The A-Star Puzzle
Proceedings IAU Symposium No. 224, 2004
J. Zverko, J. Žižňovský, S.J. Adelman, & W.W. Weiss, eds.

DOI: 10.1017/S1743921304004582

Surface abundances of Am stars as a constraint on rotational mixing

Olivier Richard[1], Suzanne Talon[2] and Georges Michaud[2]

[1]GRAAL UMR5024, Université Montpellier II, CC072, Place E. Bataillon, 34095 Montpellier, France
email: richard@graal.univ-montp2.fr

[2]Département de Physique, Université de Montréal, Montréal, PQ, H3C 3J7, Canada
email: talon@astro.umontreal.ca, michaudg@astro.umontreal.ca

Abstract. Abundance determinations obtained from spectroscopic observations of Am stars provide information concerning the transport processes present in these stars. In this paper we have used models of Am stars which include gravitational settling, thermal diffusion, and radiative accelerations for 24 elements. We used a specific model of rotation induced mixing which has reproduced anomalies in other types of stars. For this preliminary study, models of 1.7 $M_\odot$ and 1.9 $M_\odot$ have been computed. A comparison of the predicted abundances to the observed ones for the Praesepe star HD 73045 sets constraints on rotational mixing.

Keywords. Diffusion, hydrodynamics, stars: abundances, stars: atmospheres, stars: chemically peculiar, stars: individual (HD 73045), stars: rotation

1. Introduction

Am stars were first recognized by Titus & Morgan (1940) as chemicaly peculiar stars. Since then all observed Am stars have been found to be slowly rotating stars ($V_{\rm eq} \sim 100$ km s^{-1}). In these stars C, N, O, and Ca are generally underabundant compared to the Sun while iron-peak elements are overabundant. Different physical processes have been investigated to account for these abundance anomalies such as planet absorption, mass loss, turbulence, ... (see Michaud 2005).

Models of Am stars including gravitational settling, thermal diffusion, and radiative accelerations for 24 elements have been computed by the Montréal group (Riche *et al.* 2000). Using a simple parameterization of turbulent transport, they have shown that these stars need to be mixed from the surface down to at least $10^{-5}M_*$ to reproduce the observed surface abundances. It is interesting to use Am star anomalies to test the effects of a specific model of rotation induced mixing which has reproduced anomalies in other types of stars. In this paper, we will test a parameterization of rotation induced mixing for various rotational velocities in 1.7 $M_\odot$ and 1.9 $M_\odot$ models.

2. Models

2.1. *Physics*

The models were computed using the CEFF equation of state (Eggleton *et al.* 1973; Christensen-Dalsgaard & Däppen 1992) and the Bahcall & Pinsonneault (1992) nuclear energy generation routine. We used the OPAL monochromatic opacities for 24 elements to compute the Rosseland opacity at each time step, for each mesh point in the model for the current local chemical composition (Turcotte *et al.* 1998). All the models are self consistent models taking into account gravitational settling, thermal diffusion and radiative accelerations, which come from first principles. The diffusion velocity of each species is computed with the equations developed in Burgers (1969) which take into account the interactions among all these diffusing species. The radiative accelerations are from Richer *et al.* (1998) with correction for redistribution from Gonzalez *et al.* (1995) and LeBlanc *et al.* (2000). Convection, semi-convection, and the mixing processes are modeled as diffusion processes as described in Richer *et al.* (2000) and Richard et al. (2001).

2.2. *Mixing model*

In this preliminary study, we will use the simplest version of the turbulent diffusion obtained from a self-consistent treatment of meridional circulation following Zahn (1992). The reference rotation model is for a 1.7 $M_{\odot}$ star with a surface velocity of ~ 50 km s^{-1}, and we consider the turbulent diffusion associated with the internal rotation profile at 500 Myr. Turbulence is assumed to be dominated by the shear instability, and the stabilizing effect of mean molecular weight gradients is ignored, both in the development of turbulence and of meridional circulation. Furthermore, no cutoff has been imposed based on a Reynolds number criterion. Details on the model physics are described in Talon (2005).

The complete expression for the turbulent diffusion taking into account thermal diffusivity and horizontal diffusion is

$$\nu_v = \frac{8Ri_c}{5} \frac{(r\,\mathrm{d}\Omega/\mathrm{d}r)^2}{N_T^2/(K+D_h) + N_\mu^2/D_h} \tag{2.1}$$

(Talon & Zahn 1997) and the rotation profile $\mathrm{d}\Omega/\mathrm{d}r$ is the instantaneous one and evolves towards the equilibrium profile.

