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LITHIUM NUCLEAR DESTRUCTION IN STELLAR OUTER LAYERS: A CONSISTENT THEORETICAL VIEW OF THE CHARACTERISTIC FEATURES OBSERVED IN YOUNG AND OLD STARS

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ABSTRACT

Lithium nuclear destruction in young and old stars has been computed within the framework of Zahn's theory of turbulent mixing induced by rotation.

The lithium gap observed for F stars in the Hyades and other clusters by Boesgaard and her collaborators may be due to nuclear destruction, as already proposed by Boesgaard. The destruction law follows the increase of the rotation velocities with $T_{\rm eff}$ in these F stars. Above 6700 K the existence of two separate zones of meridional circulation may prevent complete mixing between the bottom of the convection zone and the lithium nuclear burning layer so that lithium remains normal at the surface as observed. A fit of the observations with the theoretical results gives a parameter-free value for the mixing length, which must be equal to 1.9 times the pressure scale height, consistent with recent computations of solar evolutionary tracks and solar oscillations.

For Population II stars, preliminary computations show that the observed lithium abundance of $\mathrm{Li/H} = 10^{-10}$ could also be due to nuclear destruction with an original value of 10^{-9}. The "plateau" observed by Spite and Spite and confirmed by more recent observations may be accounted for in this framework owing to the rapid increase of the turbulent diffusion coefficient with radius. In this case the primordial lithium abundance would be 10^{-9} instead of 10^{-10}. The two possibilities are discussed.

Subject headings: abundances — diffusion — hydrodynamics — stars: rotation

I. INTRODUCTION

The cosmological importance of lithium has been discussed many times in the literature: its primordial abundance brings one of the most severe constraints on the parameters which govern the first minutes of the universe. This primordial abundance is still a subject of debate. The maximum lithium abundance observed in young galactic clusters is $\mathrm{Li/H} = 10^{-9}$ (e.g., Boesgaard and Tripicco 1986; Boesgaard, Budge and Ramsay, 1988; Hobbs and Pilachowski 1986*a*, *b*; Pilachowski, Booth, and Hobbs 1988). This result suggests that young stars were all born with this lithium abundance, and that it has been depleted in some of them. This lithium abundance has long been taken as the primordial one. However, Spite and Spite (1982), and Spite, Maillard, and Spite (1984) observed that the maximum lithium abundance in halo stars was $\mathrm{Li/H} = 10^{-10}$. This result has further been confirmed by several authors (Boesgaard 1985; Rebolo, Molaro and Beckman 1988; Hobbs and Duncan 1987). From then on the astronomical community has been faced with this terrible dilemma: is the primordial lithium abundance the one observed in halo stars, and has lithium been further enriched in the galactic medium; or is the primordial lithium abundance the one observed in young stars, and has lithium been depleted in old stars? Most astronomers now prefer the first hypothesis, for the basic reason that the lithium abundance is remarkably constant in halo stars (except for depletion in the cool G stars), while it seems at first sight that depletion effects would lead to a large dispersion. I will show in this paper that this is not always true. After a short summary of the computational framework based on Zahn's theory of turbulent mixing induced by rotation, I will discuss the lithium nuclear destruction first in galactic clusters and second in halo stars. I will show that this theory may give a simple and consistent explanation of the lithium abundance features observed in these stars.

II. COMPUTATIONAL FRAMEWORK

As shown by Zahn (1983, 1984, 1987*a*, *b*), the thermal imbalance induced by stellar rotation leads to meridional circulation and differential rotation which give rise to horizontal shear flow instabilities (the vertical ones being damped out by the density stratification). The resulting two-dimensional turbulence decays into three-dimensional turbulence at small scales, which in turn leads to mixing (the reader is referred to Zahn's papers for a detailed description).

