The Lithium Depletion Boundary as a Clock and Thermometer

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Abstract. We take a critical look at the lithium depletion boundary (LDB) technique that has recently been used to derive the ages of open clusters. We identify the sources of experimental and systematic error and show that the probable errors are larger by approximately a factor two than presently claimed in the literature. We then use the Pleiades LDB age and photometry in combination with evolutionary models to define empirical colour-$T_{\text{eff}}$ relations that can be applied to younger clusters. We find that these relationships do not produce model isochrones that match the younger cluster data. We propose that this is due either to systematic problems in the evolutionary models or an age (gravity) sensitivity in the colour-$T_{\text{eff}}$ relation which is not present in published atmospheric models.

1. Introduction

Lithium is an ephemeral element in the atmospheres of low mass pre main sequence (PMS) stars. It burns swiftly in $p, \alpha$ reactions once the core temperature, $T_c$, approaches $3 \times 10^6$ K, with a reaction rate approximately proportional to $T_c^{20}$ (Ushomirsky et al. 1998). Because PMS stars less massive than $0.35 M_\odot$ are always fully convective, and because timescales for convective mixing are much shorter than evolutionary timescales, the surface abundance of Li is also rapidly depleted when the core reaches this Li-burning temperature. Thus, for stars of a given mass, total Li depletion occurs over a relatively narrow range of effective temperatures and luminosities. The time taken for $T_c$ to reach the Li ignition point is sensitively dependent on mass and to a lesser extent on adopted equations of state and atmospheric boundary conditions. As a result, if one observes a group of co-eval stars, the mass, and hence luminosity and temperature, at which Li is observed to be depleted from its initial value, offers a potentially precise determination of stellar age.

Analytical (Bildsten et al. 1997; Ushomirsky et al. 1998) and numerical (D’Antona & Mazzitelli 1997 (DAM97); Chabrier & Baraffe 1997 (CB97); Burrows et al. 1997 (B97)) treatments of this process have appeared. These models confirm that the “lithium depletion boundary” (LDB) is an independent age diagnostic for clusters of stars. The technique is likely to be more accurate than the better known method of fitting the upper main sequence turn-off. This is partly because the uncertain physics in high mass stellar evolution models (convective core overshoot, semi-convection, mass loss, rotational mixing) has greater effects on the observable parameters than the debatable physics in
low mass models (equation of state, convection treatment and atmospheres), and partly because there are usually only a few high mass stars (with uncertain duplicity) with which to fit isochrones, whereas there are many low mass stars around the LDB. The LDB method is also potentially superior to fitting isochrones to PMS stars as they descend towards the ZAMS. The main hazard with this technique is the extremely uncertain conversions between colours and effective temperatures for $T_{\text{eff}} < 4500$ K.

In this paper we provide an independent analysis of the likely experimental and systematic errors in the LDB technique. We also show that the LDB ages can be used in combination with observational data to yield the effective temperatures of low-mass stars and use this as an additional consistency check for the current generation of evolutionary models.

2. The LDB Error Budget

Our baseline assumption is that the age of a cluster is found by locating the LDB in a colour-magnitude diagram (see Fig.1). We convert the apparent magnitude of the LDB into an absolute magnitude and then into $L_{\text{bol}}$ using an empirical bolometric correction at the colour of the LDB. We then use models for Li depletion in cool stars to translate $L_{\text{bol}}$ at the LDB into an age. Note, that we do not use the $T_{\text{eff}}$-colour relationships or bolometric corrections provided by some evolutionary models as these would instil unquantifiable errors in the procedure and in several cases, particularly in the optical, model colours have already been shown to be systematically in error (Baraffe et al. 1998).

Experimental errors in the LDB age can be ascribed to uncertain placement of the LDB in a colour-magnitude diagram due to sparse sampling in the Li measurements, uncertain photometric calibrations and uncertainties in the distance and reddening of the cluster in question. Systematic errors arise from the chosen empirical bolometric correction-colour relation, whether one assumes the LDB defines the point at which say 90% or 99% of Li has been depleted and the choice of evolutionary model which defines the $L_{\text{bol}}$-age relation at the LDB. The first two of these systematics will alter the ages of all clusters in qualitatively the same way, whereas the latter systematic may cause individual clusters to be older or younger, as the $L_{\text{bol}}$-age relations cross for differing evolution models. There may of course be additional systematics due to common assumptions made by all the current generation of models.

