Pre-main-sequence Lithium Depletion

R. D. Jeffries

Astrophysics Group, School of Chemistry and Physics, Keele University,
Staffordshire, ST5 5BG, UK

Abstract. In this review I briefly discuss the theory of pre-main-sequence (PMS) Li depletion in low-mass ($0.075 < M < 1.2\,M_{\odot}$) stars and highlight those uncertain parameters which lead to substantial differences in model predictions. I then summarise observations of PMS stars in very young open clusters, clusters that have just reached the ZAMS and briefly highlight recent developments in the observation of Li in very low-mass PMS stars.

1 Introduction

During pre-main-sequence (PMS) evolution, Li is burned at relatively low temperatures (2.5–3.0$\times 10^6$ K) and, in low-mass stars ($< 1.2\,M_{\odot}$), convective mixing can rapidly bring Li-depleted material to the photosphere. For this reason, photospheric Li abundance measurements provide one of the few methods of probing stellar interiors and are a sensitive test of PMS evolutionary models. Understanding PMS Li depletion also offers a route to estimating the ages of young stars and of course is a pre-requisite for quantifying any subsequent main-sequence Li depletion (see Randich 2005, these proceedings).

2 Models of PMS Li depletion

2.1 Very low-mass stars

PMS stars with $M < 0.35\,M_{\odot}$ have a simple structure – they are fully convective balls of gas all the way to the ZAMS. As the star contracts along its Hayashi track the core heats up, but the temperature gradient stays very close to adiabatic except in the surface layers. Li begins to burn in p,α reactions when the core temperature, T_c reaches $\simeq 3\times 10^6$ K and, because the reaction is so temperature sensitive ($\propto T_c^{16-19}$ at typical PMS densities) and convective mixing so very rapid, all the Li is burned in a small fraction of the Kelvin-Helmholtz timescale (see Fig. 1).

The age at which Li depletion occurs increases with decreasing mass (and Li-burning temperatures are never reached for $M < 0.06\,M_{\odot}$). As luminosity, $L \propto M^2$ for PMS stars, the luminosity at which complete Li depletion takes place is therefore a sensitive function of age between about 10 and 200 Myr [6]. This relationship depends little on ingredients of the PMS models such as the treatments of convection and interior radiative opacities because the stars are fully convective. The extreme temperature dependence means nuclear physics uncertainties play little role, and there is only a small dependence on the kind of atmosphere assumed as a boundary condition, or the adopted equation of state. Indeed, whilst the chosen form of the atmosphere (grey or non-grey) changes the $T_{\rm eff}$ at which Li is burned, it hardly affects the luminosity. Ages determined from the luminosity at the "Li depletion boundary" (LDB) vary by only 10 per cent between different models and even analytical treatments [7].

2.2 Higher mass stars

Li depletion is *much* more complex in higher mass stars. They have lower central densities and as T_c rises during PMS contraction, the opacity falls sufficiently for the temperature gradient to become sub-adiabatic. A radiative core forms which pushes outward to include a rapidly increasing fraction of the stellar mass. For $M < 1\,M_{\odot}$ there is small window of opportunity to burn some Li before the radiative core develops (at $\simeq 2$ Myr for $1\,M_{\odot}$). For $M < 0.6\,M_{\odot}$ all the Li is burned in this way (see Fig. 1). For higher mass stars the radiative core develops before Li burning is complete and the temperature at the base of the convective envelope, T_{bcz}, decreases. In the absence of convective mixing, Li-depleted material cannot get to the photosphere, so once T_{bcz} drops below the Li-burning threshold, photospheric Li-depletion ceases. Photospheric Li depletion begins at about 2 Myr in a $1\,M_{\odot}$ star and should terminate at about 15 Myr. This window shifts towards older ages in lower mass stars. However, the overall amount of