2.3. *Computation*

All models were assumed homogeneous on the pre-main sequence with the abundance mix defined in Table 1 of Turcotte *et al.* (1998). We have computed models of $1.7M_{\odot}$ and $1.9M_{\odot}$ from the PMS to the subgiant branch, in around 1000 time steps. Each model has about 1500 mesh points. The effect of the mixing is included in our evolutionary models with a parametric mixing diffusion coefficient: $D_{\mathrm{T}} = \omega\rho^n$. In V50 models, ω and n are chosen to give the best fit with the mixing diffusion coefficient obtained with the mixing model for the same mass and surface velocity of ~ 50 km s^{-1} (see Figure 1).

For the V15 models and V5 models the mixing coefficients are obtained from the $\Omega(r)$ equilibrium profiles of the surface velocity of, respectively, ~ 15 km s^{-1} and ~ 5 km s^{-1}. All V50, V15, and V5 models are assumed fully homogenized between the surface and the depth where $\log(T) = 5.3$, which is the temperature where the convective zone due to iron accumulation occurs (Richard *et al.* 2001). The $1.9M_{\odot}$ V5N model have the same mixing coefficient as the V5 one but we do not assume full mixing between the surface and $\log(T) = 5.3$. In all models $n = -0.7$ and in the $1.9M_{\odot}$ V50, V15, and V5 models ω equals respectivly 180, 18, and 1.8.

3. Results

Figure 2 show the effective temperature and surface gravity range covered by our 1.7 $M_{\odot}$ and 1.9 $M_{\odot}$ models. At the age of the Pleiades (~ 100 Myr) and of Praesepe (~ 800 Myr) the 1.7 $M_{\odot}$ models have respectively $T_{\mathrm{eff}} = 8000$ K and $T_{\mathrm{eff}} = 7400$ K, and the 1.9 $M_{\odot}$ models have $T_{\mathrm{eff}} = 8600$ K and $T_{\mathrm{eff}} = 7600$ K.

https://doi.org/10.1017/S1743921304004582 Published online by Cambridge University Press

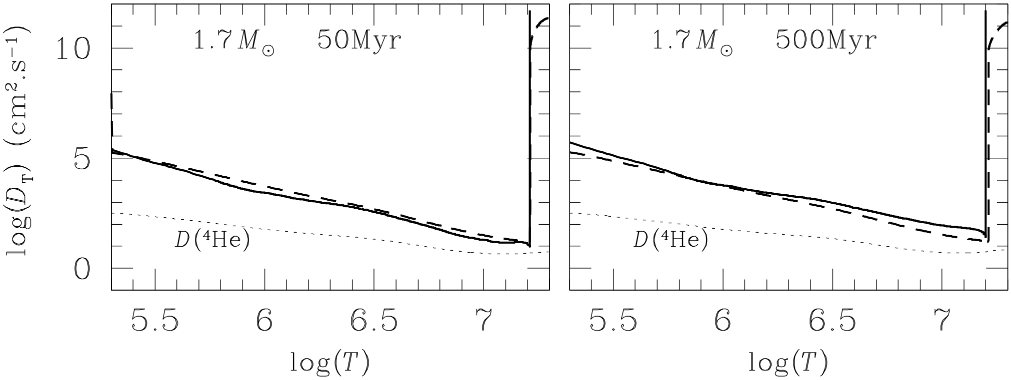

Figure 1. Profile of the mixing diffusion coefficient as a function of temperature in the $1.7\,M_\odot$ models with a surface velocity of ~ 50 km s^{-1} at two ages. The full line represent the coefficient computed in evolutionary models including a self-consistent treatment of the meridional circulation (see section 2.2), the parametric mixing coefficient used in our models of $1.7\,M_\odot$ is also shown (dashed line). The dotted line represent the ^{4}He microscopic diffusion coefficent.

