TURBULENCE AND THE LITHIUM ABUNDANCE IN GIANTS AND MAIN-SEQUENCE DISK AND HALO STARS

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ABSTRACT. The present situation concerning the observations of lithium in subgiant and giant stars is reviewed. These observations, compared to the determinations of lithium in main-sequence stars, can be used to obtain more stringents constraints on the dynamics of the stellar gas in the main-sequence as well as in the subgiant and giant stages. The macroscopic motions expected in stars are discussed from a theoretical point of view and compared to the observations, with special focusing on the theories of rotation-induced turbulence.

1. Capella and the others...[1]

1.1. FIRST OBSERVATIONS

The lithium λ6707 doublet was observed in giant stars as early as fifty years ago. Mc Kellar (1940) discovered an important lithium feature in the evolved carbon star WS Cas and it was soon recognized that the lithium line showed large variations from star to star (Greenstein and Richardson (1951), Bonsack (1959)).

The biggest puzzle came from the observations of Capella by Wallerstein (1964) and (1966). Capella (α Aurigae) is a binary system composed of two giant stars with spectral types F8 and G5. The G star ($M_v = 0.12$) is brighter than the F star ($M_v = 0.37$). Their masses are respectively 2.9 $M_\odot$ for the F component and 3.0 $M_\odot$ for the G component. Wallerstein found a lithium abundance 100 times larger than that of the Sun in the F component and no lithium in the G component. This difference in the lithium abundances between the two stars was interpreted by Iben (1965) as an evidence that the G star was more evolved than the F star due to its slightly larger mass. While the F star still kept its original lithium, the G star had lost it due to the increase of the convective depth in the giant phase. The large factor of more than 100 between the two lithium values obtained by Wallerstein was

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[1] Note : The observations of lithium in main-sequence disk and halo stars, which are discussed elsewhere in this conference, are not reviewed here.

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however difficult to reconcile with the theoretical predictions. This puzzle was solved by Boesgaard (1971) who obtained spectra of the two stars with a larger dispersion and could see the lithium feature in the G star. She then gave a lithium ratio of only 15 between the two stars, which agreed with the theoretical computations.

Other observations of lithium in F and G giants were performed by Wallerstein (1966) who found that three F stars out of 5 showed an abundance 80 to 300 larger than that of the Sun while no enhancement by more than 6 with respect to the Sun was found in the G stars. Bonsack (1959) had earlier observed a sample of 46 stars with spectral types between G8 and M0, all luminosity classes included. He found the same trend in all the luminosity classes, namely a steady decrease of the lithium abundance towards earlier spectral types. He concluded that the lithium decrease was a function of the effective temperature, not of the luminosity, and that the reason for this decrease was the increase of the depth of the convection zone in cooler stars, as suggested by Greenstein and Richardson (1951).

1.2. THEORETICAL DIGRESSION

We know now that the lithium variations in F and G stars are related indeed to the depth of the outer convection zone, but that the real processes involved are quite different in main-sequence and giant stars. As discussed elsewhere in this conference (Michaud (1990), Demarque (1990)), lithium is destroyed at the surface of cool stars during their main-sequence lifetime. It may also be partly destroyed during the pre main-sequence period (Bodenheimer (1965), d'Antona and Mazzitelli (1984), Proffitt and Michaud (1990a)), but the observations of the lithium abundance variations in galactic clusters of different ages show that most of the observed lithium destruction must occur on the main sequence (see, for example, Charbonneau and Michaud (1988)). This lithium destruction must be related to some transport of matter between the surface and the lithium nuclear destruction region, which lies in the star at a temperature of about 2.5 million degrees. The possibly implicated transport processes will be discussed in section 2.