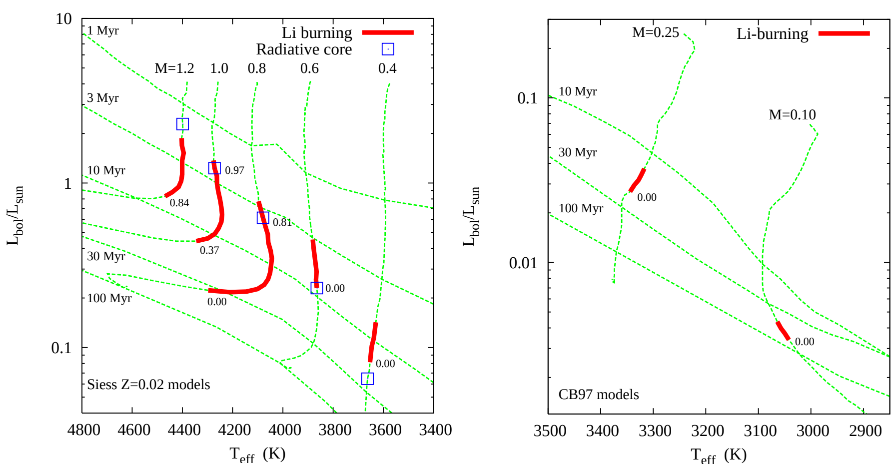

Fig. 1. Evolutionary tracks (labelled in $M_{\odot}$) and isochrones (in Myr) for low-mass stars taken from two models [8,31]. The epochs of photospheric Li depletion (and hence Li-burning in the core of a fully convective star or at the convection zone base otherwise) and the development of a radiative core are indicated. The numbers to the right of the tracks indicate the fraction of photospheric Li remaining at the point where the radiative core develops and at the end of Li burning.

Li-depletion is extremely sensitive to mass (and other model parameters – see below). There should be relatively little depletion in solar mass stars compared with lower-mass stars (see Fig. 2).

The exact amount of Li depletion expected is exquisitely dependent on a number of model details. The reason is that whilst Li depletion is occurring, even with a radiative core, the overall temperature gradient in the stars is still very close to adiabatic (see Fig. 2 in [26]). It takes only a small perturbation to this gradient to change the time at which the radiative core develops, the position of the convection zone base and hence T_{bcz}. As a result large changes in Li depletion predictions can result from relatively minor perturbations in model parameters. Similarly, because photospheric Li-depletion arises from rapid Li burning in a very thin region above the convection zone base, a model grid with temporal and spatial resolution merely sufficient to model the structure of the star may be an order of magnitude to coarse to accurately predict Li depletion [26].

Convective efficiency is a crucial model parameter. If convection is efficient then T_{bcz} is higher (at a given mass) and hence stays above the Li-burning threshold for longer, resulting in much more photospheric Li depletion [10]. A typical approach to modelling convection is to use mixing length theory with the mixing length set by requiring a model to reproduce the solar structure (revealed by helioseismology) at the age of the Sun. It is not clear that this approach is valid. The mixing length may vary with time, depending on evolutionary stage, surface gravity or effective temperature. Adopting alternate convection theories, such as the full spectrum of turbulence models which have more efficient convection in the deep layers, results in orders of magnitude more PMS Li depletion at the same mass (see [9] and Fig. 2).

Opacity effects are also important. This can refer to differences in the treatment of interior opacities or to the effects of uncertain stellar compositions on the opacities. An increase in opacity makes temperature gradients larger, keeps the star convective for longer, raises T_{bcz} once the radiative core develops and so leads to enhanced Li depletion. Opacity is increased by an increase in overall metallicity or a decrease in the Helium abundance. Changes of only 0.1 dex in metallicity can lead to an order of magnitude change in Li depletion (e.g. see Fig. 2 of [37]).

Other factors, such as the adopted equation of state or chosen treatment of the atmospheric boundary conditions have some effect on Li-depletion predictions, but are much less significant.

3 Observations

There have been more measurements of Li in stars than any other chemical element. The vast majority have been derived from high resolution spectra of the strong Li I 6708Å resonance doublet. Only a fraction of the observational material can be reviewed here. The reader is referred to some other reviews for a more complete picture [16,25].

3.1 The initial Li abundance

Theory doesn't tell us what initial Li a star has, only what depletion it suffers. An accurate estimate of the initial Li abundance is therefore a pre-requisite before observations and models can be compared. The Sun is a unique exception, where we know the present abundance, $A(\mathrm{Li}) = 1.1 \pm 0.1$ (where $A(\mathrm{Li})= \log[N(\mathrm{Li})/N(\mathrm{H})] + 12$) and the initial abundance of $A(\mathrm{Li})= 3.34$ is obtained from meteorites. For recently born stars, the initial Li abundance is estimated from photospheric measurements in young T-Tauri stars, or from the hotter F stars of slightly older clusters, where *theory suggests* that no Li depletion can yet have taken place. Results vary from $3.0 < A(\mathrm{Li}) < 3.4$, somewhat dependent on assumed atmospheres, NLTE corrections and T_{eff} scales [23,33]. It is of course quite possible that the initial Li, like Fe abundances in the solar neighbourhood, shows some cosmic scatter. Present observations certainly cannot rule this out, leading to about a ± 0.2 dex systematic uncertainty when comparing observations with Li depletion predictions.

3.2 ZAMS clusters

Clusters that are old enough for stars to have reached the ZAMS empirically show us the results of PMS Li depletion. The canonical dataset is that for the Pleiades (Fig. 2, [32]). With an age of 120 Myr, all stars with $M > 0.5\,M_{\odot}$ have reached the ZAMS. Assuming an initial $A(\mathrm{Li})$ of 3.2, then there seems to have been little PMS Li depletion among F-stars, ≤ 0.2 dex in G stars and then a strongly increasing level of Li depletion with decreasing mass. There is also evidence for a *scatter* in Li abundances that develops for $T_{\mathrm{eff}} < 5300$ K and probably continues to $T_{\mathrm{eff}} \simeq 4000$ K, where Li becomes undetectable [13].