In the barotropic approximation and assuming a small differential rotation, the turbulent diffusion coefficient takes the form:

$$D_T \approx \frac{\Omega^2 r^6}{G^2(\nabla_{\rm ad} - \nabla_{\rm rad})} \frac{L}{M^3}\left(1 - \frac{\Omega^2}{2\pi G\rho}\right)P_2(\cos\theta)\,, \qquad (1)$$

where L and M are the stellar luminosity and mass, $\nabla_{\rm ad}$ and $\nabla_{\rm rad}$ are the adiabatic and radiative gradient $[(\partial \ln P)/(\partial \ln T)]$ in the stellar gas at radius r, $P_2(\cos\theta)$ is the usual Legendre polynomial, and Ω is the angular rotational velocity. The negative term $\Omega^2/(2\pi G\rho)$ comes from the classical expression for the local energy density due to thermal imbalance. This term becomes larger than one at low densities, where the centrifugal effects take over the gravitational ones in the stellar deviation from spherical symmetry (Von Zeipel 1924). Then, in the framework of Mestel (1975) theory, the meridional circulation is reversed, and it leads to two different meridional loops (see also Pavlov and Yakovlev 1977). The turbulent diffusion coefficient (1) vanishes, and no mixing occurs between the two zones. J. L. Tassoul (private communication) pointed out that this separation into two zones may disappear when one treats the meridional circulation problem as in Tassoul and Tassoul (1982; see also Tassoul 1984). A precise study for the existence of these two zones in the same computational framework will be of great interest.

For a first approximation the lithium nuclear destruction is treated in a step model, lithium being completely destroyed at radius $r_{\rm NB}$ and not destroyed above. With the W.K.B. approximation (see Baglin, Morel, and Schatzman 1985), the variation of the lithium abundance with time in the convection zone is supposed to vary as

$$N(\mathrm{Li}) = N_0(\mathrm{Li})e^{-\lambda t} . \quad (2)$$

Assuming the negative term negligible in equation (1), and with averaged Ω, $\nabla_{\rm ad} - \nabla_{\rm rad}$ and $P_2(\cos\theta)$, λ comes out as

$$\lambda = \frac{\gamma\Omega^2}{(\nabla_{\rm ad} - \nabla_{\rm rad})}\left(\frac{r_{\rm NB}}{r_\odot}\right)^4 \frac{\beta^4}{(\beta^2-1)^2}\frac{L_*/L_\odot}{(M_*/M_\odot)^3}\ \mathrm{yr}^{-1} , \quad (3)$$

with $\beta = r_{\rm CZ}/r_{\rm NB}$ where $r_{\rm CZ}$ is the radius at the bottom of the convection zone, and γ is a factor of order 0.1. It must be clear at the present step that equations (2) and (3) are approximate. Also the variation of Ω with time (rotational braking) is not introduced here. More precise numerical computations will be given in a forthcoming paper. The interest of the present analytical formulation is to show the physics. The rapid variation of D_T with radius leads to an interesting behavior of the variation of λ with β. If β is close to one (deep convection zone), λ is large and the lithium nuclear destruction is rapid in the convection zone. If β increases (going from G to F stars) λ decreases and the lithium nuclear destruction is less effective. However, the slope of the variation of λ and β also decreases, so that the change in the lithium abundance due to the regression of the convection zone is less and less pronounced. This result is simply due to the fact that the added radiative layer is mixed by turbulence in a time scale which is short compared to the layers underneath. This effect creates a "plateau" shape of the lithium abundances as discussed below.

III. LITHIUM ABUNDANCES IN GALACTIC CLUSTERS

The lithium abundances observed in galactic clusters present spectacular characteristics, especially for the Hyades (Fig. 1): a clear and continuous depletion is observed for G stars (Duncan 1981; Cayrel *et al.* 1984) while a narrow and well defined "gap" has been discovered by Boesgaard and Tripicco (1986) for F stars around 6700 K. The "plateau" between the "F gap" and the "G depletion" presents the same lithium abundance as hot F and A stars, i.e., Li/H = 10^{-9}. Similar observations have been obtained in other galactic clusters of different ages (Hobbs and Pilachowski 1986*a*, *b*; Pilachowski, Booth, and Hobbs 1988; Boesgaard, Budge, and Ramsay 1988; Spite *et al.* 1987). It has been known for a long time that the lithium depletion in G stars was a function of time (Zappala 1972). Observations of Pleiades now show that the lithium abundance in the F gap also decreases with age. Furthermore the abundance of lithium in the "plateau" also seems to decrease with time, as it is smaller in the older clusters, the abundance observed in hot F stars remaining the same (Boesgaard, Budge, and Burck 1988; Boesgaard 1988; Charbonneau and Michaud 1988).

The lithium depletion in G stars has always been attributed to nuclear destruction. The convection zones become deeper for cooler stars, so that the bottom of these zones come closer to the depth where lithium is destroyed by proton capture ($T \approx 2.5 \times 10^6$ K). Turbulence below these convection zones has to be invoked to understand the observed depletion curves (e.g., Cayrel *et al.* 1984; Baglin, Morel, and Schatzman 1985).