After leaving the main-sequence, the stars move to the right on the H.R. diagram, towards cooler effective temperatures, and then up the "first ascent giant branch" (or "Red Giant Branch"). As pointed out by Iben (1965), the surface lithium destruction during post main-sequence evolution is negligible in the standard model. Although the depth of the outer convection zone increases dramatically when the stars come to the giant stage, it never reaches a temperature sufficient to destroy lithium, due to the cooling of the outer envelope. However the convection zone then goes down to the region in the star *where lithium has been destroyed during the main-sequence phase*. It also brings up to the surface the ^{13}C isotope formed in the hydrogen burning layer (first "dredge up"). It thus appears that the determination of the lithium abundance in first ascent giants should be a measure of the amount of lithium destroyed *inside the star* during the main-sequence. Iben (1965) and (1967a, b) computed the expected lithium dilution due to this effect during post main-sequence evolution in the standard model (no other mixing than standard convection in the stellar outer layers). In this case, the evolution of the surface lithium abundance from the main sequence to the giant stages can be written (see also Michaud and Charbonneau (1990)) :

$$(Li/H)/(Li/H)_0 = min\ [1, M_{nz}/M_{cz}]$$

where $(Li/H)_0$ is the lithium abundance at the surface of the star on the main sequence, M_{nz} is the mass above the lithium nuclear destruction zone ($\approx 0.17 M_*$) and M_{cz} the mass in the outer convection zone, which varies with time. Iben gives a final lithium abundance for giants of about log $\varepsilon(Li) = 1.5$ for all kinds of stars.[1]

If some other transport process is also at work inside the stars, the lithium depletion can be larger in the giant phase ***even if no depletion appears at the surface of the stars in the main-sequence phase.*** As the giants which are now observable in the Galaxy had main-sequence progenitors with masses larger than 1.4 $M_\odot$, the observations of lithium in giants give us information about the internal structure of these more massive main-sequence stars.

When the stars reach the tip of the first ascent giant branch, helium begins to burn in the core, which gives rise to the "helium flash" for the stars which are less massive than 2.25 $M_\odot$. After relaxation, these stars gather on the so-called "giant clump" (Cannon (1970), Sweigart and Gross (1976) and (1978), VandenBerg (1983)) and then go up again on the "second ascent giant branch" (or "Asymptotic Giant Branch"). More massive stars do not suffer any helium flash, but they also concentrate in the clump where they move smoothly, and go up the Asymptotic Giant Branch. On the AGB, the stars may suffer helium ignition in thin shells which leads to small flashes also called "helium thermal pulses". These helium pulses can lead to deep convection zones which may bring up to the surface some elements like carbon, and also possibly ^7Be which would decay at the surface into ^7Li, thus creating fresh lithium in these stars (Cameron (1955), Cameron and Fowler (1971), Sackman, Smith and Despain (1974), Scalo, Despain and Ulrich (1975), Renzini and Voli (1981)). The difficulty with this theory for lithium production is that one has to go down in the star to temperatures larger than 30 million degrees to build ^7Be by the reaction $^3He(\alpha,\gamma)^7Be$. Then ^7Be decays into ^7Li by $^7Be(e,\nu)^7Li$ if it is convected to lower temperature ($T < 3 \times 10^6 K$, otherwise ^7Be is destroyed by $^7Be(p,\gamma)^8B$). Then this newly formed lithium, in order to survive, must not go down to temperatures larger than 2.5 million degrees to survive. This is not an easy process although it is not excluded. As discussed below, giant stars with large lithium abundances do exist and have to be explained somehow.

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[1] Note : log $\varepsilon(Li)$ is the logarithm of the lithium abundance in a scale where the logarithm of the hydrogen abundance is 12; the cosmic abundance is supposed to be log $\varepsilon(Li) = 3.3$

1.3. FIELD STARS

Alschuler (1975) observed 64 field stars with spectral types between F4III and G5III. He found a smooth decrease of the lithium abundance from the F to the G stars. A comparison with Iben's predictions for the lithium dilution in such stars (with masses evaluated between 1.9 and 3.2 $M_\odot$) showed that the observed decrease was much smoother than the predicted one. Schatzman (1977) interpreted these results in terms of turbulence in the main-sequence progenitors of these giant stars : the lithium nuclear destruction zone is closer to the surface for more massive stars, which leads to a more rapid lithium destruction in the stellar outer layers and may explain Alschuler's observations.

