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**Memorie** della

# Low mass stars

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**Abstract.** Low-mass stars dominate the population of clusters and old galaxies and serve as important tools for understanding the history of galaxies. I will review some recent developments and open questions concerning our understanding of these comparatively simple stellar objects.

**Key words.** Stars: low mass – Stars: evolution – Stars: abundances

## 1. New solar abundances

New determinations of the solar abundances by Asplund et al. (2004) resulted in much lower abundances of many key elements such as O, N, C. The total solar metallicity dropped from 1.7% to 1.2%, and $Z/X$ from 0.230 to 0.165. As a consequence, the excellent agreement between the solar model and the seismic Sun in terms of depth of convective envelope, surface helium abundance, and sound speed profile has vanished (Turck-Chièze et al. 2004; Bahcall et al. 2005a). Whether the latest development of a significantly higher Ne abundance by Drake & Testa (Nature, in press) will turn out to be true and thus restore the solar model agreement (Bahcall et al. 2005b) remains to be seen. If the new total solar metallicity should be correct, however, the consequences can be far-reaching. Since J. Guzik (this volume) will discuss this development in more detail, I just emphasize that with the new solar abundances not only the reference case for low-mass stellar evolution is in a much worse state than we thought, but that also all stellar abundances derived in some way or other *relative* to the solar ones have come into question, and their meaning should be seriously reconsidered. There may also be consequences for the chemical evolution of the Galaxy: due to the increased primordial helium content of 0.245, and the decreased initial solar value of 0.261, $\triangle Y/\triangle Z = 1.3$ instead of 2.5, the number most often used.

## 2. Updated reaction rates

Recently, the $^{14}\mathrm{N}(p,\gamma)^{15}\mathrm{O}$ reaction rate has been redetermined by Formicola et al. (2004); the new astrophysical $S_0$-factor is only 53% of the NACRE-value (Angulo et al. 1999). The evolution of low-mass stars is influenced by this change around the main-sequence turn-off as well as at the core helium flash and on the horizontal branch (Weiss et al. 2005). Although the changes are small, they are not irrelevant. For example, depending on the method, age determinations of globular clusters might find ages of up to several $10^8$ years older than with the old rate (Imbriani et al. 2004; Weiss et al. 2005).

A second rate revised is that of the $3\,\alpha$ process (Fynbo et al. 2005,ISOL-experiment). In Fig. 1 we show the comparison of the new as

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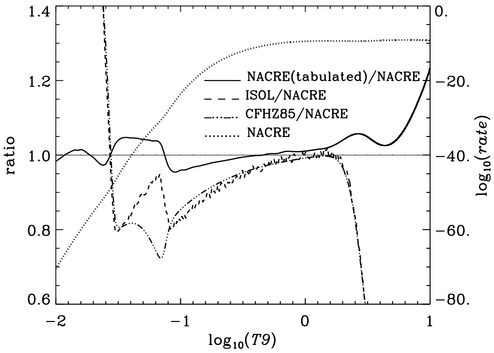

**Fig. 1.** $3\,\alpha$-reaction rate: absolute value (right axis scale; dotted) and relative rates of the new ISOL result with respect to the NACRE value, obtained from the analytical fit provided by NACRE. Also shown is the older Fowler et al. rate of 1986, which agrees surprisingly well with the newest determination.

well as of the classical Coughlan-Fowler rate with the NACRE one (both tabulated and analytical fit). For temperatures of interest for low-mass stars, the changes are within about 20%. Weiss et al. (2005) find only very small changes in the properties of low and intermediate stars, though.

## 3. Diffusion and the lithium plateau

Although diffusion, in particular *gravitational settling* is an unavoidable physical process, it is still unclear whether it actually takes place in stars. Since the diffusive timescales are usually very long, any other effect could easily dominate over diffusion and in particular counteract it. Our Sun is the most important example that sedimentation of helium and metals can happen over several billion years, as only solar models including the effect of diffusion have brought excellent agreement with helioseismology (in particular the comparison of present to initial helium content is a strong argument for diffusive depletion of the convective envelope). Even for the new solar abundances, diffusion is vital for best agreement. A further argument in favor of diffusion is provided by age determinations of metal-poor field stars on the basis of their turn-off color, which result in non-cosmological high ages if diffusion is ignored (Salaris & Weiss 2001a).

On the other hand, the absence of any variation in [Fe/H] between stars on the lower RGB and at the turn-off, where diffusive effects should be largest, in two globular clusters (NGC 6752 and NGC 6397; Gratton et al. 2001) is very strong evidence that sedimentation cannot act freely in all stars.

