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# Processes at the turnoff

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**Abstract.** Stellar evolution models taking into account the atomic diffusion of 28 species, have been calculated for Pop II stars of 0.5 to 1.2 $M_\odot$ with [Fe/H] from −4.31 to −0.71. Overabundances are expected in some turnoff stars with $T_{\rm eff} \geq 5900$ K. They depend strongly on the metallicity of the cluster. At the metallicity of M 92, they reach a factor of 10 for many species, at 12 Gyr, but a factor of at most 2, at 13.5 Gyr. Series of models were also calculated with turbulence to determine to what extent it reduces predicted abundance anomalies. The level of abundance anomalies observed in turnoff stars may then determine a level of turbulence. Even in the presence of turbulence however, allowance for diffusive processes leads to a 10%-12% reduction in age at a given turnoff luminosity. For M 92 an age of 13.5 Gyr is determined.

## 1. Atomic diffusion in stellar evolution

In self-consistent stellar evolution models, all basic physical processes must be taken into account throughout the star. In "standard" stellar evolution for turnoff stars, convection homogenizes convection zones but particle transport is arbitrarily assumed negligible outside of convection zones. However, atomic diffusion is a basic physical transport process that always occurs and must be included whenever macroscopic motions that are rapid enough to wipe out its effects are not present. The only series of models calculated up to now that include particle transport in a self-consistent manner are those of the Montreal model series starting with Turcotte et al. (1998) and Richer et al. (1998) where all effects of atomic diffusion are taken into account. Only quantities determined from first principles are used except for the mixing length parameter, $\alpha$, which is calibrated using the Sun (Turcotte et al., 1998). These are then the first self consistent models calculated from first principles.

This work was made possible by the recent availability of large atomic data bases that include the data needed to calculate radiative accelerations, $g_{\rm rad}$, throughout stellar models (Iglesias & Rogers, 1991, 1993, 1995, 1996; Rogers & Iglesias, 1992a,b; Seaton, 1993). Using this data, the $g_{\rm rad}$ and Rosseland opacities are continuously calculated during evolution as the relative concentration of species changes (Richer et al., 1998). They play the major role in the particle transport equations. The formalism of Burgers (1969) is used to calculate the transport velocities leading to 56 (28 chemical species and 2 equations per species) non-linear coupled differential equations. Uncertainties in the transport coefficients were discussed by Michaud (1991) and Schlattl & Salaris (2003).

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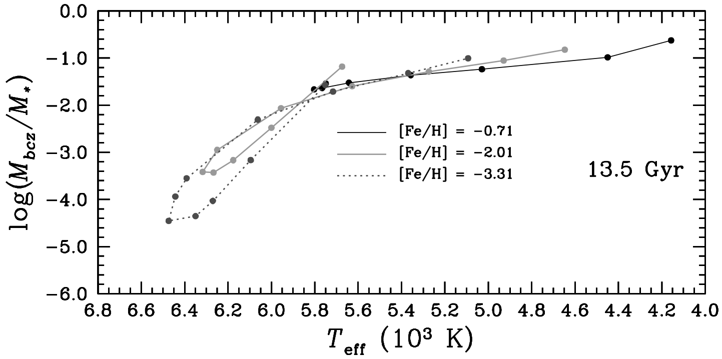


**Fig. 1.** Mass above the base of the surface convection zone in stars of 0.5 to 0.87 $M_\odot$ at 13.5 Gyr and for three different metallicities. In stars with larger original metallicity, $M_{\rm bcz}$ is larger at turnoff at a given age. At [Fe/H]]= −0.71 it is nearly 1000 times larger than at [Fe/H]= −3.31. At a given $T_{\rm eff}$, $M_{\rm bcz}$ is nearly independent of metallicity.

Evolutionary models have been calculated for Pop II stars of 0.5 to 1.2 $M_\odot$ with $[{\rm Fe/H}]_0$ from −4.31 to −0.71 (Richard et al., 2002b,a; VandenBerg et al., 2002).

