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Concluding Remarks

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1. Introduction

The main purpose of this Joint Discussion was to update the observational evidence on the mixing of chemical species which occurs inside the stars, in order to identify the physical processes which play a rôle in this mixing, and to assess their efficiency. The first goal has been clearly achieved, with most contributions, those by J. Landstreet, D. Lambert, B. Kraft, F. Grundahl and J. Norris, confirming the observational patterns which had been previously reported. There was one exception though, namely the announcement made by S. Balachandran that two tidally-locked binaries of the Hyades had undergone the same Li depletion than single stars, and this has important consequences, as we shall see. In brief, here is our present understanding of those mixing processes.

2. Microscopic processes

Microscopic processes operate on the particle level, and since their effect depends on atomic or molecular properties, they tend to induce chemical inhomogeneities in an otherwise homogeneous medium.

Diffusion, radiative levitation, gravitational settling are now well understood and their modelization has reached a high level of sophistication and accuracy (see G. Michaud's contribution). The only serious difficulty is that generally they do not operate alone, in a still medium, but that they often suffer from the interference of macroscopic mixing, such as produced by turbulence. Fortunately, in some instances this mixing has a minor impact, which is the case of 'tepid' stars, whose complex surface abundances are now relatively well interpreted. Also, the gravitational settling of helium and heavier elements below the solar convection zone is currently implemented in the *standard solar model*, where it has led to much better agreement with the helioseismic data.

3. Macroscopic processes

Macroscopic hydrodynamical processes, whether laminar or turbulent, lead to mixing and therefore they reduce the chemical inhomogeneities which are produced either by the nuclear reactions or the microscopic processes mentioned above. Convection zones are thoroughly mixed, except during the fastest phases of evolution, thus we shall only consider the milder mixing processes occurring in radiation zones. These play an important rôle in the evolution of stars, by carrying fresh fuel into the regions where nuclear energy is released.

3.1. Convective penetration and overshooting

The current modelization of this process is based on crude mixing-length prescriptions, which involve an adjustable parameter set 'by hand'. Work is in progress to improve on that situation, as was reported by B. Freytag, by carrying out quite successfully three-dimensional simulations of stellar surface convection. He is now turning to deeper convective layers, but these are much more difficult to handle, because they involve a large range of spatial and temporal scales; for that reason the results obtained so far cannot be applied beneath the convection zone of solar-type stars. Another approach is to average horizontally the governing equations, using proper closure prescriptions; this reduces the problem to one dimension and renders it much more tractable. Such a procedure has the advantage of giving a non-local description of convection, allowing for penetration and overshoot, but it involves a set of parameters which need to be calibrated. F. Kupka is presently confronting the model proposed by V. Canuto with direct 3D simulations, and encouraging results have been reported at this JD on overshoot beyond shallow convection zones.

3.2. Rotational mixing

In a rotating star, radiative equilibrium can no longer be maintained in general, and this thermal imbalance drives a large-scale meridional circulation which is well understood and relatively easy to calculate. But here again it is the interference of turbulent motions which is very crudely modelled, and these motions are expected since the circulation produces differential rotation which is liable to various hydrodynamical instabilities. What we call *rotational mixing* is the combined effect of both that circulation and the associated turbulent mixing. We consider two cases, depending on the angular momentum transport.

Rotational mixing of type I. In this case angular momentum is carried by the same process that achieves the mixing of chemical species. A consequence is then that the ^{7}Li depletion in low mass stars, which are spun down by a wind, is correlated with their loss of angular momentum. The Yale team was the first to calculate the evolution of rotating stars along these lines (Pinsonneault et al. 1989). By tuning the parameters involved in their model, they reached a reasonable agreement with the Li depletion measured in various clusters. But two predictions entered in conflict with the observations, as was emphasized by S. Balachandran in this JD. First, this type of mixing would leave a fast rotating solar core, contrary to what is revealed by helioseismology; the same result is predicted when the transport of angular momentum is treated properly as an advection (Matias & Zahn 1998). Second, this process would have depleted ^{9}Be by a factor of 3 in the Sun, whereas a careful analysis of the solar spectrum shows that Be has not been depleted at all (Balachandran & Bell 1998).

But until today one observation still seemed to support that type of mixing: two tidally locked binaries in the Hyades had been found previously to display more Li than single stars of the same mass (Thorburn et al. 1993), as one would expect since the angular momentum carried away by the wind is drawn from the orbit, and has not to be extracted from the interior of the binary components (Zahn 1994). However, during this JD S. Balachandran announced that she had re-analyzed the spectra of these binaries, and that she could not detect the presence of Li. Therefore we must conclude that rotational mixing of type I is not operating in low-mass stars, and that another mechanism, more powerful than meridional circulation, is responsible for the transport of angular momentum.

This type of mixing is more successful when applied to massive stars, as was described by G. Meynet during the JD: apparently it can account for the surface enrichment in He and N in fast rotators. More generally it seems to operate in main sequence stars which don't have an outer convection zone, and thus which are not spun down by their wind because they lack an extended magnetosphere. For instance, Talon & Charbonnel (1998) were able to explain the absence of Li depletion on the blue side of the Li gap by this type of rotational mixing. The same mechanism seems to account also for the chemical properties of subgiants (Charbonnel & Talon 1999) and even of red giants (see Denissenkov's communication; Charbonnel & Palacios 2000).

Rotational mixing of type II. Here the transport of angular momentum is achieved by other processes than meridional circulation or turbulent diffusion, and these enforce nearly uniform rotation in radiative interior. Then mixing is decoupled from the loss of angular momentum, as seems the case in solar-type stars. One obvious candidate for the transport of angular momentum within the radiation zone is magnetic torquing, as advocated by L. Mestel in his contribution; another possibility is transport by gravity waves (or gravito-inertial waves), as was proposed by Schatzman (1996) and Kumar et al. (1999).

The effect of magnetic fields has been investigated in detail by P. Charbonneau and his collaborators, for given configurations of the poloidal field (see his contribution at the JD). These simulations now permit to assess the amount of differential rotation imprinted by an outer convection zone, but they are still not self-consistent, since they do not take into account the advection of the poloidal field through the meridional circulation.

Mixing in the tachocline. The thin region beneath the solar convection zone, where the angular velocity adjusts from differential above to almost uniform below, is the seat of horizontal stresses, either magnetic or hydrodynamical, which tend to reduce the latitudinal dependence of the angular velocity. The only self-consistent model available today assumes that these stresses are due to anisotropic turbulence, generated by the differential rotation in latitude (Spiegel & Zahn 1992). The tachocline is then the seat of a meridional circulation, as explained by S. Brun; therefore some local mixing occurs, which depletes Li while preserving Be, as observed. The next step will clearly be to introduce the magnetic field, and to solve simultaneously the MHD equations with that of the conservation of thermal energy.

This exciting Joint Discussion demonstrated that we progress steadily in our understanding of diffusion and mixing in stars, with the observers providing more precise and more decisive observational constraints, and the theoreticians taking into account physical processes which have been neglected so far, in their quest for self-consistent models. On behalf of the Organizing Committee, I express our thanks to all those who have contributed to the success of this meeting, by their oral presentation, their poster paper, or by taking part in the discussion.

P.S. Unfortunately the lack of space does not allow me to list the references; they may be found in the contributions quoted above, or in the ADS data base.