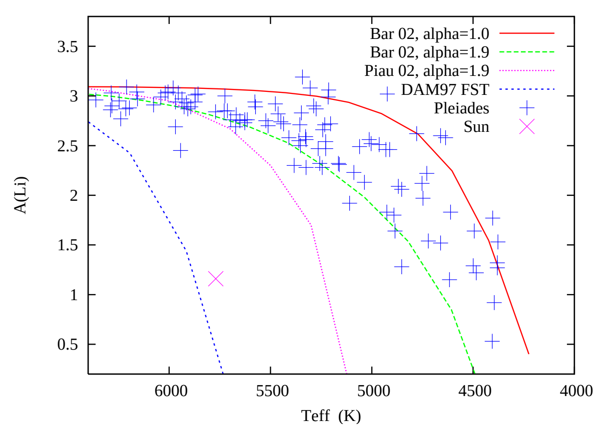

Fig. 2. Measured Li abundances for the Sun and the Pleiades [32] compared with a variety of models [5,9,26]. The majority of the differences are due to the convective efficiency used by the models

Similar results are now available for a number of clusters with ages 50-200 Myr (e.g. [2,14,18,22,29]).

The difference in the Li abundances in the G-stars of the Pleiades and the Sun, combined with the probable similarities in their overall chemical composition tell us that PMS Li depletion cannot be the whole story. Another mechanism, additional to convective mixing, must be responsible for Li depletion whilst solar-type stars are on the main-sequence. Recent PMS models that have their convective treatments tuned to match the structure of the Sun reproduce the mass dependence of Li depletion, but deplete too much Li compared with the Pleiades, and can even explain the solar A(Li) in the case of full spectrum turbulence models [9]. The over-depletion with respect to the Pleiades gets worse at lower masses. Better fits to the Pleiades data are achieved with PMS models that feature relatively inefficient convection with smaller mixing lengths.

3.3 An Li abundance scatter?

The apparent scatter among Li abundances in K-type and lower mass stars of the Pleiades and other young clusters is intriguing. It is either telling us something about the physics of mixing and Li-burning inside PMS stars or it is telling us something about the atmospheres of these stars such that we cannot properly estimate their Li abundances. Clues include: the $T_{\rm eff}$ at which the scatter develops, which coincides with those stars that did most of their Li depletion in a fully convective state; and the strong correlation between apparent Li abundance and rotation rate for the K-type stars, such that fast rotators appear to have high A(Li), whereas slower rotators can have either higher or lower A(Li) than average. This correlation may be weaker or absent in the lower mass stars [13,20]. Efforts to understand the apparent Li abundance scatter divide into those that propose a physical mechanism for the Li abundance scatter (i.e. that assume the scatter is real) and those that assume the scatter is not real and instead suggest that the strength of the Li I 6708Å feature does not reliably yield true Li abundances.

Rotationally Driven Mixing: Non-convective mixing can take place in radiative regions, driven by angular momentum loss (AML), and causes additional Li depletion. Fast rotating ZAMS stars have suffered little AML and so would have the highest Li abundances. Slow rotators may have undergone little AML (if they started out with less angular momentum), or lots (if they remained magnetically coupled to a circumstellar disc for an extended period) and so could have a range of Li abundances. Problems with this persuasive picture are that *additional* PMS Li depletion is predicted, widening the disagreement between solar-tuned models and ZAMS clusters and that very little scatter is actually produced in theoretical models even with a realistic range of initial angular momenta [27].

Structural Effects of Rotation: Rapid rotation in a fully convective star decreases the core temperature, but actually increases T_{bcz} once a radiative core has developed. The net effect on Li depletion seems to be rather small and cannot explain the dispersion of Li abundances seen among the slow rotating ZAMS stars [24].

Composition Variations: Li depletion is sensitive to interior opacities, which themselves depend on the stellar composition. Small star-to-star variations might cause an Li abundance scatter, which would grow towards lower masses. However, current limits on metallicity variations in the Pleiades (and other clusters) seem too small for this to be the dominant explanation of any scatter [38]. In addition, the correlation of Li-depletion with rotation is unexplained.

Accretion: Li abundances can be altered in two ways by accretion. During PMS Li depletion the additional mass will lead to increased Li depletion at a given $T_{\rm eff}$ when the star reaches the ZAMS [26]. If accretion occurs after Li-burning has ceased then the convective zone is enriched with Li. Too much accretion is required to be compatible with observations of disks around PMS stars unless the accreted material is H/He-deficient. But then accretion of sufficient H/He depleted material to explain the Li abundance scatter would also lead to (for instance) Fe abundance anomalies of order 0.2-0.3 dex – much higher than allowed by current observational constraints [38].

