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General Discussion II: On Current Stellar Models

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Abstract. Given the emphasis at this meeting on stellar models that treat diffusive and deep-mixing processes, as well as on recent computations for the AGB phase, a panel of experts was organized to further discuss the comparisons between theory and observations, the limitations of current models, and anticipated future advances. G. Michaud provided further insights on which stars are expected to show the largest abundance anomalies due to gravitational settling and radiative accelerations, and on the role of turbulent mixing. A. Weiss emphasized the importance of fully understanding diffusive processes and of investigating the still largely untested consequences of such processes (and deep mixing) for the late evolutionary phases of stars. S. Vauclair reported on the possible interaction between meridional circulation currents and diffusion, which could potentially explain why the observed abundance anomalies are less than those predicted by diffusive models. P. Denissenkov briefly reviewed several of the main problems that need to be solved in order to achieve an understanding of the observed abundances in giant stars, including the identification of the physical mechanism of deep mixing and an understanding of how the rotation profile in stars evolves. F. D'Antona outlined the reasons why she believes that massive AGB stars are the source of the material that produces the observed abundances in globular cluster stars (via pollution), including, in particular, the constraints provided by the observed Li abundances. Finally, J. Lattanzio commented that deep mixing is likely restricted to the upper giant branch and that some kind of primordial mechanism must be found to explain the abundance anomalies in less evolved stars: he also reminded us of some difficulties with the AGB scenario. Short contributions from each of the above are included in this paper.

Key words. Abundances in Globular Cluster stars – AGB models – deep–mixing – diffusion – rotation – self–pollution

Georges Michaud — Let us consider the abundance anomalies to be expected in turnoff stars and the existing comparisons with observations. If one assumes that atomic diffusion is the only particle transport process outside of convection zones, the largest abundance variations are to be expected in stars around the turnoff in low-metallicity clusters. Those are the stars that have the smallest mass in their outer convection zone, which leads to the largest surface abundance variations when atomic diffusion plays a role. Because the $g_{\rm rad}$

⋆ Session Chairman

(in particular for Fe) partly cancel gravitational settling in clusters with [Fe/H] ≥ -2.0, it turns out that only relatively small abundance variations are to be expected at 13.5 Gyr, among stars close to the turnoff. In such clusters, one expects a generalized Fe underabundance in main–sequence stars which reaches 0.1–0.3 dex at the turnoff. Little star-to-star variation is expected among turnoff stars. In giant stars, only about 0.03 dex is expected to remain of the Fe underabundance in main–sequence stars. One then expects a variation of [Fe/H] between turnoff and giant stars of 0.07–0.27 dex with the largest effects being in clusters with [Fe/H]= -2.01 and the smallest in clusters with [Fe/H]= -0.71.

The presence of the Spite plateau (Spite & Spite 1982) in halo stars suggests that the Li abundance is reduced very little during evolution. Using the turbulence parametrization that minimizes the Li abundance reduction (Richard et al. 2002), one may determine how this impacts the differences between giants and turnoff stars. There is then no star-to-star abundance variation expected at the turnoff. These are completely wiped out by the assumed turbulence. There remains a generalized underabundance by 0.1 dex in turnoff stars. In giants, the 0.03 underabundance of [Fe/H] is not affected by turbulence. In the presence of turbulence, one then expects a difference in [Fe/H] between turnoff and giant stars of ~ 0.1 dex.

In Pop. I stars, the effects of atomic diffusion appear to be limited by the presence of some turbulence. For instance, even in AmFm stars where atomic diffusion appears to be the cause of the abundance anomalies, there appears to be some turbulence present outside of convection zones (Richer, Michaud, & Turcotte 2000). The more rapidly rotating normal A stars have more normal abundances and probably more turbulence or other active mixing processes. One may expect a similar range of mixing in Pop. II stars. Some of the turnoff stars may have no turbulence while others would have the amount of mixing required to minimize Li underabundances.

When one compares to observations in clusters, one must not take an average among stars of a given $T_{\rm eff}$ as there are reasons to expect abundance variations among stars of a given $T_{\rm eff}$. Stars of a given $T_{\rm eff}$ just before and just after the turnoff may not have the same abundance variations. Furthermore, if there are stars with various amounts of turbulent mixing, they would have different abundance anomalies. It was emphasized by Asplund (this conference) that it is very difficult to be sure of differences between giants and turnoff stars to an accuracy better than 0.15–0.2 dex. The comparisons between turnoff and giants are then of limited accuracy because of difficulties with the $T_{\rm eff}$ scale and/or other uncertainties in the models. It thus appears premature to reach firm conclusions, from existing observations of [Fe/H] in clusters, about the expected abundance anomalies. In clusters with [Fe/H] ≥ -2.0, there are accurate observations (Gratton et al. 2001) which suggest that there are little or no [Fe/H] variations among turnoff stars. As mentioned above, however, only small variations are expected among such stars and those expected appear to be reasonably compatible with observations (see Sec. 7 of Richard, Michaud, & Richer 2002). As to the difference in abundances between giants and turnoff stars, most (but not all!) seem to agree that the observational uncertainties are too large to exclude the expected anomalies.

