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Atomic diffusion, mass loss and abundance anomalies 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 1.3-1.5 $M_{\odot}$ of solar metallicity (Z=0.02). By including homogeneous mass loss in these models we determine that mass loss rates similar to the one measured on the surface of the Sun can effectively reduce the predicted surface abundance anomalies from purely diffusive models of Fm stars. By comparing our models with the star τUMa we find that observations can be reproduced. We also find that the effects of mass loss can be distinguished from those of turbulence, but are nonetheless able to explain the particularities of the AmFm phenomenon.

Key words. Stars: abundances – Stars: evolution – Stars: atomic diffusion – Stars: mass loss

1. Introduction

This is a continuation of the Montreal stellar model development project (Richard, Michaud & Richer 2001 and references therein). Fm stars ($6500\,K \leq T_{\rm eff} \leq 7000\,K$) are at the lower $T_{\rm eff}$ limit of the Ap, Bp and Am star phenomenon for which atomic diffusion leads to surface abundance anomalies. They are Population I stars that are non-magnetic (Landstreet 1982) and slowly rotating ($v \sin i < 100\,{\rm kms}^{-1}$, Abt 2000). Prior studies (Turcotte, Michaud & Richer 1998a) have shown that stellar models in which only atomic diffusion is considered predict anomalies that are 3 to 5 times larger than the anomalies observed. This suggests that there is at least one competing hydrodynamical process that reduces the effects of atomic diffusion. These processes include turbulence (Richard et al. 2001, Richer, Michaud & Turcotte 2000), meridional circulation (Charbonneau & Michaud 1991) and mass loss (Michaud et al. 1983, Alecian 1996 for Ca). The aim is to see to what extent observations can constrain the importance of mass loss and if its effects can be deciphered from those encountered with turbulence.

2. Evolutionary models

The evolutionary calculations take into detailed account the time-dependent variations of 28 chemical species and include all effects

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of atomic diffusion and radiative accelerations (for further details on the code see Richard et al. (2001). These are the first fully self-consistent stellar models which include mass loss. Models were calculated from $1.30\,M_\odot$ to $1.50\,M_\odot$ in $0.05\,M_\odot$ increments. 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 $1\times10^{-14} M_\odot yr^{-1}$ to $3\times10^{-13} M_\odot yr^{-1}$. Mass loss is assumed spherical, chemically homogeneous and weak enough not to disturb burning in the core or stellar structure. The main 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:

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

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

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

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

Here, c is the time and depth dependent concentration, ρ is density, D is the total diffusion coefficient, $\mathbf{U}$ is the total velocity field, $\mathbf{U}_w$ is the wind velocity, M_{CZ} is the mass of the surface convection zone, $\dot{M}$ is the mass loss rate, S_{nuc} is a source/destruction term linked to nuclear reactions and S_w is a destruction term which models mass loss (Charbonneau 1993).

3. Results and discussion

3.1. The $1.5\,M_\odot$ models

In Figure 1 (left panel) we have compared our models of $1.5\,M_\odot$ to the observed abundances of the star τUMa (Hui-Bon-Hoa 2000) from the Ursa Major moving group which has an age of approximately 500 Myr (Monier 2005) and $T_{\rm eff}\sim7000$ K (Van't Veer-Menneret & Mégessier 1996). The are six models shown: a strong turbulence model (taken from Richard et al. 2001), 3 models with mass loss only, one model with mass loss and *extra mixing* immediately below the surface convection zone as well as one model with atomic diffusion only. As seen in Figure 1 (right panel), a iron convection zone naturally appears below the surface H-He convection zone for models with small mass loss ($1\times10^{-14} M_\odot yr^{-1}$).

We see that the model with a mass loss rate of $2\times10^{-14} M_\odot yr^{-1}$ (the solar mass loss rate) can reproduce quite effectively 3 of the 5 observed abundances. However, if we assume that the abundances are homogenized between the Fe and H-He convection zones (i.e. with *extra mixing*), the model with $1\times10^{-14} M_\odot yr^{-1}$ becomes the best fit, better than the model with strong turbulence. The models with stronger mass loss rates flatten the abundance profiles in such a way that they can no longer reproduce observations. Also, the internal structure of the star changes as the mass loss rate increases due to the fact that the opacity maximum due to Fe and Ni accumulation is practically eliminated by the strong advective current (Figure 1 (right panel)). Finally, it is important to note that turbulence and mass loss models have noticeable element to element differences. Moreover, the $1\times10^{-14} M_\odot yr^{-1}$ models with and without seperation show large differences between Ar and Al.

4. Conclusions

With a mass loss rate of the order of the solar mass loss rate, we can succesfully reproduce the observed abundances of τUMa. It is shown that turbulence and mass loss affect anomalies differently, though the discrepancy is slight in the models shown. Nevertheless, it is possible to constrain the relative importance of the two processes, if accurate enough observations are available. In particular, observations between Ar and Al would help in that regard as they could distinguish between models with

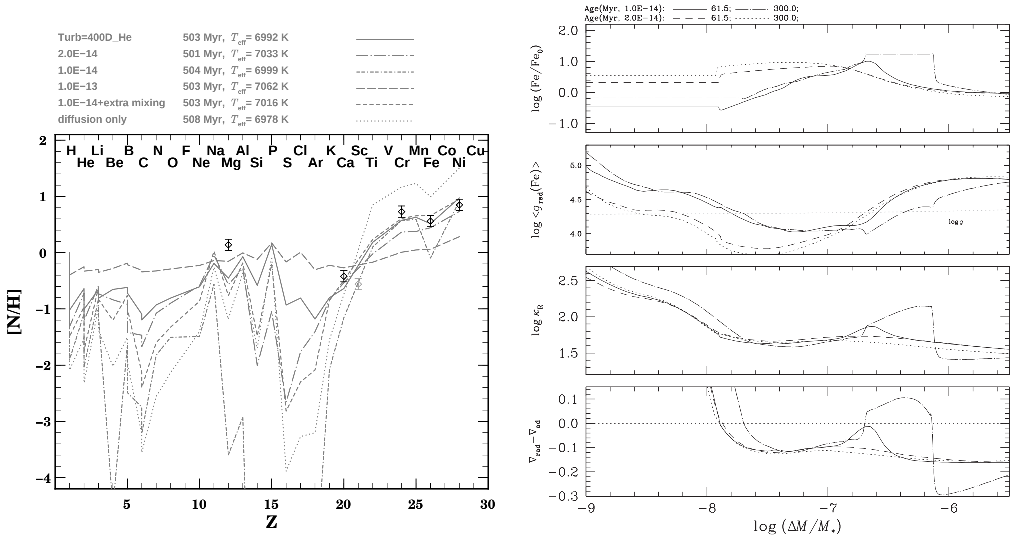

Fig. 1. [left panel] Observed surface abundances of τUMa (diamonds) compared to 1.5 $M_\odot$ models at 500 Myr. Scandium is not include in our calculations. Models with mass loss are designated by their respective rate (e.g 1.0E-14→$1 \times 10^{-14} M_\odot yr^{-1}$). [right panel] Comparison of internal abundance profiles and radiative accelerations (cm s^{-2}) of Fe, Rosseland opacity ($cm^2\,g^{-1}$) and the difference between the radiative and adiabatic temperature gradients at 61.5 Myr and 300 Myr for two 1.5 $M_\odot$ models having different mass loss rates. The accumulation of Fe caused by the space distribution of its radiative acceleration causes a convection zone only in the smaller mass loss model.

or without separation between the Fe and H-He convection zones. More massive models in the $T_{\rm eff}$ range where observations aren't 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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