More recently Brown et al. (1989) made a large survey of the lithium abundance in 644 bright G and K giants (see also Lambert, Dominy and Sivertsen (1980), Luck and Lambert (1982)). All the observed stars but ten are lithium poor compared to the "cosmic abundance" with an average of $\log \varepsilon(Li)$=0.1, well below the standard value of 1.5 predicted by Iben. Giant stars are supposed to have completed their lithium dilution when they reach effective temperatures smaller than 4500K. When only these stars are taken into account in the sample, the average lithium value drops to -0.4. As will be discussed below, these observations suggest the occurence of extra depletion *inside* the 2 to 3 $M_\odot$ main-sequence progenitors of these stars.

Ten of the giants observed by Brown et al. (1989) are "lithium rich" compared to the lithium abundance expected in giant stars, namely $\log \varepsilon(Li)$=1.8 to 2.7. Two stars have a nearly cosmic value : HD9746 and HD112127 (first observed by Wallerstein and Sneden (1982)). 9 Bootis, observed as lithium rich by Hänni (1984), is found "normal" ($\log \varepsilon(Li)$=1.5) by Brown et al. (1989). Another lithium rich giant star with a nearly cosmic abundance has been observed by Gratton and d'Antona (1988) : HD39583. Among the lithium rich giants, two at least have a small $^{12}C/^{13}C$ ratio (of about 25 compared to ≈ 90 for the sun) which shows that they have been deeply mixed in their interior. Other measurements of the carbon isotopic ratio are needed to go further in the interpretation of these stars.

Another class of giant stars may show relatively large lithium abundances : the so-called "weak G-band" stars, with anomalously weak CH bands and a very low $^{12}C/^{13}C$ ratio (3 to 4 compared to 90 for the sun). In these stars the lithium abundance can range from $\log \varepsilon(Li)$=3.0 to less than 0.8 (Hartoog (1978), Lambert and Sawyer (1984)).

Some giant stars with anomalous abundances of other elements (S-type and carbon stars) may also show large lithium abundances (Torres-Peimbert and Wallerstein (1966), Boesgaard (1970), Catchpole and Feast (1976), see also reviews by Wallerstein and Conti (1969), Michaud and Charbonneau (1990)). Contrary to the "weak G-band" stars, these giants can show lithium abundances quite in excess of the cosmic value, which suggests that they could be AGB stars in which lithium is freshly produced by nuclear reactions.

Smith and Lambert (1989) and (1990) have observed lithium rich giants in the two magellanic clouds. 12 stars out of 21 for the SMC, and 4 out of 5 for the LMC are indeed lithium rich, with log $\varepsilon(Li)$=2.0 to 4.0. They all lie in the same region of the HR diagram, corresponding to the most luminous AGB stars, with masses of 4 to 8 $M_\odot$. They suggest that all stars in this mass range go through the lithium rich stage, and that this process can enrich the lithium content of galaxies with time (see also Scalo (1976), Lambert (1990)).

1.4. CLUSTER STARS

Lithium observations in giant stars which belong to galactic clusters are summarized in Charbonneau, Michaud and Proffitt (1989), and Gilroy (1989). Stars in clusters all have the same age, equal to the main-sequence lifetime of the turnoff stars. The evolution time scale from the main-sequence to the giant stage is small, and it can be assumed with a very good approximation that the masses of the observed giant stars in the clusters are the same as the turnoff stars masses. Lithium observations in such giants is thus a test of the lithium depletion in main-sequence stars of known masses.

