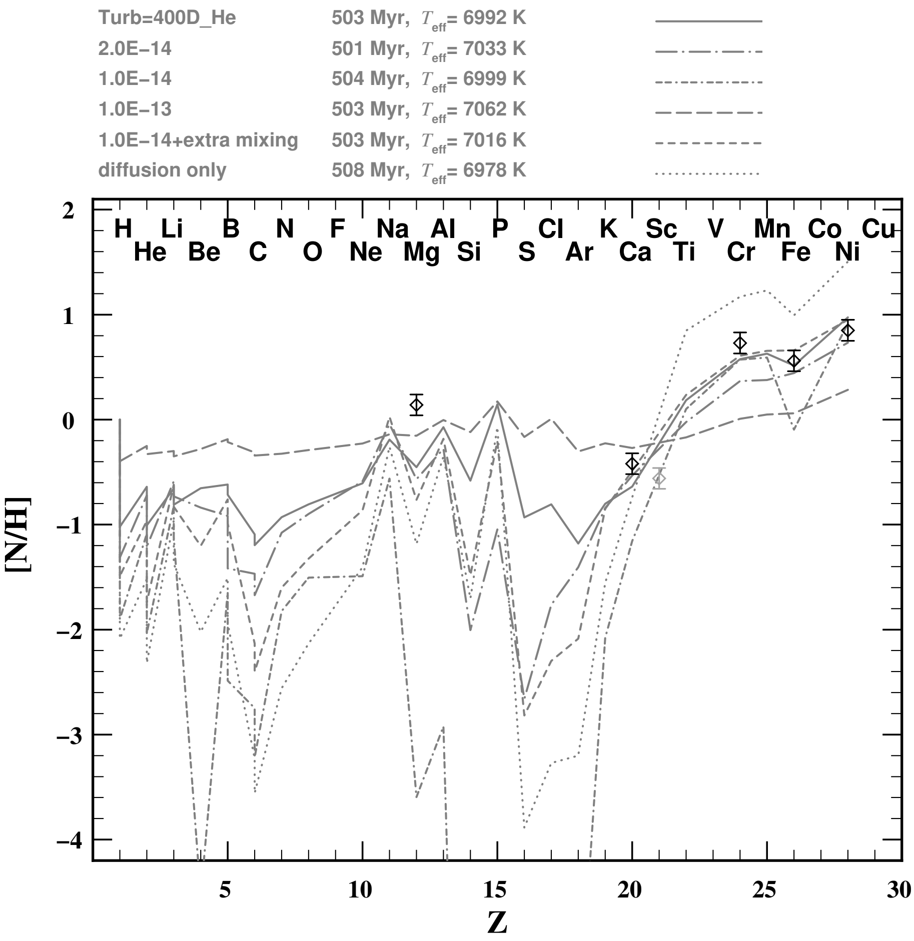

Figure 2. Observed surface abundances of τ UMa (diamonds) compared to $1.5 M_\odot$ models at 500 Myr. Scandium is not included in our calculations. Models with mass loss are designated by their respective rate (e.g. $1.0\mathrm{E}-14 \rightarrow 1 \times 10^{-14} M_\odot \mathrm{yr}^{-1}$).

panel). As mentioned above, recent evolutionary models (Richer *et al.*, 2000; Richard *et al.*, 2001; Michaud *et al.*, 2005) have successfully reproduced observations by considering that turbulence homogenizes abundances from the surface down to a temperature that corresponds to the bottom of this iron convection zone ($\log T = 5.3$). Therefore, in this context, separation must take place deeper than the classical model in which separation occurs above this convection zone. Both of these scenarios have been tested with mass loss.