## 2. Chemical composition

The mass above the base of the surface convection zone, $M_{\rm bcz}$, depends on metallicity and varies during evolution. This plays a major role in the evolution of surface abundance anomalies in turnoff stars. The $M_{\rm bcz}$ decreases as $T_{\rm eff}$ increases and, at a given age, the maximum $T_{\rm eff}$ of stars in a cluster (or turnoff $T_{\rm eff}$) varies with the cluster metallicity (see Fig. 1 of this paper and Fig. 2 of Richard et al. 2002a), though at a given $T_{\rm eff}$ the $M_{\rm bcz}$ does not vary much with metallicity. During evolution, $M_{\rm bcz}$ decreases until slightly past turnoff (see Figures 1 and 12 of Richard et al. 2002a). The reduction of $M_{\rm bcz}$ around turnoff reduces the diffusion time scale and leads to a maximum of the expected abundance anomalies there. Furthermore, $g_{\rm rad}$ (see Fig. 2 of Richard et al. 2002b and Fig. 3 of Richard et al. 2002a) are more frequently larger than gravity below a thinner surface convection zone, so that overabundances occur preferentially in turnoff stars of low metallicity globular clusters.

Consider for instance the expected Fe abundance anomalies. In Figure 2 are shown both the $g_{\rm rad}$(Fe), and the [Fe/H] isochrones for various metallicities. The $g_{\rm rad}$(Fe) is some 5 time larger in the lower metallicity cluster considered than in the cluster with [Fe/H] = −0.71. This explains part of the dependence of abundance anomalies on metallicity. But the most important cause for the variations from cluster to cluster is the dependence of $M_{\rm bcz}$ on metallicity. In a 0.8 $M_\odot$ star of 12 Gyr, the $M_{\rm bcz}$ of a star with [Fe/H] = −0.71 is larger by a factor of $10^4$ than that of a star with [Fe/H] = −2.31. While at a metallicity of [Fe/H] = −2.31, $g_{\rm rad}$ is larger than gravity over 4 orders of magnitude in mass, it just equals gravity below the surface convection zone when [Fe/H] = −1.61.

The [Fe/H] isochrones are shown on Figure 2 at 13.5 Gyr, the age determined for M 92 (see Section 4). The spread of abundance anomalies expected at turnoff depends strongly on the metallicity of the cluster. At the metallicity of M92 (original [Fe/H] = −2.31), the surface [Fe/H] is up to 0.4 dex smaller than the original value in stars slightly before turnoff while it is close to the original value in stars of the same $T_{\rm eff}$ which are just past turnoff *i.e.* starting on their subgiant branch. In M 92 one then expects a 0.4 dex range in Fe abundance for stars close to turnoff. In main-sequence stars with $T_{\rm eff} \leq 5900$ K, the settling becomes progressively less efficient as one considers cooler stars. It is by 0.3 dex at 6000 K but by 0.1 dex at $T_{\rm eff}$ = 5000 K. Similarly, on the subgiant branch, Fe is close to normal at 6200 K, 0.3 dex