Charbonneau, Michaud and Proffitt (1989) discuss the lithium observations in giants of three galactic clusters and compare them with the predictions of meridional circulation on the main sequence :

- M67, with an age of 5Gy (VandenBerg (1983)), corresponding to a turnoff mass of 1.3 $M_\odot$, have been observed by Pilachowsky, Saha and Hobbs (1988) and Garcia-Lopez, Rebolo and Beckman (1988). The former find only lithium upper limits in the 17 observed giants while the later obtain log $\varepsilon(Li)$=0.75 for the only star they observed. These results lead to a factor 30 of "extra depletion" compared to the predictions of the standard theory.

- NGC 752, with an age of 2.2 Gy (Twarog (1983)), corresponding to a turnoff mass of 1.6 $M_\odot$, have also been observed by Pilachowsky, Saha and Hobbs (1988) who find upper limits for lithium in nine giants and log $\varepsilon(Li) \approx 1.2$ in two others. This leads to a factor about 10 of "extra depletion".

- NGC 7789, with an age of 1.6 Gy (Twarog and Tyson (1985)), corresponding to a mass of 1.8 $M_\odot$, have lithium abundances compatible with the standard dilution predictions, and suffer at most a factor 3 of "extra depletion". Similar results are obtained for the Hyades giants, with an age of 0.8 Gy, corresponding to a mass of about 2 $M_\odot$.

These results could lead to the idea that the "extra depletion" needed in main-sequence stars to explain the observations of giants decrease for increasing masses. However more recent observations by Gilroy (1989) show that this is not the case. Gilroy (1989) have observed lithium in 60 stars which belong to 20 galactic clusters with ages between 50 million to 5 billion years (turnoff masses of 1.3 to 6 $M_\odot$). For all the turnoff masses the average lithium abundances range from a factor 3 to a factor up to 1000 below the predictions of the standard model. We are thus lead to the conclusion that ***for all masses there is a dispersion in the lithium mass destroyed inside the stars before they become giants.*** As no such depletion is observed for main-sequence stars of masses larger than 1.6 $M_{\odot}$, which lie on the left side of the "lithium dip" (Boesgaard and Tripicco (1986a)), Gilroy suggests that the depletion occurs between the turnoff and the giant stage. However theoretical computations show that such a depletion is unrealistic during this phase (see Sweigart and Mengel (1979)). Another possibility, which will be discussed below, is that extra lithium destruction does occur inside these main-sequence stars, but that it does not appear at the surface before the giant stage (when the lithium depleted layers are transported outwards by convection).

Gilroy (1989) also observed the $^{12}C/^{13}C$ ratio in the same clusters. She found values compatible with standard dilution as computed by Dearborn, Eggleton and Schramm (1976) for masses larger that 2 $M_{\odot}$. For smaller masses, the average value of the carbon isotopic ratio is smaller than the predicted value by a factor $\approx$ 2. Gilroy and Brown (1990) have later established a correlation between the carbon ratio and the evolutionary stage of stars in M67. They show that stars near the lower giant branch exhibit carbon ratios compatible with the "first dredge up" predictions while stars at the tip of the giant branch and in the clump exhibit anomalously low ratios. They suggest that ^{13}C is mixed up to the surface by extra mixing along the red giant branch.

1-5 GENERAL SUMMARY OF THE RELEVANT OBSERVATIONS AND DISCUSSION

We can summarize the observations of lithium in main-sequence and giant stars in the following way :

<u>In population I stars :</u>

- Main-sequence cool stars show a lithium depletion which increases for decreasing effective temperatures and which increases with age (see reviews about main-sequence stars in this conference and references therein).

- Main-sequence F stars show a lithium depletion for effective temperatures around 6600K in galactic clusters (Boesgaard and Tripicco (1986a)), which increases with age. Balachandran, Lambert and Stauffer (1988) showed that the dip also exist in field stars, although more spread than in clusters. Recent observations of subgiants in the Hyades show that the lithium dip is still present when the stars evolve off the main-sequence (Balachandran (1990)).

- On the hot side of the dip the lithium abundance seems basically "normal" (with the cosmic value) except in some peculiar A stars (Burkhart and Coupry (1989)).