An explanation of the F gap in the Hyades was proposed by Michaud (1986) in terms of gravitational and radiative diffusion. As the convection zones decrease for hotter stars, the lithium diffusion time scale also decreases and a lithium depletion may be obtained around $T_e = 6700$ K. The increase of lithium in hotter F stars may be due to the radiative acceleration on Li III. This model is very attractive. It suffers, however, from some drawbacks: the lithium abundance in hot F stars should increase above the original value, which is not observed; the theoretical minimum is larger than the observed one; finally, the condition that the stellar gas be stable under the convection zones seems difficult to reconcile with the turbulence needed to explain the G depletion. On the other hand, as pointed out by Boesgaard and Tripicco 1986 and Boesgaard 1987, the lithium depletion in the gap seems related to the increase of the stellar rotation velocities from G to F stars (Fig. 1).

The formalism described in the preceding section has been applied to the case of the Hyades. The decrease of the lithium abundance on the cool side of the "gap" is supposed to be due to nuclear destruction related to the increase of the stellar rotation, while the fact that lithium is not destroyed on the hot side of the "gap" is attributed to the development of two separate mixed zones, when the negative term in equation (1) becomes larger than one under the convection zone. This gives a *parameter-independent constraint on the mixing length.* For a good fit with the observations the negative factor $\Omega^2/(2\pi G\rho)$ must be of order one at the bottom of the convection zone for an effective temperature of $\sim$6700 K. *This is obtained with a mixing length parameter* (ratio of the mixing length to the pressure scale height) $\alpha = 1.9$. This value is not only parameter free: it is also independent of any unknown numerical factor related to the approximations in equation (3). This result gives the same value of the mixing length parameter as needed to account for *solar evolutionary tracks* (Lebreton and Maeder 1986) and it is also consistent with *solar oscillations* (Christensen-Dalsgaard *et al.* 1985).

Computations of lithium destruction have been done with model envelopes computed with $\alpha = 1.9$. Results are given in Figure 1. The values of Ω used here are those given by the solid curve in Figure 1*b*. For a best fit with the observed depletion in the Hyades gap, the factor γ in equation (3) has been given the value 0.17. Figure 1*a* shows three depletion curves: the first one for the age of the Pleiades (6×10^7 yr), the second one for the Hyades (7×10^8 yr) and the third one for 2×10^9 yr. On the hot side of the gap, lithium is not mixed down to the burning layer and remains normal at the surface. Considering that turbulence vanishes when $D_T < \nu$ (viscosity in the medium), the thickness of the "quiet zone" between the two mixed zones may be estimated as $\approx$100 km while the maximum turbulent scale is $\approx$0.1 km.

The fit is not so good for G stars. However, the step approximation used here is too crude when the distance between the bottom of the convection zone and the nuclear destruction layer is as small as in these stars and more precise numerical computations are needed for a discussion of this fit (this is outside the scope of the present paper).