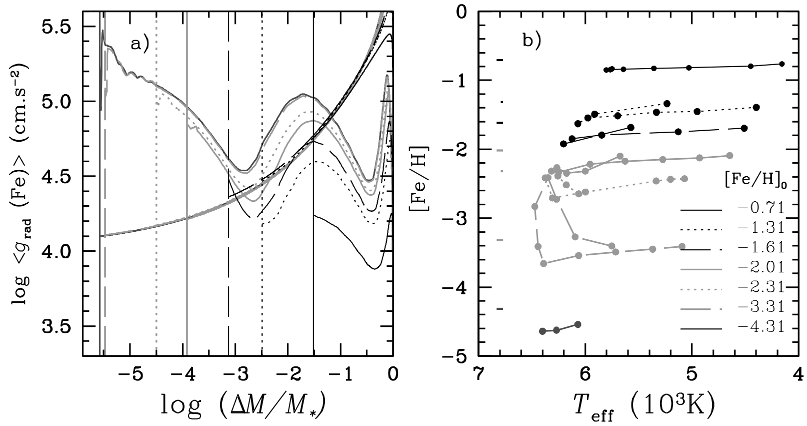


**Fig. 2.** $g_{rad}$(Fe) at 12 Gyr in a 0.8 $M_{\odot}$ star (part a) and abundance isochrones of Fe in clusters of various metallicities at 13.5 Gyr (part b). On part a), vertical lines show the position of the bottom of the surface convection zone. On part b), the original [Fe/H] values are indicated by a short line close to the left hand ordinate; there are generalized underabundances of Fe for [Fe/H] $\geq -2.01$; the underabundances reach a factor of 2 around turnoff. There is a strong dependence of the anomalies on the original [Fe/H] value. For [Fe/H] = −3.31, overabundances by a factor of 5 appear at turnoff. See Fig. 3 and Fig. 11 of Richard et al. 2002a for, respectively, the $g_{rad}$ and the isochrones of other chemical species included.

below normal at 6000 K but approaches 0.03 dex underabundance, only just before the giant branch at around 5000 K. As they further cool beyond $T_{eff}$= 5900K, all stars have larger $M_{bcz}$ after than before turnoff: as they are moving towards the giant branch their convection zones become much more massive (see for instance Fig.12 of Richard et al. 2002a). However, even quite high up on the giant branch, after the first dredge-up, there remains a 0.015 dex surface underabundace of Fe caused by some Fe remaining bound in the central core (see Fig. 3) where it accumulated by settling throughout the stellar lifetime.

Large [Fe/H] variations in turnoff stars are limited to clusters with [Fe/H] $\leq -2.31$. They disappear for clusters with [Fe/H] between −2.31 and −2.01. As metallicity is increased from [Fe/H] = −2.31 to −2.01, $M_{bcz}$ increases at turnoff, and Fe ceases being supported sufficiently by $g_{rad}$(Fe) below the convection zone for overabundances of $X$(Fe) to appear. However $g_{rad}$(Fe) still reduces gravitational settling significantly in turnoff stars.

For other atomic species larger anomalies are frequent. At 13.5 Gyr, overabundances reach factors of 3.0 for many species between Si and Ca in turnoff stars with the metallicity of M 92 (see Fig. 5 of Richard et al. 2002a). Boron and chemical species heavier than CNO are affected by $g_{rad}$. Mainly because of the larger $M_{bcz}$ the effect of $g_{rad}$ decreases as the original [Fe/H] increases. There remains a generalized underabundance by 0.18 dex at [Fe/H] = −0.71.

Much smaller abundance anomalies than in M 92 are expected in relatively metal rich globular clusters such as M 5, M 71 or 47 Tuc. Even in NGC 6397, which is only a factor of 2 more metal rich than M92, atomic diffusion is expected to lead to smaller anomalies than in M92.

Expected overabundances are much larger if the clusters are younger. At 12 Gyr (see Fig. 10 and 13 of Richard et al., 2002b), overabundance factors may reach 10 in some cases (e.g. for Al or Ni) while others are limited to 3 (e.g. for Fe).

In field stars with $T_{eff} \geq$ 6000K and [Fe/H] $< -2.3$, the abundance anomalies might be even larger than in M92.

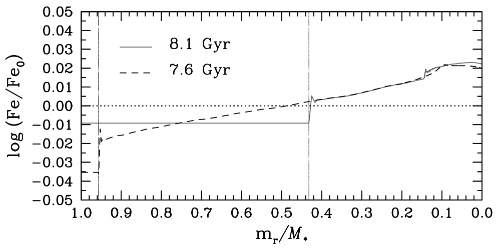


**Fig. 3.** Abundance profile of Fe within a 1.09 $M_\odot$ solar metallicity star at two evolutionary times, just before the end of the first dredge-up and 0.5 Gyr before. There remains a small central condensation of Fe that leads to an underabundance of the surface Fe by 0.01 – 0.015 dex in the older globular cluster giants even after dredge-up. The vertical lines indicate the bottom of the surface convection zone.

## 3. Turbulence

In the halo, Spite & Spite (1982) have shown that nearly all dwarf stars with $T_{\rm eff} \geq 5500$ K have very similar Li abundance. Furthermore the Li concentration is constant in stars when the Fe concentration varies by more than a factor of 100 from [Fe/H] = −3.7 to −1.5 (Cayrel, 1998).