In Figure 2 we have compared 6 different models of $1.5 M_\odot$ to the ob-

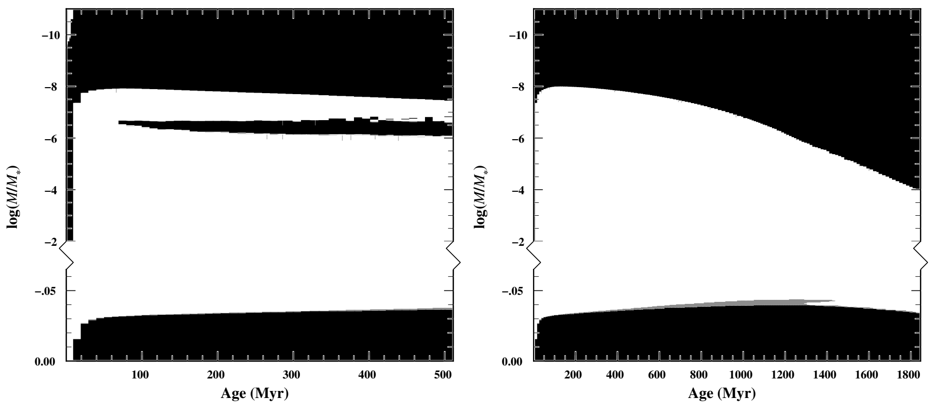

Figure 3. Evolution of convection (black) and semiconvection (gray) zones in two $1.5M_{\odot}$ models ($1 \times 10^{-14} M_{\odot}\mathrm{yr}^{-1}$, right; $2 \times 10^{-14} M_{\odot}\mathrm{yr}^{-1}$, left). In the left panel, we see that an Fe convection zone develops under the main H-He convection zone. In the right panel, this convection zone does not appear because the stronger wind flattens the opacity spike due to Fe accumulation which is responsible for the Fe convection zone.

served abundances of the star τ UMa (Hui-Bon-Hoa, 2000) from the Ursa Major moving group which has an age of approximately 500 Myr (Monier, 2005) and $T_{\mathrm{eff}} \sim 7000\,\mathrm{K}$ (van't Veer-Menneret *et al.*, 1996). There are 4 models in which separation is allowed immediately below the H-He convection zone (3 mass loss models, and one diffusion only model), as well as 2 models in which mixing was enforced to $\log T = 5.3$ or deeper (which is the case for the turbulence model).

It appears from the plot that the two models which best fit the data are the turbulence model as well as the model with a mass loss rate of $1 \times 10^{-14} M_{\odot}\mathrm{yr}^{-1}$ with enforced mixing down to the bottom of the Fe convection zone. However the model with a mass loss rate of $2 \times 10^{-14} M_{\odot}\mathrm{yr}^{-1}$ and without any turbulent mixing does very nearly as well. We also see that the model with the mass loss rate $1 \times 10^{-14} M_{\odot}\mathrm{yr}^{-1}$ without homogenized abundances between convection zones can reproduce quite effectively 3 of the 5 observed abundances. It would therefore be premature to rule out the validity of the classical scenario in the context of mass loss. As we can see in the same plot, observations between Al and Ar would help in identifying if the zone between the H-He and Fe convections zones is mixed. Another important result is that turbulence and mass loss models have noticeable element to element differences which is necessary if we wish to eventually constrain the importance of both these processes. Finally, the models with the mass loss rate of $10^{-13} M_{\odot}\mathrm{yr}^{-1}$ flatten the abundance profiles in such a way that they can no longer reproduce observations (see also Cayrel *et al.*, 1991).

4. Conclusions

Our results seem to suggest that the scenario in which separation is to take place at $T \sim 2 \times 10^5$ K in Fm stars must be favored over the classical scenario. In this framework, a mass loss rate of the order of the solar mass loss rate is able to reduce predicted anomalies to the observed abundances of τ UMa. However, it is too early to eliminate the possibility of separation below the H convection zone. Abundance determinations between Al and Ar could help distinguish between these two regimes. It is also shown that turbulence and mass loss affect anomalies differently, though the discrepancy is slight in the models shown. Once again, more observations are required to further constrain these two mechanisms. More massive models in the $T_{\rm eff}$ range where observations are not as scarce are also needed. They are currently being calculated. In any case, it is shown that reasonable mass loss rates can effectively reduce the anomalies predicted by atomic diffusion models to the observed levels.

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