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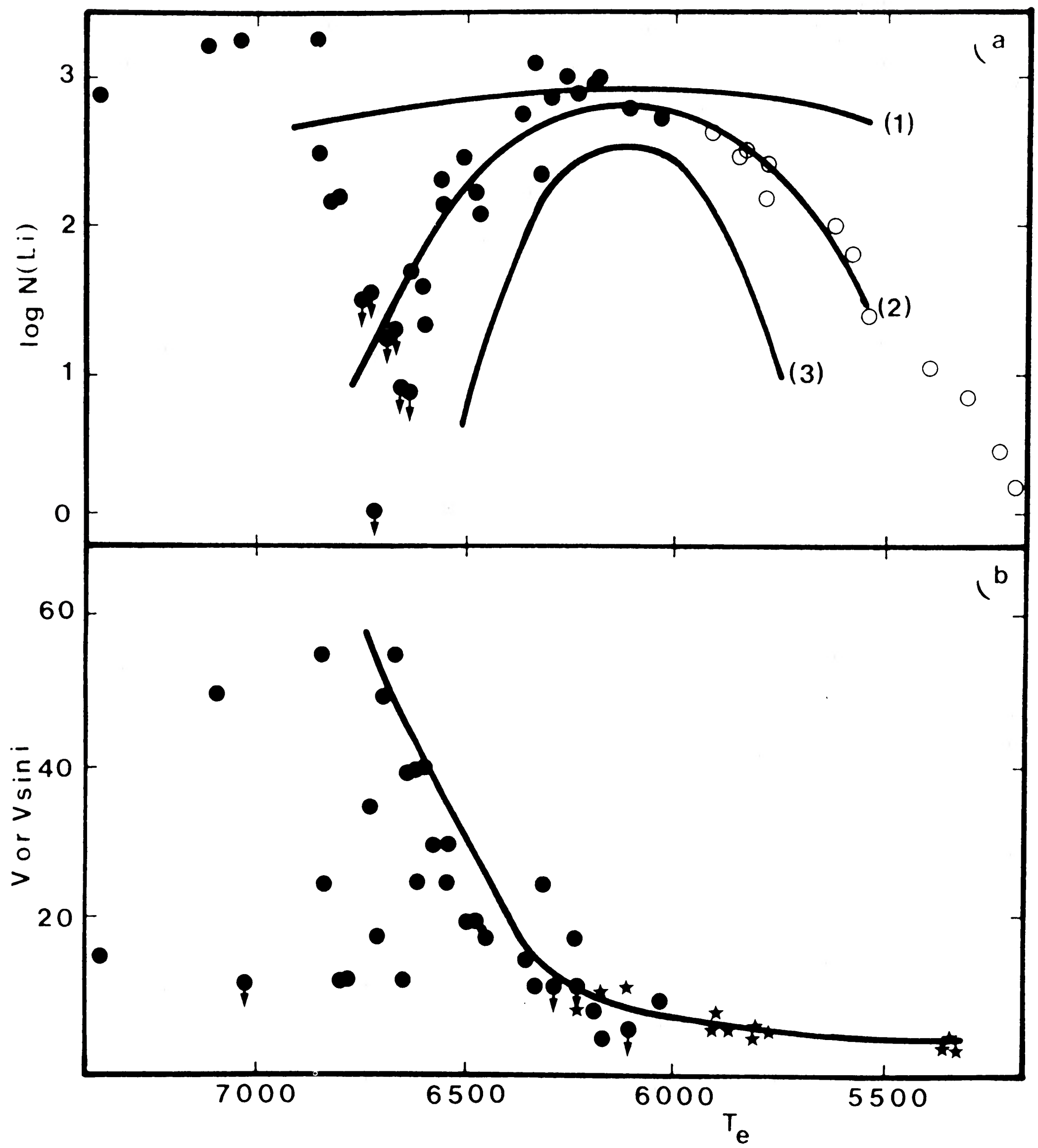

FIG. 1.—Lithium depletion and stellar rotation velocities in Hyades. The filled dots represent Boesgaard (1987) observations for lithium in (*a*) and $V \sin i$ for the same stars in (*b*). The open circles in (*a*) are Cayrel *et al.* 1984 observations while the stars in (*b*) are the rotation velocities measured from activity periods by Radick *et al.* 1987. Theoretical lithium depletion curves are shown for (1) 6×10^7 yr, (2) 7×10^8 yr, and (3) 2×10^9 yr. They have been obtained with the rotation velocities given by the solid curve in (*b*). The lithium depletion curves are less precise on the right side than on the left side due to the approximation.

IV. HALO STARS

Computations of lithium nuclear destruction have been done using VandenBerg 1983 evolutionary tracks for 0.7 and 0.8 $M_\odot$ with $Y = 0.2$ and $Z = 10^{-4}$. The extrapolation values given by VandenBerg have been used to obtain parameters for evolutionary tracks with $\alpha = 1.9$. Three model envelopes have been computed with these parameters for 0.7 $M_\odot$ (ages 0.297, 4.047 and 13.481 billion yr) and four for 0.8 $M_\odot$ (ages 0.197, 3.187, 9.276, and 13.448 billion yr). The lithium nuclear destruction has been deduced by interpolation in the two cases for 4, 9, and 15 billion years. These values are given in Figure 2. The numerical factor in equation (2) has been adjusted for a best fit with the observations at 15 billion yr. If $\gamma = 0.17$ as deduced from Hyades, the needed value leads to an average rotation velocity of 10 km s^{-1} The rotation velocity of halo stars is not known from observations except for HD 13095, where it is only ~ 1.6 km s^{-1} (Noyes, Weiss, and Vaughan 1984), but it may have been larger in the past. The interesting result here is that the lithium depletion is parallel along the two tracks. As already mentioned, a plateau appears naturally in this framework because of the rapid increase of the turbulent diffusion coefficient with radius. The increase of L/M^3 for hotter stars balances the remaining effect. Also shown on Figure 2 (*arrow*) is the effective temperature for stars in which lithium is completely destroyed (the bottom of the convection zone reaches the nuclear destruction layer in the zero-age main-sequence model). This occurs for stars of ~ 0.6 $M_\odot$.