The constancy of the Li concentration appears to contradict results presented in Section 2. This may be seen from the upper part of Figure 4 where is shown the calculated surface Li concentration (open circles) in 100 stars of initial metallicity $\log Z = -4$. These are the result of a Monte Carlo simulation based on interpolations among a dozen complete evolutionary tracks (see Fig. 15 of Richard et al. 2002a for the results of a different draw in which $Z$ was also allowed to vary). The age of stars was randomly generated around 13.5 Gyr with a gaussian distribution of 1.0 Gyr standard deviation. No turbulence is assumed outside of convection zones in these evolutionary models. Observations of Li abundance in metal poor halo stars by Spite et al. (1984) (filled triangles) and by Ryan et al. (1999) (filled squares with error bars) are also shown. No effort was made to fit the Li observations below 5500 K since these may have been affected by pre-main sequence evolution. However it does not appear possible to avoid a progressive reduction of the Li abundance as $T_{\rm eff}$ increases above 6000 K in our models without turbulence. This is not observed.

As in *normal* Pop I stars, this seems to require that an additional mixing process be present at least in some stars (Michaud & Charbonneau, 1991). The effect of tubulence has been investigated in detail and is discussed below. Mass loss (Vauclair & Charbonnel, 1995) and meridional circulation (Théado & Vauclair, 2003) have also been suggested and while we do not discuss them here, we do not exclude their potential role.

The turbulence parametrization used is shown in Fig. 6 of Richard et al. (2002b). In the T6.09 model, the turbulent diffusion coefficient, $D_T$, is 400 times larger than the He atomic diffusion coefficient, $D$(He), at $\log T = 6.09$ and varying as $\rho^{-3}$. The various models considered differ only by the temperature at which $D_T/D(\mathrm{He}) = 400$. Varying this depth is equivalent to varying the strenth of turbulent transport at a given temperature. Richard et al. (2002b) chose to link $D_T$ to temperature in order to link turbulent transport to Li destruction, since the $^7\mathrm{Li}(p,\alpha)^4\mathrm{He}$ reaction is highly $T$ sensitive. This allows determining a $D_T$ which minimizes Li destruction throughout the evolution of all stellar masses considered, but which still minimizes Li settling. The physical origin of such a $D_T$ remains to be determined. It is a constraint that physical models of turbulence for those stars must pass if the reduction of surface Li abundance is to be minimized; it is a constraint imposed by observations.

Series of models with different assumptions about the strength of turbulence were calculated in order to determine the turbulent transport coefficient that minimizes Li abundance variations. The results of a Monte Carlo simulation for 100 stars obtained with the series of models that minimizes the spread on the Li plateau are shown on the lower part of Figure 4. This shows that the high constancy of the Li abundance observed above 5600 K can

