*Inside the Stars, IAU Colloquium 137*
*ASP Conference Series, Vol. 40, 1993*
*Werner W. Weiss and Annie Baglin (eds.)*

# NEW CONSTRAINTS ON THE ROTATION-INDUCED MIXING IN STARS, FROM LITHIUM OBSERVATIONS IN MAIN SEQUENCE F-TYPE STARS AND SUBGIANTS

CORINNE CHARBONNEL, SYLVIE VAUCLAIR
Observatoire Midi-Pyrénées, 14,av.E.Belin, 31400 Toulouse, France

ABSTRACT Observations of lithium in F type main sequence stars and subgiants lead to specific constraints on the rotation-induced mixing. The fact that lithium is smoothly depleted in subgiants down to factors as large as 1000 at the end of the sequence can be explained if lithium suffered extra depletion inside the star while it was on the main sequence. We propose a simple consistent model, based on the discussion of rotation-induced mixing developed by Chaboyer and Zahn (1992), which could account for these observations, as well as the observations of lithium on the main sequence.

## INTRODUCTION

Since the discovery of the lithium dip in the Hyades by Boesgaard and Tripicco (1986), different explanations have been proposed to account for this characteristic feature. The most severe constraints which may help chosing between the various theoretical models may be found in the study of stars with effective temperatures larger than those of the dip.

- In galactic clusters, the lithium abundance is normal (Log N(Li)=3.1) for main-sequence stars of the hot side of the dip, except for some peculiar A stars.
- The observed lithium abundance smoothly decreases along the subgiant sequence while the lithium abundance predicted by standard models would be constant in most of the sequence, and would fall at the end of the sequence when the convection zone reaches the region inside the star where lithium has been destroyed by nuclear reactions.
- Giants which belong to galactic clusters show a lithium depletion larger than the one expected from standard evolutionary models. This observation suggests that some extra lithium-depletion occurs inside the stars when they are on the main sequence, even if this extra-depletion does not appear at the surface.

A consistent treatment of hydrodynamical processes inside stars should explain not only the lithium dip, but also the lithium extra-depletion in main sequence stars on the hot side of the dip needed to account for the observations of giants and the smooth decrease in the subgiants.

## MIXING INDUCED BY MERIDIONAL CIRCULATION IN ROTATING STARS

The thermal imbalance in a rotating star generates meridional flows known as "Eddington-Sweet meridional circulation". Zahn (1983) evaluated the turbulence induced by the circulation in terms of a turbulent diffusion coefficient, of the order of $|rU(r)|$, where r is the radius inside the star and U(r) the vertical velocity of the circulation at the radius r. In a uniformly rotating star, the turbulent diffusion coefficient may be written (Charbonnel et al. 1992a, hereafter CVZ) :

$$D_T = \gamma \left| \frac{L}{M^3} \frac{r^6 \Omega^2}{G^2(\nabla_{ad} - \nabla_{rad})} \left(1 - \frac{\Omega^2}{2\pi G\rho}\right) \right| \tag{1}$$

where $\Omega$ is the angular velocity in the star, G the gravitational constant, L, M and $\rho$ the luminosity, the mass and the density at radius r, $\nabla_{ad}$ and $\nabla_{rad}$ the adiabatic and radiative gradients, and $\gamma$ a factor of order one. In a radiatively stable star with a near solid body rotation, the meridional circulation splits up in two loops, which develop above and below the boundary layer for which $\Omega^2 = 2\pi G\rho$. The boundary between the two meridional loops lies inside the convection zone for stars cooler than the temperature of the lithium dip, and in the radiative zone for hotter stars (Vauclair 1988, Charbonnel et al. 1992a and b). This result suggests that the split up into two separate loops of meridional circulation is related to the fact that lithium is destroyed at the surface of stars below this effective temperature and not above. However, the screening effect of the "quiet zone" which lies between the two meridional loops is not sufficient to stop the lithium decrease at the surface of F stars (Charbonneau and Michaud 1990, Charbonnel and Vauclair 1992). Another effect must be introduced to account for the observations.

