ELEMENT SEGREGATION IN LOW-METALLICITY STARS AND THE PRIMORDIAL LITHIUM ABUNDANCE

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ABSTRACT

Observational constraints on the primordial lithium abundance are important for the evaluation of the baryonic density of the universe. Its precise determination, however, suffers from uncertainties arising from the possible depletion of this element inside stars. Here we present and discuss new results for the lithium abundances in Population II stars obtained with the most recent stellar models including the best available physics. We show that it is possible to account for the general behavior of lithium observed in Population II stars without any free parameters. Macroscopic motions inside the stars are needed, but it is not necessary to specify their exact nature in order to interpret the observational data. This fact allows us to derive a parameter-free value for the primordial lithium abundance: log \( Li_p = 2.35 \pm 0.10 \) in the log \( H = 12 \) scale.

Subject headings: diffusion — early universe — stars: abundances — stars: interiors — stars: Population II

1. INTRODUCTION

\(^7\)Li has long been recognized as one of the four primordial isotopes, formed by nuclear reactions during the first minutes of the Universe. Together with deuterium, \(^3\)He, and \(^4\)He, its abundance is used as a constraint on the baryonic density of the universe. The fact that the observed abundances of these four isotopes are consistent, within the uncertainties, with the same baryonic density represents a success of the standard big bang theory. Recent improvements in observational techniques (using large ground-based telescopes, Hubble Space Telescope, and new image-processing techniques), together with a better understanding of the chemical evolution of galaxies, should help to reduce the uncertainties. At present, however, some ambiguities do remain, which must be solved in order to gain a better understanding of the primordial universe (see Sarkar 1996 for a recent review on the subject).

In the present paper we address the question of the primordial \(^7\)Li value. Its determination relies on the spectroscopic observations of Population II stars and on our knowledge of stellar physics. The lithium abundances observed in the oldest stars with effective temperatures larger than 5500 K lie around \( 2 \times 10^{-10} \) compared to hydrogen (the “Spite plateau”; Spite & Spite 1982). While cooler stars present a large dispersion with strong evidences of lithium depletion, the abundance scatter in the plateau is very small, except for a few stars with no lithium detection (Thorburn 1994; Ryan et al. 1996; Spite et al. 1996; Bonifacio & Molaro 1997, hereafter BM97). This observational fact is often taken as an evidence that the average lithium value in these stars indeed represents the primordial abundance.

Such a conclusion relies on a comparison of observations with stellar models in which standard element segregation induced by gravitational and thermal settling is simply ignored, while no other process among those that could prevent this segregation is introduced. In stars, element segregation may indeed be counteracted by macroscopic motions such as turbulent mixing or mass loss. These motions can, in turn, lead to the nuclear destruction of lithium (Vauclair 1988; Pinsonneault, Deliyannis, & Demarque 1992).

A realistic derivation of the primordial lithium must rely on a consistent study of the internal structure of Population II stars. In standard models, where nothing prevents element segregation, lithium is depleted at the surface of the stars through settling. Its abundance increases with depth, reaches a maximum value (\( Li_{\text{max}} \)), and then decreases abruptly as a result of nuclear destruction. In Vauclair & Charbonnel (1995, hereafter VC95), we discussed how this structure is modified in the presence of a stellar wind. We showed that mass loss could rub out the lithium depletion induced by segregation and lead to a surface lithium value close to \( Li_{\text{max}} \). The average mass-loss rate should be around 10 to 30 times that of the present solar wind. In this case, the lithium behavior observed in Population II stars can be correctly reproduced.

Here we give more precise computations of the internal structure of Population II stars, in which we include better physics, used in recent solar models tested by comparison with helioseismology (Richard et al. 1996, hereafter RVCD; Basu 1997). We show that the maximum lithium value inside standard stellar models (\( Li_{\text{max}} \)) is remarkably constant from star to star in the effective temperature range of the Spite plateau. Varying the effective temperature, the metallicity, or the mixing-length parameter never changes \( Li_{\text{max}} \) by more than 10%. We give physical reasons for this behavior.