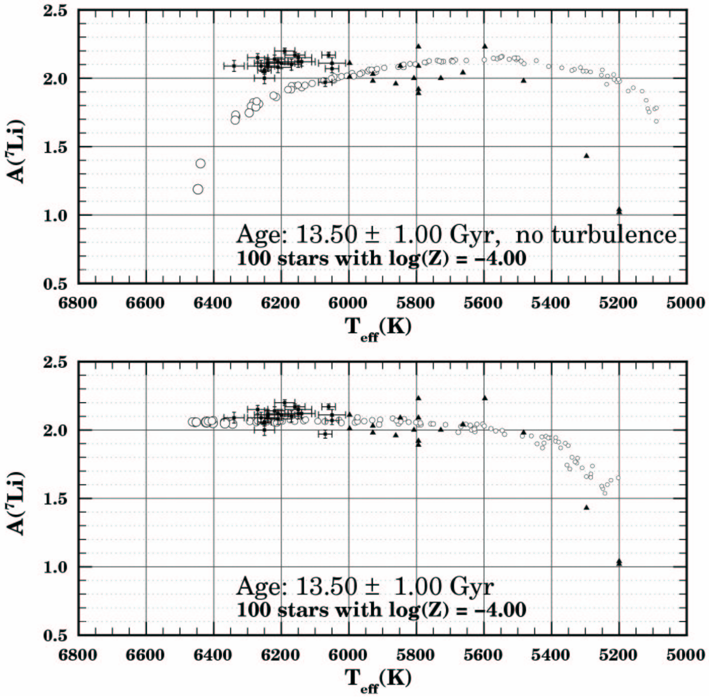


**Fig. 4.** Predicted Li abundance in stars without turbulence (upper part) and with just enough turbulence to minimize Li abundance reduction. The size of circles is a function of the radius of the stars in order to indicate roughly their evolutionary stage. For the calculations, the initial value of A($^7$Li) is 2.3. Further description is found in the text. Also shown are observations in metal poor halo stars by Spite et al. (1984; triangles) and by Ryan et al. (1999; squares with error bars).

be easily reproduced[1] in self consistent models with turbulence. Even when turbulence is adjusted to minimize the reduction of Li abundance, there remains a reduction by a factor of at least 1.6 from the original Li abundance.

The level of abundance anomalies observed in turnoff stars may then determine a level of turbulence. In addition to observations of Li in halo stars, recent observations of abundances of metals in globular clusters may also be compared to calculated surface abundances. Expected abundance anomalies in a 0.8 $M_\odot$ star of 12 Gyr are shown in Figure 5 for two different turbulent transport coefficients and compared to results for atomic diffusion only. The T5.5 model was found by Richer et al. (2000) to reproduce approximately the anomalies observed in AmFm stars. In this 0.8 $M_\odot$ Pop II star, it reduces the logarithm of abundance anomalies by a factor of order 2 for many species. The T6.09 model leaves a 0.1−0.2 general underabundance of metals but largely eliminates variations between species.

In Figures 13 and 14 of Richard et al. (2002b) are shown abundance isochrones for many species at 12 and 13.5 Gyr in a cluster with the metallicity of M 92. The T5.5 and T6.09 models were used. They allow to generalize to different stellar masses the remarks just made for a 0.8 $M_\odot$ star. However one notes that there remains a noticeable (0.1dex) effect of $g_{\rm rad}$ for Fe peak species in stars around turnoff even with T6.09 turbulence.

[1] The simulated abundances are perhaps more constant than required by observations, so turbulence could be a little smaller.

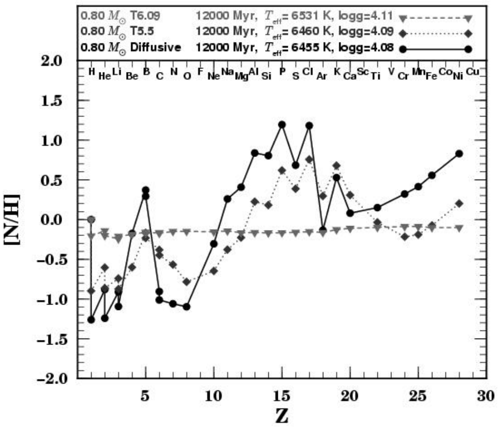


**Fig. 5.** Abundances of various species at 12 Gyr at the surface of a 0.8 $M_\odot$ star ($[Fe/H]_0 = -2.31$) in the case of atomic diffusion only and when two turbulent transport parametrizations (T6.09 and T5.5) are included. Even in presence of the turbulent transport that minimizes Li abundance variations (T6.09), there remains a 0.1−0.2 dex underabundance of metals.

Comparisons were made to abundance observations of metals in a number of clusters by Richard et al. (2002b,a) to determine if hydrodynamical processes competing with atomic diffusion are required by observations of metals. For most metals the situation remains ambiguous: observations, taking into account the error bars, do not yet require additional processes. Monte Carlo simulations show that the Spite plateau for Li in low metallicity field stars remains the strongest argument for the presence of a process competing with atomic diffusion. Salaris & Weiss (2001) question this conclusion. They consider it is premature until larger samples of stars are available or it is confirmed by the observations of metals in turnoff stars of clusters.