- Field giants as well as galactic cluster giants show an average lithium depletion larger than expected with the simple dilution theory, and a large spread in lithium abundances is observed. This suggests that lithium has been more depleted in their main-sequence progenitors than expected by the standard nuclear destruction, even if this extra depletion is not seen at the surface of main-sequence stars with masses larger than 1.4 $M_\odot$.

– On the other hand some giants show a lithium enrichment with respect to the expected value. Here we must distinguish giants on the RGB, in which no lithium production is expected, and which must have retained more of their original lithium than usual, and giants on the AGB where some fresh lithium may have been formed by nuclear reactions.

In population II stars :

– A similar depletion as for population I stars is obtained for cool halo stars, but for lower masses, which is certainly related to the depth of the convection zones (convection zones are shallower for smaller metallicities, and similar depths are obtained for smaller masses in pop II stars than in pop I stars).

– The maximum lithium abundance in halo stars ("plateau value") is 10 times smaller than the present "cosmic value" (see reviews in this conference and references therein).

– No "Boesgaard dip" is observed for halo stars, probably because those stars which could suffer it are already evolved off the main-sequence.

2. Mixing or not mixing?

2.1. WHY TURBULENCE?

Let us suppose for a moment that there is no macroscopic motions of any kind in stars. What would be the lithium abundance? Figure 1 give a possible prediction for population I main-sequence stars at the age of the Hyades. Some depletion could have occured in G stars on the pre main-sequence (d'Antona and Mazzitelli (1984), Proffitt and Michaud (1990a)), but not enough to account for the observations unless some arbitrary changes are introduced in the opacities (Swenson, Stringfellow and Faulkner (1990)). In any case, pre main-sequence depletion could not account for the decrease of the average lithium abundance with age in open clusters G stars. The Boesgaard dip could be explained by gravitational settling and radiative acceleration (Michaud (1986)), but the computed lithium abundance is too high compared to the observations in A stars. In population II main-sequence stars, the lithium depletion in early G stars could be accounted for in this standard theory (Deliyannis et al. (1990)); however lithium would be depleted due to gravitational settling in more massive stars which would lead to a dispersion in the abundances, contrary to the observations (Michaud, Fontaine and Beaudet (1984), Proffitt and Michaud (1990b)). Finally the lithium abundances in giants could not be explained in this standard theory (see section 1). So macroscopic motions are needed indeed to account for the observations of lithium in stars.

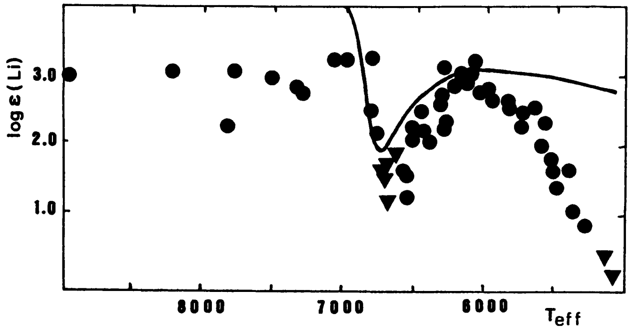

FIGURE 1. — Observations of the lithium abundances in the Hyades after Boesgaard (1970), Cayrel et al. (1984), Burckhart and Coupry (1989). The solid curve represents the theoretical results if no macroscopic motions exist in these stars. Lithium is slightly depleted in cool stars due to pre main-sequence burning. The lithium decrease in the dip is due to gravitational settling (Michaud (1986)). In this case lithium is expected to be overabundant in early F and A stars due to the radiative acceleration, which is not observed.