M 92 is one cluster where larger star-to-star variations are expected at the turnoff, due to its very low metallicity ([Fe/H] ≤ -2.31): it has been observed recently by King et al. (1998). These authors have found Fe abundance variations from star to star in the three near-turnoff stars in their sample. These are roughly consistent with those expected when atomic diffusion, including the effects of radiative accelerations, is taken into account in the evolutionary model calculations (Richard et al. 2002). However, these observations are not of such high precision as those of Gratton et al. (2001) and require confirmation by more accurate data. This cluster (and/or other extremely metal-deficient systems like NGC 5053) may well offer the most sensitive test of the predicted metal abundance anomalies in turnoff stars.

Achim Weiss — We certainly would like to have full-scale 3-dimensional hydro-simulations of rotation, convection, and the interaction between them to model the various mixing processes in the stars under discussion at this meeting. However, this being a "grand aim" for future decades, we should also look at important physics closer to our understanding and modeling capabilities.

I think that it is time to accept that diffusion is a vital part of stellar physics (see the solar model) and we need to understand if and how it works in other stars. Michaud's talk excellently demonstrated the progress made in understanding the physics and incorporating it into a stellar evolution code. The reason why I emphasize diffusion is that it is able to affect both the "nuclear clock" of stars by changing the central helium content in addition to nuclear fusion as well as the surface conditions (radius, effective temperature). The latter is only partially due to modifications of the composition of the outermost layers; indeed the work of the ESO Large Program (Gratton and coworkers) strongly indicates that there is no effect at the surface (but such work tells us only about the surface!). However, changes in the interior, such as a more compact core due to sedimentation, affect also the density structure in the outer regions, and stars with diffusion working only in the center are cooler than their canonical counterparts.

I would like to digress briefly to the talk by Stanford about ω Cen, where the question was raised as to why the ages determined by her were so large (larger than any reasonable cosmic age). The answer is simple: Standford determined the age of an observed star by assigning an evolutionary track to it, reading off the age from the stellar luminosity. Assuming that the composition is known, the star's mass is the crucial parameter in the age-luminosity relation. The mass, however, is not known. Instead, it is obtained by requiring that the observed $T_{\rm eff}$ matches that of the track. Suppose now that the star is affected by diffusion as described above, such that it is cooler than stellar evolution without diffusion predicts. The consequence is that an evolutionary track of lower mass will be assigned. Such a star takes a longer time to reach the same luminosity, and therefore a higher age is the result.

Independent of this, modifications of the interior composition profile usually affect later evolutionary phases and might be crucial for the physics of deep mixing due to rotation (see the work by Charbonnel and Denissenkov). Therefore, I think that diffusion presently is the most interesting and important aspect of stellar structure physics at the present time that needs to be fully understood.

Sylvie Vauclair — The computations of diffusion processes in stars and their influence on the stellar structure are not trivial and much work still has to be done on this subject. Microscopic diffusion induced by pressure and thermal gradients and radiative acceleration has become a standard process which may be computed without any free parameter. However, it has to compete with macroscopic processes, which are far from being well-known. In the computations of rotation-induced turbulence, several parameters are still uncertain, even when the transport of angular momentum and that of chemical species are treated consistently. At least one free parameter remains in the computations, namely the horizontal diffusivity. The importance of the meridional circulation of the μ–gradients created by helium diffusion is also a difficult problem, which has been addressed in a recent series of papers (see Théado & Vauclair 2003, and previous papers in the series). We have shown, using 2D-simulations, that even in the presence of meridional circulation, microscopic diffusion can lead to helium gradients which rapidly produce "μ–currents" opposite to the classical "Ω–currents". The circulation should stop when the two currents become of equal magnitude, but we show that, in this case, microscopic diffusion keeps on disturbing this equilibrium. As a result, both turbulence and diffusion should be reduced.

In any case, the asteroseismology of solar type stars should, in the near future, bring important constraints to bear on these transport processes.