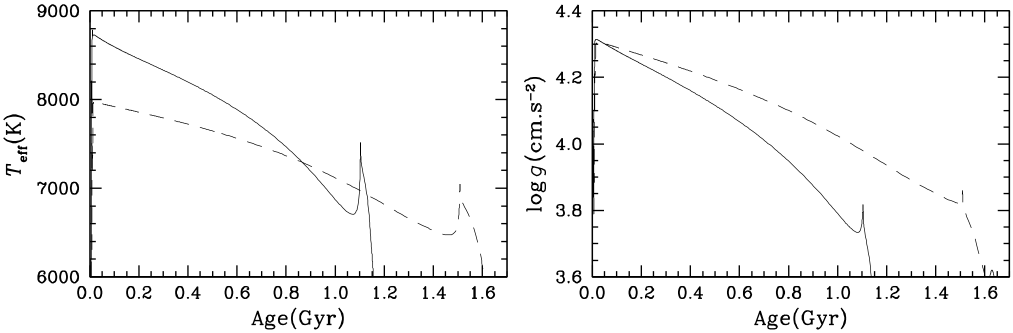

Figure 2. Evolution of the effective temperature and surface gravity in the 1.7 $M_\odot$ (dashed line) and 1.9 $M_\odot$ (full line) models.

Figure 3 presents the mixing coefficent profile as a fonction of depth in our 1.9 $M_\odot$ models and for two models of Richer *et al.* (2000) which reproduce quit well the surface abundances of the Praesepe star HD 73045. Our V15 and V5 models and the Richer *et al.* (2000) models have similar mixing coefficients around $\log(\Delta M/M_*) = -5.0$. The increase of $D_{\rm T}$ around $\log(\Delta M/M_*) = -6.0$, in the V5N model is due to the appearance of the convective zone due to the iron accumulation (Richard *et al.* 2001).

The radiative acceleration profile (upper panels) and abundance profile (lower panels) for Ca and Fe are shown in Figure 4 in our different models at 800 Myr. The right part and the left part of Figure 4 correspond, respectively, to 1.9 $M_\odot$ and 1.7 $M_\odot$ models. One can see the effect of saturation on the Fe radiative acceleration for $\log(\Delta M/M_*) \lesssim -4.5$, reducing the mixing coefficent from V50 to V5 reduces the mixed mass to the depth where Fe is supported by radiative acceleration so its abundance increases, which reduces the radiative acceleration due to saturation. The same effect of saturation is present for Ca in the 1.9 $M_\odot$ V5N model for $\log(\Delta M/M_*) \lesssim -6.6$.

From Figure 4 we also see that to obtain a Ca underabundance, one needs to have a mixed mass of $\sim 10^{-10} M_*$ to $\sim 6\times10^{-9} M_*$, which is even less mixing between the surface convective zone and the iron convective zone than in our V5N model, or $\sim 3\times10^{-7} M_*$ to

https://doi.org/10.1017/S1743921304004582 Published online by Cambridge University Press

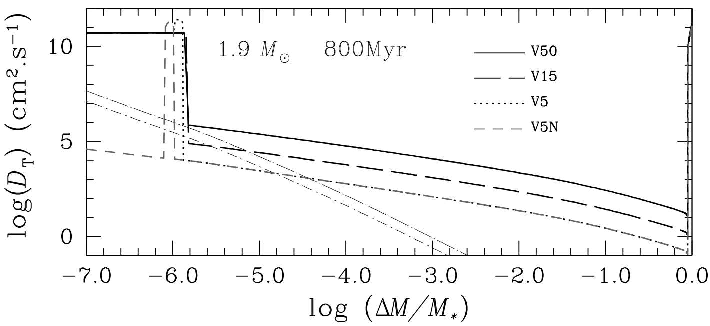

Figure 3. Mixing coefficient vs depth, $\log(\Delta M/M_*) = \log((M_* - m_r)/M_*)$, in the 1.9 $M_\odot$ models at the age of Praesepe cluster ($\sim$ 800 Myr). Richer et a.l (2000) 1.9R300-2 (dot-dashed line) and 1.9R1K-2 (dot-long dashed line) models are also plotted for comparison.

