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# Main Sequence Evolution, Abundance Anomalies and Particle Transport

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**Abstract.** The availability of large atomic data bases has made it possible to calculate stellar evolution models taking into detailed account the abundance variations of all important contributors to opacity. In a first step, in addition to nuclear reactions, the atomic diffusion, radiative accelerations and opacity are continuously calculated during evolution taking the abundance changes of 28 species into account. This leads to the first self consistent main sequence stellar evolution models. In A and F stars ($M \geq 1.5M_{\odot}$) an iron peak convection zone is shown to appear at a temperature of 200 000 K. The calculated surface abundance anomalies, that follow without any arbitrary parameter, are very similar to those observed in AmFm stars in open clusters except that they are larger by a factor of about 3. The second step, is then to introduce a competing hydrodynamical process. To reduce the calculated anomalies to the observed ones, turbulence has been introduced. It is found that the mixed zone must be about 5 times deeper than the iron convection zone. Detailed comparisons to a few AmFm stars have been carried out. The determination of the abundance anomalies of a large number of atomic species (20 to 30 are probably accessible) makes it possible to constrain stellar hydrodynamics. In clusters, the original abundances and age may be known and the accurate determination of surface abundances may constrain turbulence, mass loss and differential rotation when the required atomic data bases are available and used for the modeling of particle transport in stellar evolution.

## 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, convection is assumed to homogenize 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 absent. The only series of models calculated up to now that include particle transport in a self-consistent manner are those of Turcotte et al. (1998b) where all effects of atomic diffusion are taken into account. They were made

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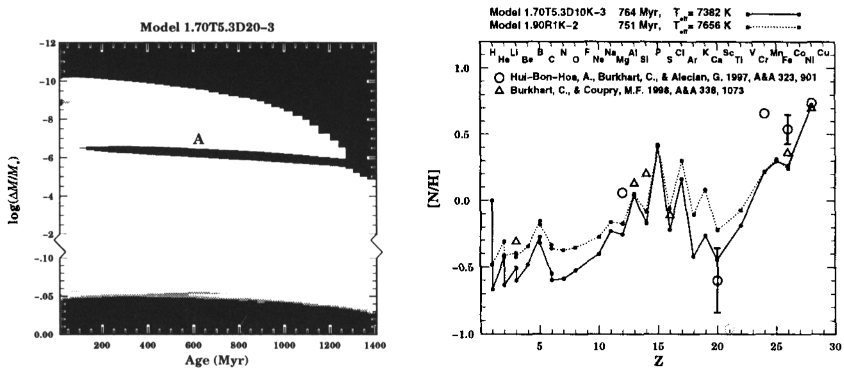


Figure 1. The evolution of convection zones is shown in the left panel for a $1.7 M_\odot$ model (see Richer et al. 2000 for notation); the iron convection, noted A, appears after 100Myr. The comparison of the observed abundances for HD73045 in Praesepe with the surface abundances predicted by a 1.7 and a $1.9\,M_\odot$ model, are illustrated in the right panel.

possible by the recent availability of large atomic data bases that include the atomic data needed to calculate radiative accelerations throughout stellar models (Seaton 1993; Iglesias & Rogers 1996 and refs. therein). Using this data the radiative accelerations and Rosseland opacities are continuously calculated during evolution. They are included in the particle transport equations leading to 56 ($2 \times 28$) non-linear coupled differential equations (Burgers 1969). Models were evolved from the zero age main sequence to the bottom of the giant branch for stars with mass from 1.0 to $4.0\,M_\odot$. In them, selective radiative acceleration causes an accumulation of iron-peak elements, and especially Fe, at a temperature of about 200 000 K where these elements are a major contributor to opacity (Turcotte et al. 1998a). An iron convection zone then appears in models of $1.5\,M_\odot$ or more (see Fig. 1a).

While 1 CPU of the SGI Origin 2000 used takes 30 minutes to compute the evolutionary track of a standard model, it takes 4 CPUs 4 days for a self-consistent model. The particle transport equations, along with an approximate treatment of turbulent transport, were described in Richer et al. (2000).

## 2. AmFm stars

Evolutionary model calculations have been carried out (Richer et al. 2000) varying turbulence in the outer stellar regions in order to improve the agreement with the observed anomalies in AmFm stars. It is shown that the anomalies depend on only one parameter, namely the depth of the zone mixed by turbulence. The calculated surface abundances are compared to observations of a number of recently observed AmFm stars. For Sirius A, 16 abundances (including 4 upper limits) are available for comparison. Of these, 12 are well reproduced by the model, while 3 are not so well reproduced and one is a very uncertain observation. 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 are compared) agree reasonably well with the calculated models for the five stars which are compared (see Fig. 1b for one example). The zone mixed by turbulence must be slightly deeper than the iron convection zone, reducing the abundance anomalies to values which are too small for iron peak convection zones to develop in our models. The origin of the mixing process then remains uncertain.

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. The pulsational properties of these models appear to be compatible with the observed pulsations of $\delta$ Scuti and AmFm stars (see Turcotte et al. 2000).

## 3. Constraints on stellar turbulence

From a comparison of observations to a large number of calculated evolutionary tracks (a few hundred have been calculated), it is possible to impose constraints on stellar hydrodynamics. **1)** In AmFm stars (Richer et al. 2000) spanning the range $7000 < T_{\rm eff} < 10000$ K the mixed mass $\sim 10^{-5}M$ and the anomalies $\sim \times 10$. **2)** Furthermore, since it takes some $10^8$ yr to establish the anomalies, the maximum mass loss rate that is allowed, is of order $\sim 10^{-5}M/10^8$ yr $\sim 10^{-13}M_\odot$ yr$^{-1}$. **3)** For stars to have anomalies $< 0.1$ dex, it is necessary (Turcotte et al. 1998a) that the mixed mass $\gtrsim 10^{-3}M$. **4)** For the p+Li reaction to lead to Li destruction by $\times 10^{-2}$, a mixed mass $\sim 10^{-2}M$ is needed in the Sun, in Li gap stars ($T_{\rm eff} \sim 6700$ K) and in stars of other masses. See Richard, Michaud, Richer, and Talon (in preparation) for this and the following properties. **5)** The same formula $D_T = D_0(\rho/\rho_0)^{-n}$ that reproduces the Li gap also leads to the observed Li destruction in the Sun within a factor of $\sim 10$. **6)** For Be to be destroyed by less than $\times 2$ in the Sun, one needs $n \gtrsim 2.5$. **7)** In F or A stars, for Li not to be destroyed the mixed mass must be $< 10^{-2}$ while for metals to be normal it must be $> 10^{-3}M$ so that those stars whose mixed mass remains within that range throughout their main sequence evolution would be normal stars with their original Li. This constraint is however rather severe.

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