Pavel Denissenkov — From my point of view, here are the most important uncertainties of the stellar models that are related to the problem of abundance anomalies in globular clusters (GCs):

(i) The physical mechanism of extra mixing in RGB stars. Even though there is some evidence that this extra mixing is related to rotation (turbulent diffusion or meridional circulation), its rate is still very uncertain. For single K giants, Drake et al. (2002) find that "among rapid ($v \sin i \geq 8\,\mathrm{km\,s^{-1}}$) rotators, a very large proportion ($\sim 50\%$) are Li-rich giants" and that "this proportion is in contrast with a very low proportion ($\sim 2\%$) of Li-rich stars among the much more common slowly rotating K giants." We know that, for the internal Li-production by extra mixing via the "^{7}Be-transport" mechanism (Cameron & Fowler 1971), diffusion coefficients of an order of $D_{\mathrm{mix}} \approx 10^{11}\,\mathrm{cm^2\,s^{-1}}$ are required (Denissenkov & Weiss 2000). These exceed by a factor of ~ 100 the adjusted diffusion coefficients needed to explain the evolutionary carbon abundance decrease seen in metal-poor upper RGB stars, both in the field and in GCs (Denissenkov & VandenBerg 2003). This difference is probably caused by the faster rotation of the Li-rich giants, as e.g., for the rotation-driven turbulent diffusion $D_{\mathrm{mix}} \propto \Omega^2$ (Maeder & Meynet 1996).

The recent 3D hydrodynamical simulations by Brüggen & Hillebrandt (2001) of the turbulent mixing induced by the shear instability have shown that the equation for D_{mix} derived by Maeder & Meynet (1996), which is now widely used in stellar models with extra mixing, may underestimate the coefficient of turbulent diffusion by 3 orders of magnitude. On the other hand, it is not yet clear whether the results of Brüggen & Hillebrandt can be applied directly to real upper RGB stars, given that they were obtained assuming plane-parallel geometry and without taking into account "the effects of rotation, nuclear reactions, and variations in radiative processes".

It should be also borne in mind that the Zahn theory of meridional circulation (Zahn 1992; Maeder & Zahn 1998), which is widely used to model rotational extra mixing in stars as well, uses series expansions with respect to the parameter $\varepsilon = (\Omega^2 r^3 / G M_r)$ (< 1) that keep only the linear terms. Therefore, it may be inapplicable to the description of extra mixing in the vicinity of rapidly rotating cores of the spun-up red giants.

(ii) The rotation profile in the convective envelope of an RGB star. The observed abundance anomalies in GCs can be reproduced theoretically [with the diffusion coefficients provided by Maeder & Meynet (1996) and by Maeder & Zahn (1998)] only if one assumes that the convective envelope rotates differentially, with the deeper layers moving much faster than the outer ones (Denissenkov & Tout 2000). Of course, this conclusion depends on the applied mechanism of extra mixing (therefore this uncertainty is closely related to the first one). However, the measured surface rotational velocities of some Li-rich giants are so large that they can not be obtained as a result of the evolution of the main-sequence rotation profile under the assumption of the constant specific angular momentum law in the convective envelope.

(iii) The quick transition from the RGB to the HB triggered by the He-core flash and the associated angular momentum redistribution inside the star (e.g. Sills & Pinsonneault 2000). Understanding this process is crucial for establishing a connection between rotation (and mass-loss) on the RGB and the (observed) rotational velocities and distribution of stars on the HB.

(iv) The extent to which oxygen is dredged up (if at all) in metal-poor intermediate-mass AGB stars.

(v) The large uncertainties that still exist for some of the important reaction rates of the NeNa and MgAl cycles (Angulo et al. 1999). (However, their reduction is a task for nuclear physicists.)

Francesca D'Antona — In some clusters, GC stars seem to possess peculiar (very high) abundances of Nitrogen (for instance) WITHOUT apparent changes to the Li abundance (Bonifacio et al. 2002, for NGC 6397), which remains very close to, and with a small dispersion around, the Big Bang abundance.

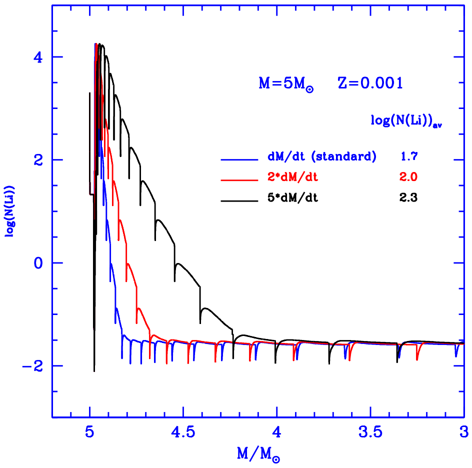

Fig. 1. The lithium abundance, log N(Li), at the surface of a 5 $M_\odot$ during the HBB phase. The abscissa is the total mass of the star during the evolution, which goes down due to mass loss. If the mass-loss rate is larger, the amount of matter expelled with high lithium is larger, and so is the lithium yield of the star. In the case shown, if the mass loss rate is 5 times the rate which was adopted in the models from Ventura, D'Antona, & Mazzitelli (2002), the average abundance in the ejecta is about the primordial value log N(Li)=2.3.