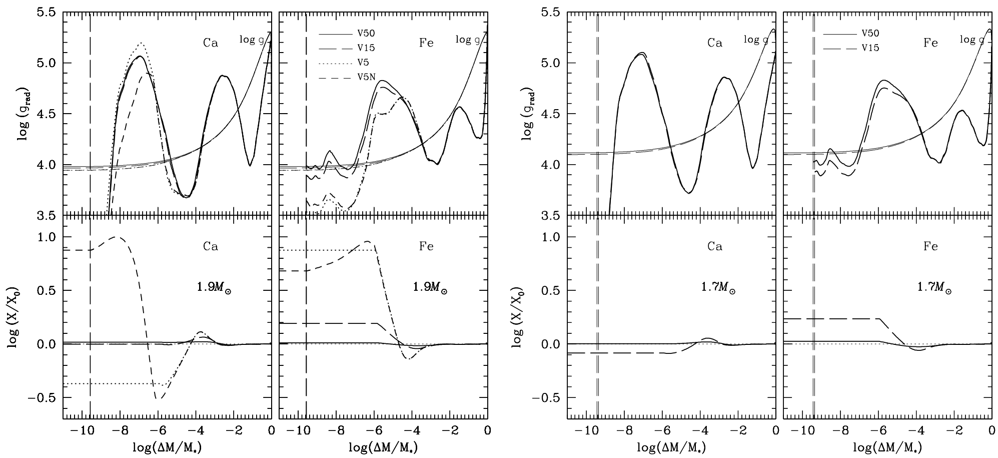

Figure 4. Profiles of radiative acceleration (upper panels) and abundance (lower panels) of Ca and Fe at 800 Myr in our different models (left part: 1.9 $M_\odot$; right part: 1.7 $M_\odot$). The vertical long dashed lines show the bottom of the surface convective zone.

$\sim 10^{-4} M_*$. The V5N model show a Ca overabundance due to the partial mixing between the surface convective zone and the iron convective zone which is not compatible with AmFm stars.

Figure 5 shows the comparison between the predicted abundances of our models at 800 Myr and the abundances determined from spectroscopic observation of the Praesepe star HD 73045 (Hui-Bon-Hoa *et al.* 1997, Burkhart & Coupry 1998). The 1.7 $M_\odot$ and 1.9 $M_\odot$ models have compatible effective temperature with HD 73045 ($T_{\rm eff} \simeq 7500$ K) at the age of Praesepe. The left panel shows the predicted abundances in our 1.7 $M_\odot$ and 1.9 $M_\odot$ V15 models which have similar abundance anomalies. The central panel shows the predicted abundances in our 1.9 $M_\odot$ models with different mixing parametrization and in Richer *et al.* (2000) R1K-2 model. The V15 and V5 models bracket the abundances of HD 73045. The right panel shows the effect of the different prescription on the mixing between the surface convective zone and the Iron convective zone, elements between Cl and Mn are more supported by radiative acceleration in the V5N model than in the V5 model while elements between He and S settle faster in the V5N model than in the V5 model.

https://doi.org/10.1017/S1743921304004582 Published online by Cambridge University Press