These computations have been done with the hypothesis that all the stars had the same average rotation velocity, the same age, and the same metallicity. These points have to be discussed. The weakest point of this theory is the strong constraint needed on the rotation velocity. The dispersion in the

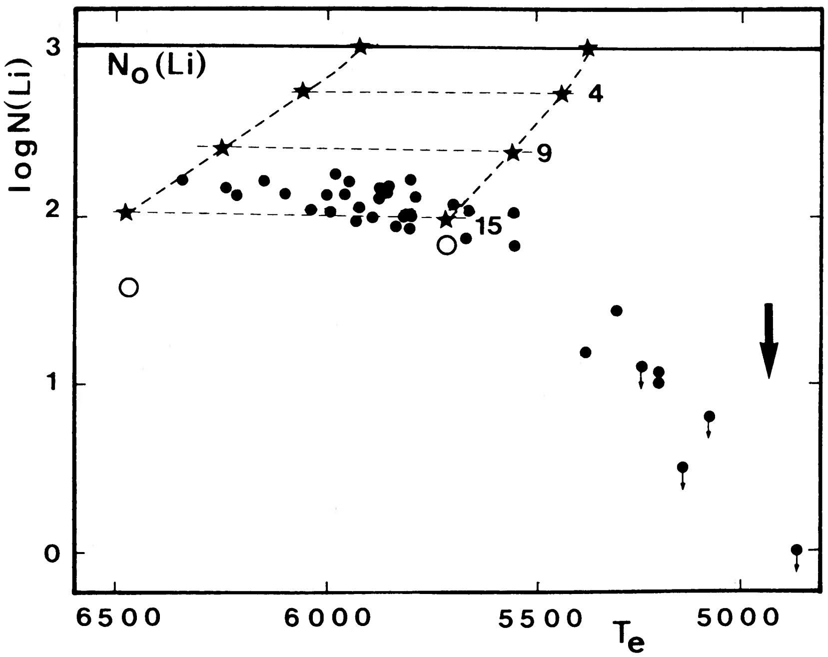

FIG. 2.—Lithium nuclear burning in Population II stars, computed in VandenBerg (1983) evolutionary tracks for 0.70 and 0.80 solar masses, with $\alpha = 1.9$ and an initial abundance of Li/H $= 10^{-9}$. The stars show the computed lithium abundances after 4, 9, and 15 billion yr. The arrow shows the effective temperature for which lithium is completely destroyed in the convection zone. The circles represent the theoretical values of the lithium abundance obtained by gravitational diffusion, in case of an initial abundance of 10^{-10} and no turbulence under the convection zone. The points represent Spite and Spite (1982) and Rebolo, Molaro, and Beckman (1987) observations.

rotation velocity for G stars of a given effective temperature must be less than 10%, for the dispersion in the lithium abundance not to exceed 20% as observed in the "plateau" (Spite and Spite 1982, 1986). Recent measurements of rotation periods in G stars from the observations of activity show a remarkably low dispersion for a given spectral type (Duncan *et al.* 1984; Rebolo and Beckman 1987; Radick *et al.* 1987). This leads to the idea of a self-regulating braking mechanism, which would take place early in the stellar life (see also Endal and Sofia 1981). As proposed by Gray (1982, 1983), this braking could be due to a dynamo-generated magnetic field. This effect would depend on the depth of the convection zone and would stop for a rotation velocity typical for each spectral type ("rotostat").