## 4. Age

Using evolutionary tracks calculated with the T6.09 model by Richard et al. (2002b), VandenBerg et al. (2002) determined an age of 13.5 Gyr for M 92 or ~2.0 Gyr less than had been obtained in the absence of diffusion by Grundahl et al. (2000). It is consistent with the age determined using WMAP data. Abundance variations of [Fe/H] were taken into account in the isochrone determination (see also Salaris et al. 2000 and Weiss 2002). The observed color magnitude isochrone is very well reproduced (see Fig. 6). Note that the evolutionary models used here include T6.09 turbulence and satisfy the requirement of the Li Spite plateau (see Sec. 3).

Independent of the degree of turbulence in the outer regions, gravitational settling of He in the central region reduces the lifetime of Pop II stars by 4 to 7 % depending on the criterion used. The age reduction obtained by isochrone fitting is larger than that because of other subtle effects brought by the use of diffusive models. For instance, the value of $\alpha$ determined using the Sun is different for diffusive and non-diffusive models (Turcotte et al., 1998). In their review of age determinations using globular clusters, VandenBerg et al. (1996) emphasized that the giant branch $T_{\rm eff}$ is sensitive to $\alpha$. This turns out to be important in fitting M 67 color magnitude isochrones (Michaud et al., in preparation).

If *some* stars did not have T6.09 turbulence, this would lead to a color spread, equivalent to a difference between isochrones of 1.0 Gyr as may be seen from Figure 3 of VandenBerg et al. (2002). If abundance variations seen in turnoff stars of M 92 are confirmed (see Section 2), it suggests that turbulence varies among these stars and then a color spread is expected.

## 5. Conclusion

We summarize what to expect for M 92. Atomic diffusion processes can lead to both under and overabundances. Star to star variations are expected at turnoff and have perhaps been seen in some turnoff stars (King et al., 1998). This needs not be in all stars since only a fraction may not have turbulence below their surface convection zone. If turbulence is to minimize lithium variations (T6.09) in Pop II field stars, one still expects a 0.2 dex reduction of lithium from its original abundance and a 0.1 dex reduction of metals also follows in turnoff stars. Turnoff stars have 0.1 dex

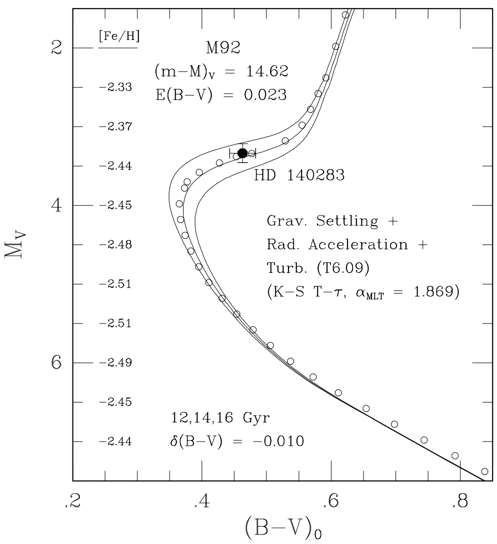


**Fig. 6.** Fit of the M 92 fiducial to the field subgiant HD 140283 (Stetson & Harris, 1988); isochrones were calculated with the T6.09 model and are shown at three evolutionary epochs. The predicted variation in [Fe/H] at 14 Gyr is indicated along the ordinate. From VandenBerg et al. (2002).

lower metallicity than luminous giants (even in presence of T6.09 turbulence). According to VandenBerg et al. (2002) with T6.09 turbulence, the morphology of cluster isochrones is very well reproduced. M 92 then has an age of 13.5 Gyr, or 2 Gyr less than determined by Grundahl et al. (2000). If some stars did not have T6.09 turbulence, this would lead to a color spread equivalent to a difference between isochrones of 1.0 Gyr.

In M 92, Richard et al. (2002b) have shown that, at least in a 0.8 $M_\odot$ star, *it is a better approximation not to let Fe diffuse* than to calculate its gravitational settling without including the effects of $g_{\rm rad}$(Fe). This is not true in all cluster stars however since, below 0.7 $M_\odot$, $g_{\rm rad}$(Fe) plays a relatively small role.