Our conclusion is that the constancy and robustness of this value may present a clue for understanding the lithium plateau in Population II stars. We suggest that the lithium abundance that is actually observed in these stars is directly
related to $\text{Li}_{\text{max}}$. Within this framework, a comparison of $\text{Li}_{\text{max}}$ with the lithium observations (BM97) allows to derive the primordial lithium abundance.

2. SETTING THE STAGE

2.1. Observational Constraints

Lithium is observed in the atmospheres of stars with metallicities ranging from 2 down to $10^{-4}$ times solar. The upper envelope of the observed abundances follows a well-defined trend: in the log $H_{\odot}$ scale, the lithium upper values decrease from about 3.3 for solar metallicity down to about 2.3 for metallicities 10 times smaller, and remain constant for still smaller metallicities (Rebolo et al. 1988; Spite 1991).

When plotted as a function of the effective temperatures, the average lithium abundance for low-metallicity stars does not vary significantly for effective temperatures larger than 5500 K (the plateau). For smaller effective temperatures, lithium is depleted through nuclear destruction. According to various observers (e.g., Thorburn 1994; Molaro, Primas, & Bonifacio 1995; Ryan et al. 1996), the plateau either is horizontal or has a very small positive slope. In any case, the small dispersion of the abundances (Deliyannis, Pinsonneault, & Duncan 1993; Molaro et al. 1995; Spite et al. 1996; BM97) is a strong constraint on the type of processes that may have occurred in these stars since their formation. Furthermore, observations of the more fragile $^6\text{Li}$ isotope in a few halo stars (Smith, Lambert, & Nissen 1992; Hobbs & Thorburn 1994), if confirmed, offer evidence that lithium has suffered no, or only very small, nuclear destruction in these stars.

2.2. The Physics

In the radiative regions of stars, the various chemical species move with respect to the bulk of stellar gas because of the selective diffusion induced by the pressure, temperature, concentration gradients, the electric field, and the radiative acceleration. A self-gravitating gas mixture cannot be in complete equilibrium and remain chemically homogeneous. During the pre-main-sequence phase, stars are convectively mixed, which forces homogeneity. When they become radiative, the elements begin to migrate from the initial stage toward a never-reached equilibrium stage. This process creates an element segregation in stable stars.

As a result, the abundances observed at the surface of the stars may be different from the original ones. For main-sequence Population I stars, evidence of this effect was first found in the so-called peculiar A stars, where it can lead to variations of up to several orders of magnitude (Vauclair & Vauclair 1982). More recently, its signature has been found in the Sun from helioseismology (see RVCD and references therein). Theoretical computations predicted abundance variations on the order of 10% to 20% in the Sun as a result of this process. The fact that helioseismology confirmed it represents a great success for the theory of element segregation in stars.

Macrosopic motions, such as shear-induced turbulence, rotational mixing, or mass loss, may slow down the migration process and reduce the abundance variations. There is evidence both from helioseismology and from the solar lithium abundance that some mild motions must occur below the solar convection zone (RVCD; Basu 1997). While these motions reduce the slope of the concentration gradients, they do not completely stop the segregation.

When comparing stellar models with the observations, all these physical effects should be taken into account. However, while pure segregation models are parameter-free (except for the mixing length), macroscopic motions depend on the stellar history and may be different for various stars of the same mass and effective temperature. For this reason, we chose here to study Population II star models including element segregation only. We show that such precise standard models give enough information to allow us to derive a consistent value of the primordial lithium abundance.

3. COMPUTATIONS AND RESULTS: THE LITHIUM ABUNDANCES

The present stellar models were calculated with the Toulouse-Genève stellar evolutionary code (Charbonnel, Vauclair, & Zahn 1992), in which improved microphysics has been implemented since VC95. Element segregation is treated as in RVCD, using the diffusion coefficients obtained with the Paquette et al. (1986) approximation. We use the radiative opacities of Iglesias & Rogers (1996), completed with the atomic and molecular opacities of Alexander & Ferguson (1994). The equation of state is described with a set of MHD tables (Mihalas, Hummer, & Däppen 1988) specifically calculated for the mass and metallicity domain we study here (Charbonnel et al. 1998).