Let us now discuss the problem of age and metallicity. Rebolo, Molaro, and Beckman (1988) have shown that the Li/H abundance is constant for stars with [Fe/H] less than (-1.0), while for larger metallicities its upper value increases and the dispersion becomes larger and larger. These characteristics would show quite a different behavior if plotted against time. The current observations of metallicity versus age in old stars show that the iron abundance has reached a value within a factor of 10 of the present value in less than 1 billion yr (e.g., Twarog 1980). Then [Fe/H] increased somewhat linearly with time in the Galaxy. The constant Li abundance found by Rebolo, Molaro, and Beckman between [Fe/H] $= -3.5$ to -1.0 is due to a stretching of the scale. *If plotted against time all these points would appear clustered at the same abscissa.* The fact that the lithium value appears as unique for halo stars while a dispersion is observed for young stars is due to the interval in effective temperature chosen by the authors to be represented on their Figure 3 ($T_{eff} > 5500$ K). Due to opacity effects, the distance between the bottom of the convection zone and the nuclear burning layer is larger in low-metallicity stars than in high-metallicity stars of the same effective temperature. For T_{eff} larger than 5500 K low-metallicity stars are in the "plateau" domain so that their G side depletion domain is not included.

Now the question arises whether the opposite hypothesis (namely, that the primordial lithium abundance is that of halo stars and that this abundance has remained unchanged during 15 billion yr, except for the coolest ones) is possible. Computations of lithium gravitation settling have been done along the same evolutionary tracks, with an initial lithium abundance of Li/H $= 10^{-10}$ and with the assumption of no turbulence under the convection zone. Results are given in Figure 1*a*: lithium should have been depleted by a factor of 3 on the hot part of the plateau (see also Michaud, Fontaine, and Beaudet 1984). However, as shown by Vauclair *et al.* (1978), a turbulent diffusion coefficient larger than 10 times the gravitational one would prevent this depletion. Here the gravitational diffusion coefficient is of order 1 cm^2 s^{-1}. On the other hand, the turbulent diffusion coefficient needed to destroy lithium by a factor of 10 (as in the preceding computations) is of order 10^4 at the bottom of the convection zone. For a lithium destruction of less than 10%, D_T must be smaller than 10^3. So it is possible that the lithium abundance has not evolved with time *if the turbulent diffusion at the bottom of the convection zone has remained between 10 and 10^3 cm^2 s^{-1}*. With $\gamma = 1.7$ these values would correspond to rotation velocities between 0.3 and 3 km s^{-1}.

V. CONCLUSION

Hydrodynamical instabilities in stars are far from being well known, and the mixing effects induced by rotation are still a subject of discussion. However, the lithium abundances computed by using the phenomenological theory proposed by

Zahn (1983) give an interesting fit of the observed features for young clusters and for halo stars.

The Hyades lithium gap may be used in this framework to derive a parameter independent value of the mixing length ($\alpha = 1.9$, consistent with stellar evolution and solar oscillations). Observational tests of the two scenarii of lithium depletion by nuclear destruction or by gravitational settling may be found in the observations of the isotopic ratio $^6Li/^7Li$ (which would be normal in case of gravitational diffusion while no ^6Li would be left in case of nuclear destruction), in the observations of beryllium (depleted in case of gravitational settling, but less destroyed than lithium by nuclear reactions) and in the observation of metals (whose abundances may show some variation in case of settling). Recent observations of beryllium in Hyades and field stars by Budge, Boesgaard, and Varsik (1987) are in favor of the nuclear scenario, as no evidence of beryllium depletion is found in the lithium gap.

For halo stars, the only added abitrary parameter is their rotation velocity, which is of prime importance in the computation of the turbulent diffusion coefficient. At the present stage of the computations and observational data, it is not yet possible to decide what was the primordial lithium abundance. According to the value of D_T at the bottom of the convection zone, it may have been 10^{-9} (the present value being the result of nuclear destruction) or 10^{-10} (with a lithium abundance unchanged during 15 billion yr). Numerical computations of lithium destruction introduced in an evolutionary sequence with a rotation braking law will help in getting further. The necessity of reproducing correctly the depletion domain on the cool side of the plateau will bring constraints on D_T.

An observational test of the lithium primordial abundance could be found in measurements of the $^6Li/^9Be$ ratio. In case of no nuclear destruction we expect for this ratio the spallation value (≈ 4.5). For a ^7Li destruction by a factor of 10, ^6Li would be depleted by more than five orders of magnitude while ^9Be would be depleted by less than a factor of 2. For a ^7Li destruction smaller than 20% ^6Li could not be depleted by more than 70% ($^6Li/^9Be \geq 1.3$). Unfortunately, while Be has been detected in some metal deficient stars with $Be/H \approx 10^{-12}$ (Rebolo *et al.* 1988), only upper limits have yet been found for ^6Li (Maurice *et al.* 1984), leading to $^6Li/^9Be \leq 5$. More precise observations of these elements would be very interesting in that respect.

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