Very large mass loss, as proposed by Willson, Bowen and Struck-Marcell (1987), in the early times of main-sequence stars would lead to a complete lithium destruction, so that all the lithium observed now should be fresh one (Guzik, Willson and Brunish (1987)). It seems unlikely to reproduce, in this case by chance, all the observed lithium features. On the other hand, there are more and more evidences that small mass loss of the order of the solar wind do occur in late type stars up to early F and A stars (Michaud (1986), Michaud et al. (1983) and (1987), Dolez, Vauclair and Gough (1990)). Such a small mass loss could prevent the lithium abundance from becoming too high in early F and A stars, but it cannot help explaining the other lithium features observed in stars. Mass loss in G stars can be theoretically adjusted to lead to the observed present lithium solar depletion, due to the lifting of the lithium depleted layers. Hobbs, Iben and Pilachovsky (1989) have shown that this would need an average solar wind 500 times larger than the present observed one. This "ad hoc" theory would not account anyway for the other observed lithium features in stars.

Meridional circulation, as computed by Tassoul and Tassoul (1982), has been proposed by Charbonneau and Michaud (1988) as an alternative to microscopic diffusion in order to explain the Boesgaard dip in galactic clusters. The red side of the dip is well reproduced with realistic rotational velocities but a combination of meridional circulation and radiative acceleration has to be invoked to explain the blue side. Meridional circulation is not able to account for the lithium depletion in main-sequence G stars. On the other hand it predicts lithium extra destruction in main sequence A and F stars which is incompatible with the observations of red giants in clusters like NGC 7789 (Charbonneau, Michaud and Proffitt (1989), see section 1-4).

2.2. WHICH TURBULENCE?

A general review of the hydrodynamical instabilities in stellar interiors may be found in Zahn (1983). After a short description of the possible instabilities induced by gravity waves, I will basically focus here on the instabilities induced by rotation and/or related to the angular momentum loss is stars.

Instabilities induced by gravity waves have recently been suggested as a possible mechanism for explaining the lithium dip in galactic clusters and field stars (Garcia Lopez and Spruit (1990)). This is a new and original idea, although still somewhat speculative. Gravity waves are produced at the bottom of outer convection zones and may propagate downwards if their frequency is smaller than the local Brunt-Väisälä frequency. The interesting point is that the flux of produced gravity waves increases with increasing stellar mass due to the increase of the turnover frequency of the convective eddies, and that it stops when this frequency becomes larger than the relevant Brunt-Väisälä frequency. This occurs for masses around 1.5 $M_\odot$. The authors derive a condition which is "likely to be sufficient" for effective mixing by these waves. This condition is not satisfied in stars if the convection zones are treated in the frame of the mixing length approximation. However, if one supposes that the downwards eddies have a velocity 20 times that of the upwards eddies (which is not excluded), the condition is fulfilled for stellar masses smaller than 1.35 $M_\odot$. Quantitative computations show that in this case the Hyades lithium dip can be well reproduced. This possible mixing process must be kept in mind although it is not able to account for either the lithium depletion in G-type stars or for the lithium "extra depletion" in more massive stars.

As pointed out by Pinsonneault et al. (1989), angular momentum must be transported inside late type stars during their main-sequence life-time, at a greater rate than chemical species. If the decrease of angular momentum in solar-type stars was due to turbulence, no lithium nor beryllium would be left at all at the surface. Transport of angular momentum inside stars is still a subject of debate, hard enough to give headaches to astrophysicists (see Schatzman (1990)). Two extreme positions have been taken : Pinsonneault et al. (1989) supposed that matter was mixed at a rate proportional to the rate of transport of angular momentum. They adjusted the proportionality constant to obtain the right lithium abundance in the right sun and found that a factor 20 was needed. Then they used this parametrisation to compute the lithium deficiency in other solar type stars and found a good agreement with the observations. This parametrisation of turbulence however cannot account for the blue side of the lithium dip nor for the observations of lithium in giant stars.