Stellar models of 0.80, 0.75, and 0.70 $M_\odot$ have been computed from the pre-main-sequence up to the turnoff, with a metallicity $[\text{Fe/H}] = -2$ and a mixing-length parameter $\alpha = 1.6$ (Fig. 1). The effect on the Li profile of varying $[\text{Fe/H}]$ and $\alpha$ has been tested for the 0.80 $M_\odot$ models (Fig. 2).

The lithium profiles inside the stars are given in Figure 1 for three ages, 10, 12, and 14 Gyr. The corresponding effective temperatures are given in Table 1, together with the luminosities, temperatures, and densities at the base of the convection zone, and the surface and maximum lithium abundances. For the models of 0.80, 0.75, and 0.70 $M_\odot$, lithium is depleted in the convection zone as a result of segregation. The abundance increases inwardly, up to its maximum value, $\text{Li}_{\text{max}}$. Deeper in the star, lithium is destroyed by nuclear reactions. In the coolest 0.65 $M_\odot$ model, the two effects merge and no maximum appears. In any case, none of these stars has kept its original abundance in any part of the internal structure.

The maximum lithium value inside the stars ($\text{Li}_{\text{max}}$) is remarkably constant from star to star. Figure 2 shows, for the case of a 0.8 $M_\odot$ star, the lithium profiles obtained at 12 Gyr for three different values of the mixing-length parameter and the metallicity (see also Table 2). For a given value of $[\text{Fe/H}]$, the star has a deeper convection zone, and consequently a higher surface lithium abundance when $\alpha$ increases. On the other hand, decreasing $[\text{Fe/H}]$ for a given value of $\alpha$ leads to a cooler effective temperature, deeper convection zone, and less important element segregation at the surface of the star. Yet in spite of the changes in the surface lithium values and in the effective temperatures of the model, the $\text{Li}_{\text{max}}$ value never varies by more than 10%.

This remarkable result can be understood in the following way. In first approximation, the lithium maximum appears at the point where the segregation and nuclear destruction timescales are of the same order. The segregation timescale is defined as $\tau_s = H_e^2 / D$, where $H_e$ is the pressure scale height and $D$ is the diffusion coefficient. The nuclear timescale is defined as $\tau_N = (\lambda_{\text{Li},H} N_H)^{-1}$, where
Fig. 1.—Lithium profiles inside standard models for Population II stars, including segregation at three ages (10, 12, and 14 Gyr). The ordinates are normalized to 1, and the abscissae are given in terms of the mass fraction of the considered layer. Lithium is depleted in the convection zones by downward diffusion. Its abundance increases with depth up to \( \text{Li}_{\text{max}} \) until it reaches the nuclear destruction zone. While the surface depletion increases with increasing mass, the maximum values inside the stars are nearly constant.

\( \lambda_{\text{Li,H}} \) represents the nuclear reaction rate per particle and \( N_{\text{H}} \) is the number of protons per unit volume. Above the lithium maximum, \( \tau_{\text{S}} < \tau_{\text{N}} \) and lithium is depleted through element settling. Below the maximum, \( \tau_{\text{S}} > \tau_{\text{N}} \) and lithium is destroyed through nuclear reaction. The local values of \( \tau_{\text{N}} \) and \( \tau_{\text{S}} \) only depend on the local temperature and density. For this reason, the lithium maximum always appears at about the same position inside the star, with about the same