Finally, the existence and narrowness of the Spite or Li-plateau is in contradiction with all models including diffusion, since they all predict a significant decline of the Li-abundance close to the turn-off. Although Salaris & Weiss (2001b) pointed out that the increased evolutionary speed in this phase necessitates large samples of stars to detect the predicted downturn unequivocally, there has so far been no sign for Li-depletion due to pure sedimentation (see Hill et. al 2005 for a collection of talks on this subject and Charbonnel & Primas 2005 for a survey of available data).

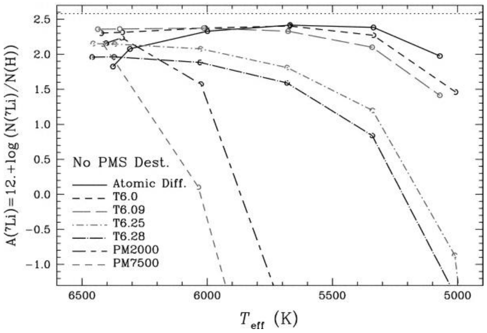

**Fig. 2.** Lithium as function of $T_{\rm eff}$ for models including various descriptions of diffusion and turbulent diffusion. All models were started from a primordial lithium abundance of [Li] = 2.6, and no pre-MS depletion was taken into account. For more information, see Richard et al. (2005), from which this figure was taken.

However, such uniform depletion of the surface Li content from the primordial value of [Li] = 2.61 ± 0.05 (WMAP baryon density plus standard BBN) to the presently measured value of around 2.1 ± 0.1 would be needed. Alternative attempts to explain the Li plateau and its current value include rotation

(Pinsonneault et al. 2002) and turbulent diffusion (Richard et al. 2005). From the latter paper I took Fig. 2, which shows both the standard Li-depletion due to generic diffusion (solid line) as well as that including turbulent diffusion, characterized by a parameter specifying at which temperature ($\log T$) the turbulent diffusion coefficient is 400 times that of standard diffusion. Indeed, for a suitable choice, both the required depletion can be achieved while keeping a plateau.

I close this section by adding that recently very detailed models that include the effect of radiative levitation have been developed (Michaud et al. 2004). Such models will, in the future, enable detailed predictions of element-to-element abundance variations caused by diffusive processes. In addition, the mutual influence of slow rotation (see next section) and diffusion is being considered by Théado & Vauclair (2003 and ref. therein), who found that both circulation and diffusion could be effectively frozen below an outer convective zone.

## 4. Rotation and abundance anomalies

Thanks to theoretical studies, for example by Zahn (1992) and Maeder & Zahn (1998), a number of stellar evolution programs have been extended to take into account the effects of rotation both on the structure of stars (which is rather small except for fast rotating massive stars) and on the chemical composition, which can be appreciable if matter from deeper layers is mixed to the surface by the rotationally induced mixing. Instead of entering into the vast literature, I mention just a few examples. The interested reader should consult the published work for more information.

An overview over the achievements in this field includes again Li, but this time Li-abundances as function of effective temperatures in open cluster. Models with rotation, which include self-consistently the transport of angular momentum explain consistently the hot side of the so-called Li-dip (Palacios et al. 2003). The cool side of the Li-dip, however, cannot be explained by rotation. Here, to the contrary, angular momentum has to be extracted from the convective envelope. One way of doing this could be the inclusion of *gravity waves* (Talon & Chabonnel 2003), which are yet another new physical feature considered currently in stellar evolution theory. It came into the focus of interest as it can explain the flat solar rotation profile (see, for example, Kumar & Quataert 1997).

In massive stars (Maeder & Meynet 2005 and ref. therein) the evolution on and past the main sequence is convincingly explained, including the number of blue-to-red supergiants.

Finally, abundance anomalies in Pop. II giants can be explained by invoking rotational mixing (Denissenkov & Weiss 2004 and ref. therein). In particular, the CN-anticorrelation found in basically all field stars and globular cluster red giants, which exceeds the prediction of the canonical first dredge-up in low-mass stars by far, and which sets in at the RGB bump (an increase of star density on the RGB due to the encounter of the hydrogen burning shell with the increase of hydrogen abundance left behind by the convective envelope), has been modeled convincingly by Charbonnel and Denissenkov and their coworkers, if rotation-induced mixing is taken into account, although a number of physical questions still remain to be answered. These are in particular the transport of angular momentum in the convective envelope and the interaction between rotation and energy production.