Vauclair (1988) and Charbonnel, Vauclair and Zahn (1990) (CVZ) computed turbulence induced by stellar rotation independently of the loss of angular momentum (except that CVZ took into account in their computations the variation of the stellar rotation velocity with time). Turbulence induced by stellar rotation has been extensively discussed in Zahn (1975), (1983) and (1990). Thermal imbalance due to the ellipsoidal shape of the gravity potential surfaces in rotating stars leads to meridional circulation. The induced transport of angular momentum creates a 2-D shear flow instability, which becomes 3-D at small scales, and leads to mixing of matter inside the star. For a barotropic star with negligible differential rotation, the resulting turbulent diffusion coefficient may simply be written :

$$D_T = \gamma \left| \frac{L}{M^3} \frac{r^6 \Omega^2}{G^2(\nabla_{ad} - \nabla_{rad})} \left[1 - \frac{\Omega^2}{2\pi G \rho} \right] P_2(cos\theta) \right|$$

where L and M are the luminosity and mass of the star, G the gravitational constant, r the local radius, ρ the local density, Ω the angular rotation velocity, ∇_{ad} and ∇_{rad} the usual adiabatic and radiative gradients, $P_2(cos\theta)$ the 2-order Legendre polynomial and γ a factor of order one.

This turbulent diffusion coefficient has been used by Vauclair (1988) and CVZ to account for the lithium features observed in galactic clusters and halo stars. Contrary to Vauclair (1988), who did approximate analytical computations, and who did not take into account the angular momentum loss with time in stars, CVZ thoroughly resolved the diffusion and nuclear destruction equations for lithium (and also beryllium) with an implicit numerical code. CVZ first confirmed Vauclair's (1988) results under the same conditions (constant rotation velocity). Then they computed lithium abundance variations in main-sequence disk and halo stars by taking into account the variation of the rotation velocity with time. Several laws were tested for the decrease of the angular momentum with time (Skumanich (1972), Schatzman (1988), (1990)). The initial angular momentum on the main-sequence as given by Kraft (1970) and Kawaler (1987) and (1988) was used. Pre main-sequence depletion was introduced in some computations only by a parametrisation following d'Antona and Mazzitelli (1984) or Proffitt and Michaud (1990a). Results are given by Charbonnel (1990). The lithium dip in the Hyades and other galactic clusters is well reproduced with the assumption that all stars began their life on the main-sequence with a velocity of 100 km.s^{-1} and then were slowed down to their present velocities.

The blue side of the dip has been attributed by Vauclair (1988) to a separation of two mixed zones in the stars due to the occurence of two loops of meridional circulation (figure 2). "Dead points" are found in the computations of meridional currents in stars in the layers where the effect of the centrifugal force compensates that of gravity. Then $\Omega^2/2\pi G\rho = 1$ where Ω is the angular velocity in the star, G the constant of gravitation and ρ the local density. Such a quiet zone occurs only if the star rotates like a solid body or with a negligible differential rotation (Pavlov and Yakovlev (1978)). This assumption is realistic, as found in the sun from solar oscillations (T. M. Brown et al. (1989)). For the G-type stars a good agreement between theory and observations can be obtained with pre main-sequence depletion as computed by Michaud and Proffitt (1990) followed by turbulent depletion computed with the Zahn turbulent diffusion coefficient.

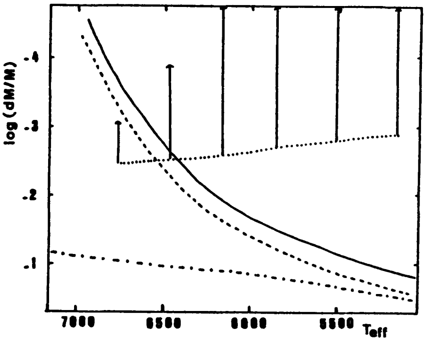

FIGURE 2. — The "quiet zone" in main-sequence stars. The ordinates represent the outer mass ratio in the stars while the absissae show is the effective temperature. The solid line is the bottom of the convection zone for $\alpha = 1.9$ (ratio of the mixing length to the pressure scale height). The dashed line is the same with one pressure scale height added for overshooting. The dotted line represents the quiet zone for a rotation velocity $V_{rot} = 100\mathrm{km.s}^{-1}$. The end of the arrows are for $V_{rot} = 50\mathrm{km.s}^{-1}$. The quiet zone gets out of the convection zone just at the place of the lithium dip, which may explain that lithium is normal in hotter stars. This model assumes that matter is mixed below and above the quiet zone but not in between.