\begin{table}[h]
\centering
\begin{tabular}{cccccccc}
\hline
\( M_\text{M}/M_\odot \) & \( t \) & \( T_{\text{eff}} \) & \( \log L/L_\odot \) & \( T_{\text{BPH}} \) & \( 10^{13} \text{ K} \) & \( \rho_{\text{BPH}} \) & \( \text{Li}/\text{Li}_0 \) & \( \text{Li}/\text{max}/\text{Li}_0 \) \\
\hline
0.65 & 10 & 5363 & -0.615 & 0.204 & 1.289 & 0.741 & ... & \\
     & 12 & 5392 & -0.589 & 0.197 & 1.110 & 0.700 & ... & \\
     & 14 & 5424 & -0.560 & 0.195 & 0.987 & 0.662 & ... & \\
0.70 & 10 & 5675 & -0.416 & 0.173 & 0.554 & 0.710 & 0.759 & \\
     & 12 & 5723 & -0.374 & 0.151 & 0.339 & 0.652 & 0.715 & \\
     & 14 & 5773 & -0.326 & 0.142 & 0.258 & 0.595 & 0.676 & \\
0.75 & 10 & 5978 & -0.205 & 0.117 & 0.108 & 0.547 & 0.778 & \\
     & 12 & 6044 & -0.137 & 0.105 & 0.066 & 0.465 & 0.738 & \\
     & 14 & 6087 & -0.050 & 0.087 & 0.032 & 0.384 & 0.680 & \\
0.80 & 10 & 6257 & 0.034 & 0.065 & 0.010 & 0.288 & 0.769 & \\
     & 12 & 6322 & 0.166 & 0.048 & 0.003 & 0.172 & 0.738 & \\
     & 14 & 6230 & 0.339 & 0.044 & 0.002 & 0.125 & 0.714 & \\
\hline
\end{tabular}
\caption{Parameters of the Pure Diffusion Models ([Fe/H] = -2, \( x = 1.6 \))}
\end{table}
value. It does not depend on the depth of the convection zone. This explains the constancy and robustness of the lithium maximum.

4. DISCUSSION: THE PRIMORDIAL LITHIUM ABUNDANCE

Stellar models that include element segregation predict a surface lithium depletion that depends on the effective temperature, the age, and the metallicity of the stars. This prediction contradicts the observations of the lithium plateau in Population II stars. However, as discussed above, the lithium profiles in the standard models present a maximum, \( \text{Li}_{\text{max}} \), that remains remarkably constant (within 10%) and stable from star to star. This result leads to the idea that the observed lithium abundances may be related to this maximum value.

When we previously (see VC95) computed the effect of mass loss on the lithium abundances in Population II stars, we found the following characteristic behavior. For very small mass-loss rates, the surface lithium abundance is depleted through element settling. Increasing the mass-loss

| [Fe/H]  | \( \alpha \) | \( T_{\text{eff}} \) | \( \log L/L_\odot \) | \( T_{\text{eff}} \) \( (10^7 \text{ K}) \) | \( \rho_{\text{boz}} \) | \( \text{Li}/\text{Li}_0 \) | \( \text{Li}_{\text{max}}/\text{Li}_0 \) |
|--------|-----------|------------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 1       | 1.6       | 6000             | -0.011          | 0.136           | 0.078           | 0.530           | 0.691           |
| 1.5     | 1.6       | 6157             | 0.076           | 0.091           | 0.002           | 0.392           | 0.722           |
| 2       | 1.6       | 6322             | 0.166           | 0.048           | 0.003           | 0.172           | 0.738           |
| 2       | 1.4       | 6243             | 0.164           | 0.044           | 0.002           | 0.119           | 0.739           |
| 2       | 1.8       | 6389             | 0.166           | 0.060           | 0.006           | 0.230           | 0.735           |