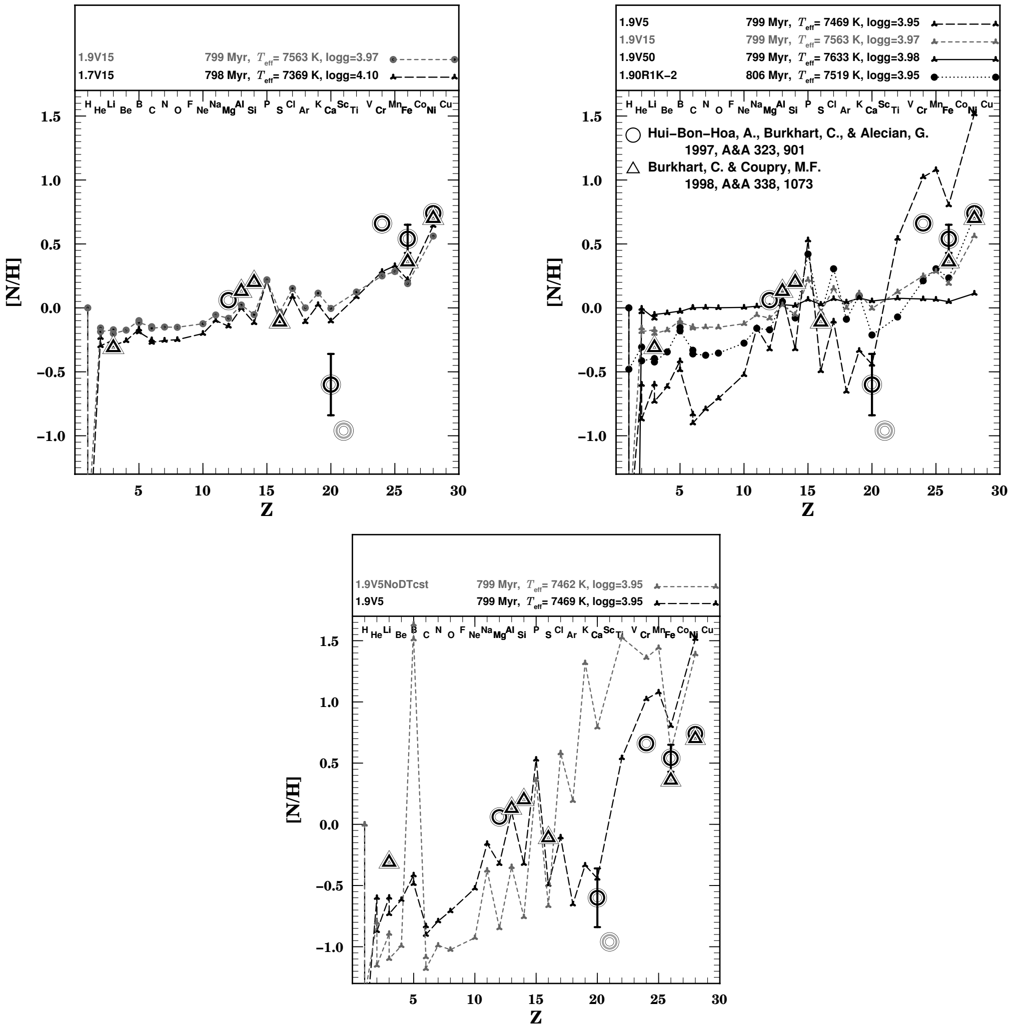

Figure 5. Predicted abundances around 800 Myr in different models compared to the abundance determined from spectroscopic observation of the Praesepe star HD 73045. (HIP 42247)

4. Discussion

The results presented here show that, in the model, turbulence seems to be too strong to allow the Am phenomenon to occur at a reasonable velocity (i.e., 50 km s^{-1}). This could be related to several features that have been neglected here:

• The leading coefficient of the turbulent diffusion coefficient $8Ri_c/5$ (cf. Eq. 2.1) is not determined from first principles and could vary by a factor of a few;

• The effect of the build up of mean molecular weight gradients has been overlooked here;

• Strong horizontal diffusion could reduce the efficiency of mixing (cf. Vincent *et al.* 1996).

The first factor is most probably not sufficient to explain the discrepancy. However, the stabilizing effect of mean molecular weight gradients on turbulence as well as the role of strong horizontal diffusion should be examined in more details.

https://doi.org/10.1017/S1743921304004582 Published online by Cambridge University Press

Acknowledgements

This research was partially supported at the Université de Montréal by NSERC. We thank the Réseau Québécois de Calcul Haute Performance (RQCHP) for providing us with the computational resources required for this work.

References

Bahcall, J.N. & Pinsonneault, M.H., 1992 *Rev. Mod. Phys.* **64**, 885
Burgers, J. M., 1969, *Flow equations for composite gases* (New York: Academic Press)
Burkhart, C. & Coupry, M.F. , 1998, *A&A* **338**, 1073
Christensen-Dalsgaard, J. & Däppen, W., 1992 *ARA&A* **4**, 267
Eggleton, P.P., Faulkner, J. & Flannery, B.P., 1973 *A&A* **23**, 325
Gonzalez, J.-F., LeBlanc, F., Artru, M.-C. & Michaud, G. , 1995, *A&A* **297**, 223
Hui-Bon-Hoa, A., Burkhart, C. & Alecian, G. , 1997, *A&A* **323**, 901
LeBlanc, F., Michaud, G. & Richer, J., 2000, *ApJ* **538**, 876
Michaud G. 2005, *These Proceedings*, 173
Richard, O., Michaud, G. & Richer, J., 2001, *ApJ* **558**, 377
Richer, J., Michaud, G., Rogers, F., Iglesias, C., Turcotte, S. & LeBlanc, F., 1998, *ApJ* **492**, 833
Richer, J., Michaud, G. & Turcotte, S., 2000, *ApJ* **529**, 338
Talon, S. & Zahn, J.-P., 1998 *A&A* **329**, 315
Talon S. 2005, *These Proceedings*, 59
Titus, J. & Morgan, W.W., 1940 *ApJ* **92**, 256
Turcotte, S., Richer, J., Michaud, G., Iglesias, C. A. & Rogers, F. J., 1998 *ApJ* **504**, 539
Vincent, A., Michaud, G. & Meneguzzi, M., 1996 *Phys. Fluids* **8 (5)**, 1312
Zahn, J.-P., 1992 *A&A* **265**, 115

https://doi.org/10.1017/S1743921304004582 Published online by Cambridge University Press