The rapid increase of the turbulent diffusion coefficient with radius leads to a "plateau effect", as discussed by Vauclair (198)8 and confirmed by CVZ. Once the bottom of the convection zone is far enough from the lithium destruction region, changes in the convective depth introduce negligible changes in the resulting surface lithium abundance. This effect could lead to a lithium destruction in halo stars with a shape similar to that observed (Spite and Spite (1982) and (1986), Rebolo, Molaro and Beckman (1988)). This process would however require a very small dispersion in the initial angular momentum for halo stars.

2.3. THE QUIET ZONE AND OTHER QUESTION MARKS

Four different models have now been proposed to account for the lithium dip in galactic clusters.

The first one is microscopic diffusion, as computed by Michaud (1986) (see also Vauclair et al. (1978), Thevenin, Vauclair, Vauclair (1986)). This process gives the lithium dip at the right place, but it cannot account for all the observations. It needs some mass loss or other macroscopic motions to prevent lithium from becoming overabundant on the blue side of the dip.

In the second model, developed by Charbonneau and Michaud (1988), meridional circulation becomes the main process involved (lithium is then destroyed by nuclear reactions) and microscopic diffusion is now the secondary process which prevents lithium from being destroyed on the blue side, owing to the radiative acceleration which lifts it up (note that, in this model, there must be a fine tuning between the velocity of meridional circulation downwards and the microscopic diffusion velocity upwards for the lithium abundance to remain constant at the surface).

The third model is the rotation-induced turbulence model developped by Vauclair (1988) and Charbonnel, Vauclair and Zahn (1990). It can account for the red and blue side of the dip if the separation between the two mixing zones is effective (see below).

The fourth model involves mixing induced by gravity waves as already discussed above (Garcia Lopez and Spruit (1990)). This model could account for the dip but not for the depletion in G stars.

Observations of giant stars give new constraints on these theories. The observed giants, which had main-sequence progenitors with masses of 1.4 to 4 $M_\odot$, show evidences of extra lithium depletion compared to that of the standard theory, while this depletion do not appear on the main-sequence stars. As shown by Sweigart and Mengel (1979) for the carbon isotopic ratios, meridional currents cannot be efficient on the subgiant branch. They could have some effect later during the giant evolution on the RGB (it would be important in this respect to be able to discriminate correctly between stars on their first ascent and stars on the giant clump). Note however that such meridional currents could be important on the giant branch only in case of rapid rotation on the main-sequence (periods less than one day), which means that the effects of meridional circulation on these main-sequence stars should have to be taken into account first.

Mass ($M_\odot$)	2.0	1.8	1.6	1.35
200 km s^{-1}	2.9	3.5	4.1	5.8
100 km s^{-1}	13.0	13.3	15.1	24.2
50 km s^{-1}	52	59	69	96

Table 1 : Lithium dilution ratios

It is more likely indeed that the lithium observations in giants be due to extra depletion during the main-sequence stage. Such a depletion could be accounted for in the frame of theories which involve a separation between two zones of meridional circulation. Then lithium could be destroyed inside the star up to the "quiet zone" in between the two mixed zones, and not above. During the evolution of the star to the giant stage, the deep convection zone would dig up this lithium-free region. As the depth of this zone is closer to the surface for more slowly rotating stars, *slow rotators are expected to retain less lithium than rapid rotators*. Table 1 displays the ratios of the lithium depletion with and without mixing for various masses and rotation velocities on the main sequence.

The problem remains of the existence and efficiency of this "quiet zone". It does exist if the differential rotation is small enough inside the star. Charbonneau and Michaud (1990) claim that this zone would be too small to prevent the diffusion of the chemical species. This drawback could however be overcome by a μ barrier, as discussed in CVZ. More observations of lithium in giants and in main-sequence A stars will hopefully help constraining these theories in the near future.

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