| [Fe/H]  | \( \alpha \) | \( T_{\text{eff}} \) | \( \log L/L_\odot \) | \( T_{\text{eff}} \) \( (10^7 \text{ K}) \) | \( \rho_{\text{boz}} \) | \( \text{Li}/\text{Li}_0 \) | \( \text{Li}_{\text{max}}/\text{Li}_0 \) |
|--------|-----------|------------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 2       | 1.6       | 6000             | -0.011          | 0.136           | 0.078           | 0.530           | 0.691           |
| 2       | 1.5       | 6157             | 0.076           | 0.091           | 0.002           | 0.392           | 0.722           |
| 2       | 2         | 6322             | 0.166           | 0.048           | 0.003           | 0.172           | 0.738           |
| 2       | 2         | 6243             | 0.164           | 0.044           | 0.002           | 0.119           | 0.739           |
| 2       | 2         | 6389             | 0.166           | 0.060           | 0.006           | 0.230           | 0.735           |
rate contradicts this settling, and the surface lithium abun-
dance at first increases. It goes through a maximum for a
rate of about 10 times the solar wind, then decreases for
larger rates, as a result of nuclear destruction. The most
remarkable result is that the maximum surface lithium
abundance obtained lies very close to \( \text{Li}_{\text{max}} \). This behavior
has a simple physical reason, related to the macroscopic
timescale (here \( t_{\text{ML}} = H_p/|V_{\text{ML}}| \), where \( V_{\text{ML}} \) is the mass-loss
velocity averaged over \( H_p \)); the maximum surface lithium
value is obtained when the macroscopic timescale at the
\( \text{Li}_{\text{max}} \) depth is on the order of the two other timescales, \( \tau_S \) and \( \tau_N \).

The same behavior is expected for all kinds of macro-
scopic motions; the surface lithium value should always
have a maximum on the order of \( \text{Li}_{\text{max}} \). Since the observ-
ations of lithium in the plateau reveal a very small disper-
sion around a stable value, this value must indeed lie close
to \( \text{Li}_{\text{max}} \). The shape of the lithium profiles as a function of
mass (Figs. 1 and 2) shows indeed that small macroscopic
motions acting just below the convective envelope will on
the average give values close to \( \text{Li}_{\text{max}} \).

In Figure 3, the observations compiled by BM97 are
shown for the plateau stars \( T_{\text{eff}} > 5500 \) K. In the same
graph we have plotted the \( \text{Li}_{\text{max}} \) values obtained for 12 Gyr,
\( \alpha = 1.6 \), and \([\text{Fe/H}] = -2 \). The initial value is taken as
\( A(\text{Li}) = 2.35 \) (where \( A(\text{Li}) \) represents the logarithm of the
lithium abundance in the log \( H = 12 \) scale). A comparison
of the \( \text{Li}_{\text{max}} \) curve with the observed lithium plateau allows
to determine the primordial lithium value.

Table 3 gives the values of \( A(\text{Li}) \) obtained without any
correction from the analytical fits of BM97 (see their Table
2). These values are precisely computed for the effective
temperatures given by our models for three masses and
three ages. As a further step, they are then increased by the
logarithm of the corresponding \( \text{Li}_{\text{max}}/\text{Li}_0 \) value (given in
Table 1). The new values are labeled \( A(\text{Li}_0) \) in Table 4.

If the observed lithium were exactly all the \( \text{Li}_{\text{max}} \), all the \( A(\text{Li}_0) \)
values should be identical. In reality, we expect the 0.70 \( M_\odot \)
star to suffer extra nuclear depletion, as the bottom of the
convection zone is very close to the nuclear destruction
layer. In addition, the age of these Population II stars is
supposedly larger than 10 Gyr. For these reasons, we chose
to compare the four values given by the 0.75 and 0.80 \( M_\odot \)
models at 12 and 14 Gyr.

Considering an uncertainty of about 10% for the surface
lithium abundance compared to \( \text{Li}_{\text{max}} \), and taking into
account the systematic error in the observations quoted by
BM97, we give for the primordial lithium abundance\( A(\text{Li}_0) = 2.35 \pm 0.10 \). When compared to big bang nucleo-
synthesis computations (e.g., Copi, Schramm, & Turner
1995), this result leads to a baryonic number between 1.2
and \( 5 \times 10^{-10} \). For \( H = 50 \), this value corresponds to
\( 0.018 < \Omega_b < 0.075 \).

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