Expression (1) was obtained without taking into account the particle transport due to advection nor the mixing due to horizontal turbulence. Chaboyer and Zahn (1992) computed the combined effects of advection and mixing. With the assumption that the horizontal diffusion coefficient varies like rU(r), they obtained an effective diffusion coefficient which can be written :

$$D_{eff} = \gamma |rU(r)| \tag{2}$$

and is similar to equation (1), although the physics is somewhat different. The factor $\gamma$ is unknown and depends on the efficiency of horizontal diffusion.

The cool side of the lithium dip is explained by meridional transport and nuclear destruction only if the efficiency of the meridional circulation in the deepest loop is not decreased (CVZ). We thus suppose that the horizontal turbulence in this loop is small enough to leave the advection unperturbated ($\gamma \simeq 1$). This may not be the case in the outer meridional loop. There we adjusted $\gamma$ so that the lithium depletion at the surface is negligible as observed on the blue side of the dip. This result is obtained for $\gamma \leq 10^{-3}$ (Charbonnel and Vauclair 1992). While such a configuration prevents any observable lithium depletion at the surface of F stars at the age of the Hyades, it leads to more lithium destruction inside the star : lithium is now destroyed not only in the nuclear destruction region below $2.5 \times 10^6$K, but also up to the boundary beetween the two meridional

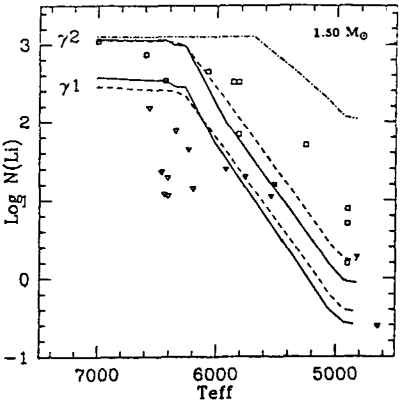

FIGURE I Observations of lithium abundance in field subgiants (open symbols) and in M67 subgiants (black symbols). The solid and dashed lines correspond respectively to a main sequence rotation velocity of 100 and 150km.s$^{-1}$. The dashed-dotted line represents the lithium abundance variation on the subgiant branch in case of no turbulence (our standard model).

loops. This prepares the star to the lithium abundance variations observed on the subgiant branch and at the bottom of the giant branch.

Using the Geneva stellar evolutionary code in which we have introduced the numerical method described in CVZ to solve the diffusion equation, we have computed the lithium abundance evolution on the main sequence and on the subgiant branch for a 1.5M$_\odot$ star. In figure 1 we compare the predicted lithium abundance variations along the subgiant branch for two values of $\gamma$ in the upper loop ($\gamma_1 = 10^{-3}$, $\gamma_2 = 10^{-4}$) and two values of the rotation velocity of the star with the observations of lithium abundance in field subgiants and in M67 subgiants. These theoretical results account much better for the observations than the computations done in standard models.

## REFERENCES

Boesgaard, A,M., and Tripicco, M.J., 1986, *Ap.J. Letters*, **302**, L49

Chaboyer, B., and Zahn, J.P., 1992, *Astr.Ap.*, **253**, 173

Charbonneau, P., and Michaud, G., 1990, *Ap.J.*, **352**, 681

Charbonnel, C., and Vauclair, S., 1992, *Astr.Ap.*, in press

Charbonnel, C., Vauclair, S., and Zahn, J.P., 1992a, *Astr.Ap.*, **255**, 191

Charbonnel, C., Vauclair, S., Maeder, A., Meynet, G., and Schaller, G., 1992b, *Astr.Ap.*, in preparation

Vauclair, S., 1988, *Ap.J.*, **335**, 971

Zahn, J.P., 1983, *Astrophysical Processes in Upper Main Sequence Stars*, ed. B.Hauck and A.Maeder, Publ. Geneva Observatory, 253