But CN cycling operates at temperatures at which the burning of lithium by proton capture is unavoidable. Even if, for instance, diffusion is deceiving us and we are not witnessing the Big Bang abundance at the surface of GC dwarfs, the observations indicate that there MUST be a lot of Lithium in a deeply CNO processed environment. How is this possible?

This very peculiar situation is, in fact, one of the main reasons why I am confident that massive AGBs are the site for the chemical evolution which leads to GC inhomogeneities. In fact, in these stars we can have CN cycling – and even ON cycling, as shown by Ventura et al. (2001) – by Hot Bottom Burning (HBB), without invoking non-predicted extra–mixing or very deep mixing. They lose their nuclear-processed envelopes by low-velocity winds, and there is no reason why the envelopes should be expelled from the cluster before they have the occasion of producing some kind of self pollution. In addition, the Cameron-Fowler mechanism operates at the bottom of the AGB envelopes and leads to the natural manufacturing of lithium! Although the lifetime of lithium in the envelope is not longer than a few tens of thousand years, a huge amount of this element is produced so that the average abundance of lithium in the ejecta is comparable to the Population II abundance, in spite of the fact that most of the envelope matter lost in the winds actually has no lithium. If we think that the winds from all the AGB stars merge in a central cloud, from which other stars are formed, as suggested in D'Antona et al. (2002) – or which pollutes by accretion the stars passing through it – what matters is, in fact, the *average* abundance in the ejecta.

The models by Ventura, D'Antona, & Mazzitelli (2002) have shown that the yield of lithium does not have a strong dependence on the mass, so that we should not expect large lithium abundances in the polluted stars, even if the pollution comes from stars spanning a relatively large mass range (e.g., from 4 to 6 $M_\odot$). These models predict, however, a depletion of Li by a factor of 2–5 with respect to the observed value log N(Li)=2.2–2.3. Figure 1 shows that a larger abundance of lithium in the polluting material can be achieved if the mass-loss rate is larger, as, in this case, a larger amount of lithium is lost into the intercluster medium. The necessity of calibrating the mass loss to obtain the correct abundance is not a nice feature of the model, unless the same kind of calibration is found to be necessary to explain other chemical features. In any case, it is evident that, at least in the clusters most heavily subject to self-pollution, we should expect a spread of lithium among main-sequence stars.

John Lattanzio — First, I think the attraction of "deep-mixing" is largely passing. With the discovery that many abundance anomalies are present below the giant branch, we are forced to look at primoridial enrichment or primoridal pollution. Evidence for deep-mixing would be the variation of some element with luminosity.

At present, to the best of my knowledge, this is limited to C (and N) in such low-metallicity clusters as M 92. There are hints that there may be some variation in Na, but the data are not convincing. If deep-mixing is limited to C and N, then the globular cluster stars are no different than field stars, which also require mixing below the convective zone to provide a match to the $^{12}C/^{13}C$ ratios seen in stars (and in presolar grains). This would be good news, in my opinion, because the internal structure of a star should not depend on its environment! So my guess (and hope?) is that the only deep-mixing we must add is not particularly deep, and matches that seen in all other stars.

So we are led to the"primordial" solution to explain the other anomalies. I think it is wise to distinguish between two ways of providing primordial abundance anomlaies: *true* pollution and primoridal enrichment. In the former, mass that is ejected from other stars is accreted onto the envelope of the current generation of stars. This is *true* pollution of an existing star. In the latter case, there is a subsequent round of star formation, using primarily (exclusively?) the enriched material ejected by the earlier generations. The strong O depletions and the lack of variation in CN strength between the main-sequence and post-first-dredge-up stars argues against true pollution, in my opinion. And everything we know about star formation in GCs argues against a subsequent generation of star formation. That is why the problems still exist, and attract so much effort!

A final nail in the AGB coffin should be the C+N+O abundances. If it is AGB stars that enriched the gas that we are seeing, then not only should the He abundance be large ($Y \approx 0.35$?) but the C+N+O should be dramatically higher than in the original material. An intermediate mass AGB star of low metallicity will make a substantial amount of primary ^{12}C and ^{14}N (the latter via hot bottom burning). Dredge-up has essentially no effect on O. Hence the C+N+O in the envelope of these stars is much higher than in the material they formed from, perhaps by 2 orders of magnitude. Hence, if the CN strong stars are made of this material, then C+N+O for these stars should be 10–100 times the C+N+O for the CN weak stars. The few stars in the handful of clusters that have been checked have shown no change in C+N+O from the CN weak to the CN strong. We have known this for years, but it seems to have been forgotten in the rush to implicate AGB stars. Although I am frequently warned about the difficulties in quantitative analysis in these stars (especially for O), we must remember that the effect we are looking for is a factor of at least ten, maybe closer to 100. I think we would have noticed that!

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