Reduction of metallicity beyond [Fe/H]= −3.31 does not cause further structural changes to models (see Fig. 1 of Richard et al. 2002a). Below that metallicity, all metals may be treated as trace elements.

In globular clusters, atomic diffusion is now known to play a role in white dwarfs, HB stars, for age determination and for abundance anomalies in some turnoff stars.

Since most of the halo field stars observed by Ivans et al. (2003) have $T_{\rm eff} \geq 5900$ K, their abundances may have been modified by atomic diffusion. Many of their relatively more abundant species are expected to have overabundances as may be seen in Figure 5.

The turbulent transport coefficients required in the Sun to lead to the observed Li abundance (Proffitt & Michaud, 1991) turn out to be only a factor of about 10 larger than the one needed to minimize Li destruction in Pop II stars. This should not be viewed as implying a fundamental value to these coefficients. It merely shows surprisingly similar mixing in both cases.

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## References

Burgers, J. M. 1969, Flow Equations for Composite Gases (New York: Academic Press)
Cayrel, R. 1998, Space Science Reviews, 84, 145
Grundahl, F. et al. 2000, AJ, 120, 1884
Iglesias, C. A. & Rogers, F. J. 1991, ApJ, 371, L73
—. 1993, ApJ, 412, 752
—. 1995, ApJ, 443, 460
—. 1996, ApJ, 464, 943
Ivans, I. I. et al. 2003, ApJ, 592, 906
King, J. R., Stephens, A., Boesgaard, A. M., & Deliyannis, C. F. 1998, AJ, 115, 666
Michaud, G. 1991, Ann. Phys. (Paris), 16, 481
Michaud, G. & Charbonneau, P. 1991, Space Sci. Rev., 57, 1
Proffitt, C. R. & Michaud, G. 1991, ApJ, 380, 238
Richard, O., Michaud, G., & Richer, J. 2002a, ApJ, 580, 1100
Richard, O. et al. 2002b, ApJ, 568, 979
Richer, J. et al. 1998, ApJ, 492, 833

Richer, J., Michaud, G., & Turcotte, S. 2000, ApJ, 529, 338
Rogers, F. J. & Iglesias, C. A. 1992a, ApJS, 79, 507
—. 1992b, ApJ, 401, 361
Ryan, S. G., Norris, J. E., & Beers, T. C. 1999, ApJ, 523, 654
Salaris, M., Groenewegen, M. A. T., & Weiss, A. 2000, A&A, 355, 299
Salaris, M. & Weiss, A. 2001, A&A, 376, 955
Schlattl, H. & Salaris, M. 2003, A&A, 402, 29
Seaton, M. J. 1993, in Inside the Stars, IAU COLLOQUIUM 137, Vienna, April 1992, ASP Conference Series, 40, ed. W. W. Weiss & A. Baglin (San Francisco: ASP), 222
Spite, F. & Spite, M. 1982, A&A, 115, 357
Spite, M., Maillard, J.-P., & Spite, F. 1984, A&A, 141, 56
Stetson, P. B. & Harris, W. E. 1988, AJ, 96, 909
Théado, S. & Vauclair, S. 2003, ApJ, 587, 784
Turcotte, S., Richer, J., Michaud, G., Iglesias, C., & Rogers, F. 1998, ApJ, 504, 539
VandenBerg, D. A., Bolte, M., & Stetsson, P. B. 1996, ARA&A, 34, 461
VandenBerg, D. A., Richard, O., Michaud, G., & Richer, J. 2002, ApJ, 571, 487
Vauclair, S. & Charbonnel, C. 1995, A&A, 295, 715
Weiss, A. 2002, in Proceedings of the First Eddington Workshop on Stellar Structure and Habitable Planet Finding, 11 - 15 June 2001, Córdoba, Spain. Editor: B. Battrick, Scientific editors: F. Favata, I. W. Roxburgh & D. Galadi. ESA SP-485, Noordwijk: ESA Publications Division, 2002, 57