## 5. Initial abundances

In the context of abundance anomalies in globular cluster red giants, also (anti-)correlations between O and Na (see Fig. 3), and Mg and Al were found, which point as well to proton capture nucleosynthesis, though at higher temperatures than for the CNO-cycle (from 30 to 90 MK). However, the "evolutionary scenario", which explains them in terms of nucleosynthesis and extra-mixing on the RGB cannot be the (sole) explanation, as the same anomalies now have been found in unevolved stars in a number of globular clusters (M3, M13, M5, 47Tuc, NGC 6752, …; see the papers by Gratton, Carretta, Cohen, Briley, and others.)

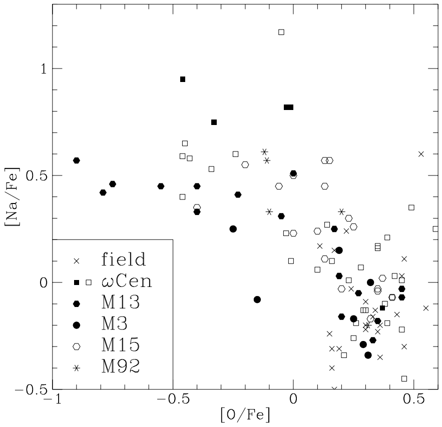

**Fig. 3.** The oxygen–sodium–anticorrelation in several globular clusters. The depletion of oxygen takes place in the CNO-cycle, while the enrichment of sodium is due to the NeNa-cycle operating at the same temperature. Note that this anticorrelation is absent in field stars, but appears to be quite common in globular clusters, though its extent may vary, and is most extreme in M13.

To explain these abundance variations, which are contrary to the canonical notion that all stars in globular clusters share the same initial composition, some "primordial" effect has to be invoked. As the rather high proton-capture temperatures required by some of the abundance variations point to Asymptotic Giant Branch stars, contamination of low-mass stars prior to or during the main-sequence phase by more massive AGB stars of an earlier generation is one possibility discussed, e.g. by D'Antona et al. (2002). However, this scenario has its own difficulties, as models of AGB nucleosyntheses are not able to reproduce fully the observered anomalies (Fenner et al. 2004; Denissenkov & Weiss 2004) and as a very top-heavy IMF for this initial GC population would be required.

One of the interesting effects of pollution by AGB stars is that it predicts enhanced helium in the ejected AGB material. Therefore, the anomalous GC stars should have higher helium contents (up to $Y \approx 0.40$). The question is whether this can be verified? A higher helium content might influence the morphology of the Horizontal Branch (D'Antona et al. 2002), but also the CMD around the main-sequence. Although hardly discernible, the He variation leads to a broadening of the MS (Fig. 4). Indeed, there is now increasing evidence for helium abundance variations in globular clusters, most notably in the case of $\omega$ Cen, where the main-sequence is split into at least two separate ones. Piotto et al. (2005) found that the stars on the *bluer* of these main-sequences have the *higher* metallicity. This surprising finding can be explained by requiring a higher helium content (again, $Y \approx 0.4$) for the more metal-rich sequence (see the contribution by D'Antona to this volume).

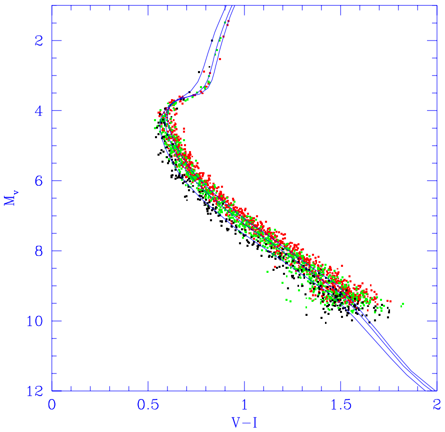

**Fig. 4.** Isochrones with increasing helium abundance (from $Y = 0.24$ to 0.40) and a simulated CMD intended to match that of NGC 2808 (taken from D'Antona et al., astro-ph/0505347). All isochrones have an age of 13 Gyr and the same metallicity of $Z = 0.002$. There is hardly a change in turn-off brightness, but a broadening of the lower main-sequence.

In connection with pollution of stellar surfaces, the finding of a correlation between the existence of giant extra-solar planets and a higher metallicity of the parent star opens the possibility that the higher metallicity is due to the engulfment of rocky (or rocky-core) planets. Dotter & Chaboyer (2003) have investigated the effect of such events on the evolution of low-mass main-sequence stars, finding higher $T_{\rm eff}$ in such cases (see Fig. 5).