We have investigated these uncertainties, focussing on clusters with LDB ages defined in the $I$ vs $R - I$ diagram, and using the theoretical models of B97, CB97 and DAM97. We find that for clusters with data quality similar to that available for the Pleiades (Fig.1), the experimental error in age rises from $\pm 9\%$ at $\sim 25$ Myr, to $\pm 16\%$ at 200 Myr. These errors are dominated by uncertain placement of the LDB (typically $\pm 0.15$ mag in $I$ and $\pm 0.05$ in colour) along with distance modulus errors and uncertainties in the $I$ photometric calibration (both around $\pm 0.1$ mag). Obtaining Li data for more points around the LDB, distinguishing binaries from single stars and tightening up the photometric calibration could reduce these errors considerably. The increase in error with age is due to the propinquity of the Li depletion isochrones at older ages. The systematic errors are more constant, ranging between 7% and 11% over a similar
Figure 1. An $I$ versus $R-I$ plot for the Pleiades. Triangles are stars with detailed spectroscopy of the Li$\text{I}$ 6708Å line. Filled triangles have a Li$\text{I}$ 6708Å EW above 0.3Å, while open triangles show no Li. Spots are proper motion members with photoelectric photometry, crosses are proper motion members with mainly photographic photometry. Dashed lines are isochrones of 99% Li depletion using the models of CB97, labelled in Myr. The diamond marks the position we have chosen for the LDB and the cross represents the other random errors (distance modulus, photometric calibration etc.) that make the LDB age determination uncertain.
Figure 2. An isochrone fit to the Pleiades at 120 Myr, obtained by tuning the $T_{\text{eff}} - (V - I)$ relationship.

Figure 3. Isochrones fitted to the IC 2391 data, assuming the same $T_{\text{eff}} - (V - I)$ relationship that worked for the Pleiades data. The LDB age for IC2391 is indicated by the dashed isochrone.
age range. The systematics are due mainly to the choice of model and whether there is any age dependence in the bolometric corrections as a function of colour, which are usually derived from mature stars. The influence of whether Li is depleted by 90\% or 99\% at the LDB (say for Li 6708Å EWs < 0.3Å) only alters ages by ±3\%.

Table 1. LDB Ages and errors for young clusters

| Cluster   | LDB Age (Myr) | Experimental Error | Systematic Error |
|-----------|---------------|--------------------|------------------|
| Pleiades  | 122           | +20/−17            | ±11              |
| Alpha Per | 85            | +12/−10            | ±8               |
| IC 2391   | 48            | ±5                 | ±3               |

Table 1 and Figure 1 present example results of our analysis for the Pleiades, Alpha Per and IC 2391 clusters using Li spectra, $I$ and $R−I$ data from the literature. The ages result from the average of using the CB97, B97 and DAM97 models. These ages are similar to those previously estimated (Stauffer et al. 1998, 1999; Barrado y Navascués et al. 1999), but the estimated errors are larger by a factor of two. This does not alter the main conclusions of this set of papers – that the LDB ages are older (by a factor 1.6 or so) than high mass turn-off ages with no core overshoot. However, the larger errors certainly obscure whether the amount of core overshoot required to bring turn-off and LDB ages into agreement might be mass dependent.

3. The effective temperature-colour relationship

The $T_{\text{eff}}$-colour relationship in cool ($< 4500$K) stars has long been a source of considerable uncertainty. If one knew the ages of clusters, then their photometric data provide an empirical isochrone from which a $T_{\text{eff}}$-colour relationship can be derived, such that a theoretical isochrone at the same age will match the same data. If one further assumes the $T_{\text{eff}}$-colour relationship is age-independent, then one could produce isochrones in colour-magnitude diagrams which should match other clusters at their LDB ages.

We have performed these tests using the CB97 and DAM97 models and with $V$ vs $V−I$ and $I$ vs $R−I$ diagrams, with very similar results. Figure 2 shows an example of the empirical isochrone defined by the Pleiades $V$ vs $V−I$ diagram obtained by choosing a $T_{\text{eff}}$-colour relation to yield a good match at the LDB age and assuming a distance modulus of 5.6. Figure 3 shows the result of using this relationship to try and fit isochrones to the available IC 2391 data. The indicated isochronal age ($\approx 30$ Myr) is younger than the LDB age and may be in keeping with the more traditional nuclear turn-off age. There is some indication that the ages converge for the coolest stars in the sample. However,
tests using the available $R - I$ data in the Pleiades and IC 2391 for even cooler stars show that the discrepancy still exists there, so we attribute the convergence perhaps to poor photometric calibration at the most extreme colours. Changing the age (or distance modulus) of the Pleiades (or IC 2391) within their errors makes no difference to this conclusion. Using the Hipparcos Pleiades distance modulus of 5.3 makes the Pleiades LDB age older by $\sim 25$ Myr and increases the discrepancy between isochronal and LDB ages for IC 2391.

4. Conclusions

Could the discrepancy between isochronal and LDB ages, assuming a universal $T_{\text{eff}}$-colour relationship, mean that there are systematic problems in the current generation of low-mass evolution models? Or, could the $T_{\text{eff}}$-colour relationship change sufficiently between 50 Myr and 125 Myr to explain our results? Given the discrepancies between LDB and isochronal ages, this also begs the question as to how accurate isochronal ages derived in even younger clusters and associations could possibly be? If the LDB ages are correct and our empirical isochrones are not, then the implication is that low-mass objects in very young star forming regions and associations could be twice as old as inferred from current evolutionary models combined with similar $T_{\text{eff}}$-colour relations.

The models of Baraffe et al. (1998) suggest that any age dependence of the $T_{\text{eff}}$-colour relationship is small in this age range. However, the reliability of the optical colours, particularly $V - I$ and $R - I$, in these models has been called into question by the authors themselves, so any conclusions based on these is perhaps premature. Unfortunately there is presently insufficient near IR data in young clusters, especially IC 2391, to do a similar test in a spectral region where the model colours are likely to be more realistic.

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