Magnetic Fields: Low-mass PMS stars are known to be magnetically active. B-fields in the convection zone can provide additional support, raise the adiabatic temperature gradient, hasten the onset of a radiative core and hence decrease Li depletion. Magnetic activity *may* be correlated with rotation in PMS stars at the critical ages of 2-20 Myr but this remains to be established. Basic models including B-fields in the convection zone have now been developed [11,37], suggesting this mechanism could inhibit Li depletion by orders of magnitude!

Atmospheric effects: The atmospheres of PMS stars are doubtless more complicated than the 1-d, homogeneous models usually used to estimate their Li abundances. Starspots and plages complicate the interpretation and could lead to a scatter in the strength of Li I spectral features at a given abundance [3,12]. The 6708Å line is also formed high in the atmosphere and is susceptible to NLTE effects and possible overionisation from an overlying chromosphere [36]. It is telling that the analogous K I resonance line mimics the behaviour of the Li I line, despite there being no possibility of significant K abundance variations [21,28,32]. Varying activity levels could at least be responsible for some of the *apparent* Li abundance scatter. Arguing against this are that very little time variability is seen in the strength of the Li I 6708Å line, despite magnetic/chromospheric activity being quite variable in cool ZAMS stars [15]. In addition, measurements of the weak Li I 6104Å feature, which is probably less susceptible to details of the model atmosphere, have implied a scatter in Li abundances at least as large as that derived from the resonance line [12].

3.4 The metallicity dependence of PMS Li depletion

PMS Li depletion is supposed to be very sensitive to overall metallicity. Groups of ZAMS clusters with similar ages but differing metallicities can be used to test this prediction. The results are surprising. Metallicity variations of 0.1-0.2 dex appear to make no difference to PMS Li depletion [2,17]. An explanation might be that whilst [Fe/H] (what is usually measured as a proxy for metallicity) varies, other elements which are important for interior opacities, especially O, Si, Mg, might vary in the opposite direction to compensate. Quite small differences of 0.1–0.2 dex in [O/Fe] would be required [26], but these differences are still uncomfortably high compared with the spread in [O/Fe] measured for field dwarfs [30]. In addition, it would require a cosmic conspiracy of some proportions to ensure that the half dozen ZAMS clusters investigated so far, all had similar interior opacities. Careful and consistent multi-element abundance determinations are required for these clusters to definitively address the issue.

An interesting aside to this discussion concerns the composition mix assumed in the theoretical models. Recent measurements have suggested that the solar O abundance might be 0.2 dex lower than previously believed [1]. A change of this size in the model compositions could lead to significantly less PMS Li depletion among solar-type stars, reducing the discrepancy between the Li depletion predicted by solar-tuned convective models and the ZAMS cluster data.

3.5 Very low-mass stars

Whilst problems remain in the modelling and interpretation of $0.6 < M < 1.2\,M_{\odot}$ stars, the situation is more favourable in lower mass objects that are always fully convective. In agreement with theory, observations of four young clusters (Pleiades, Alpha Per, IC 2391 and NGC 2547) have now found the sharply defined LDB, where the original undepleted Li abundance is seen in the coolest objects and which marks the age-dependent point at which cores are still too cool to burn Li [4,19,34,35]. Because the LDB is a model-insensitive chronometer, these LDB ages can be used to test the physics which goes into isochronal ages determined from higher-mass stars. The conclusions are that LDB ages are 50 per cent older than nuclear turn-off ages without convective core overshoot, but in reasonable agreement with isochronal ages defined by the descent of low-mass stars to the ZAMS.

4 Summary

The study of PMS Li depletion divides into two regimes. For very low mass stars $0.075 < M < 0.35\,M_{\odot}$, the few extant observations are fully in agreement with available theoretical predictions. Furthermore there is little variation in the predictions of different models and little dependence on uncertain physical processes or parameters. However, models of PMS Li depletion for higher mass stars ($0.35 < M < 1.2\,M_{\odot}$ in which a radiative core develops, make wildly varying (by orders of magnitude) quantitative predictions for Li depletion. None of these models satisfactorily explain all aspects of the data, particularly the presence of an apparent scatter in Li abundances at the end of the PMS phase and the lack of any sensitivity of Li-depletion to stellar metallicity. The model dependence does at least give hope that some aspects of PMS evolution may ultimately be tightly constrained by Li abundance measurements. As an example the current data-model comparisons suggest that PMS convective efficiency is lower than suggested by tuning models to produce the Sun, particularly among cooler stars.

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