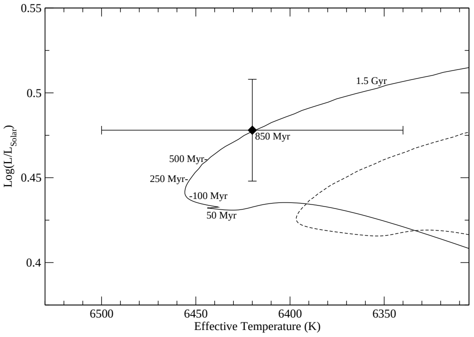

**Fig. 5.** Polluted (solid; 2 $M_\oplus$ of polluted Fe) and unpolluted (dotted) evolution of a 1.36 $M_\odot$ model for $\tau$ Boo (Dotter & Chaboyer 2003); the surface [Fe/H] abundance is in both cases identical.

## 6. Evolution along the RGB

I close this brief review with two items concerning the theory of low-mass star evolution along the RGB, which has been reviewed in Salaris et al. (2002). The first one is the brightness of the already mentioned *RGB bump*, which now can be found routinely in GC CMDs and luminosity functions. As Fusi Pecci et al. (1990) pointed out, the theoretical models predict the bump too bright. Although newer models, the inclusion of $\alpha$-element enhancements and new and consistent opacities have decreased the discrepancy, and in particular brought the brightness difference between HB and bump within the errors into agreement with observations (see Cassisi & Salaris 1997; Riello et al. 2003), the bump brightness is still too high by about 0.3 mag, as we recently verified ourselves (Meissner & Weiss, in preparation). One way to mend this deficiency is too include overshooting from the bottom of the convective envelope.

The second recent development concerns the core helium flash. It is now possible to do full calculations through this almost dynamical event at the RGB tip thanks to improvements in the numerical stability of the evolutionary codes, which allow, for example, to follow the evolution of a low-mass star from the pre-main sequence until the white dwarf stage without interruption (see Serenelli & Weiss 2005 for the question of HB model construction). On the other hand, in connection with modeling metal-free Pop. III stars (Schlattl et al. 2002 and ref. therein) and Pop. II stars with extreme mass loss on the RGB (Cassisi et al. 2003) it became evident that mixing between the flashing helium-burning regions and the outermost convective envelope is possible, leading to strong carbon and nitrogen enhancement of the envelope due to a combination of violent helium- and CNO-burning. While this is challenging the numerical stability even more, the codes are now able to handle even such extreme events. Figure 6 shows the complicated evolution of an $M = 0.86\,M_\odot$ star with varying mass loss prescriptions through and after the core helium flash.

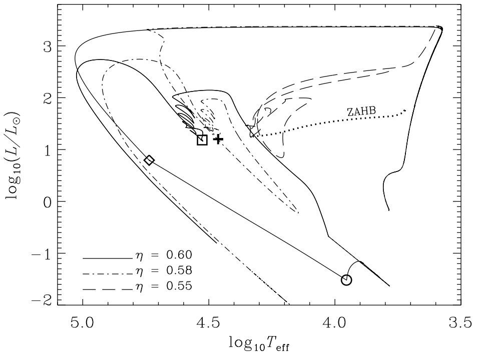

**Fig. 6.** Evolution of a star with $M = 0.86\,M_\odot$, $Z = 0.0015$ and various amounts of mass loss (characterized by $\eta$, the scaling parameter of the usual Reimers mass loss formula). Flash, envelope mixing and ZAHB of the $\eta = 0.60$ sequence are indicated by diamond, circle, square. At the flash the parameters in this case are: $M = 0.492\,M_\odot$; $M_{\rm env} = 1.2 \cdot 10^{-3}\,M_\odot$ (from Cassisi et al. 2003).

## 7. Summary

In this review I have tried to summarize briefly the most recent developments in the field of low-mass star evolution. Besides some improvements in the constituting physics (nuclear reaction rates) the main theoretical concern is about non-canonical physics such as rotation, gravity waves, convective overshooting and its effect on the evolution and abundance patterns of low-mass stars. Of similar importance is the increasing need for better knowledge of the true initial abundances and how they may be changed due to polluting effects, either by sister stars or even planets. In both respects (mixing and composition) pulsations and seismology will be able to give additional information as they help to infer the internal structure of stars.

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