Lithium depletion in open clusters

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Abstract. The current status of observational studies of lithium depletion in open clusters is reviewed, concentrating mainly on G and K type stars. I attempt to answer the following questions: Can the lithium depletion patterns seen in open clusters be explained in terms of standard stellar evolution models? What is the observational evidence for non-standard mixing processes and on what timescales do they operate? Does metallicity play a significant role in lithium depletion? Can lithium still be used as a means of dating young stars? What future observations might yield better answers to these questions?

1. Introduction

Lithium is the only metal produced in significant quantities in the Big Bang. In principle, measurements of Li in old Population II stars yield the primordial Li abundance, which would (in conjunction with $H_0$) strongly constrain the universal baryon density and Big Bang nucleosynthesis models. Sadly, in addition to processes which create Li in the universe, there are mechanisms which lead to its destruction in stellar interiors via $p, \alpha$ reactions at only $(2-3) \times 10^6$ K. There is debate about whether the $A$(Li) (= $12 + \log\left[N(Li)/N(H)\right]$) value of 2.1-2.2 measured in Population II stars is almost undepleted from the primordial value, or whether the primordial value is closer to the $A$(Li) of 3.3 measured in the youngest stars and solar system meteorites, and has been significantly depleted in Population II stars (Bonifacio & Molaro 1997, Deliyannis & Ryan 1997).

The former interpretation requires processes that increase the Galactic Li abundance by factors of 10 in $\simeq 5$ Gyr, while the latter requires us to rethink the way that material is mixed in stellar interiors. Standard models, which incorporate only convective mixing, predict little ($\simeq 0.1$ dex) Li depletion in Population II stars. However, many extensions to the standard model, incorporating non-standard mixing such as microscopic diffusion, turbulence induced by rotational instabilities, meridional circulation and gravitational waves have been proposed and developed in some detail by a number of groups (see Pinsonneault 1997 for a review).

Open clusters are excellent laboratories for investigating non-standard stellar physics relating to Li depletion. We can assume that we have co-eval groups of stars with very similar compositions and by choosing clusters with a range of ages and compositions we can hope to answer the questions posed in the abstract. The observational database for Li in open clusters has grown enormously in the last 10 years, thanks to sensitive detectors and the accessibility and strength of
the Li $6708\text{Å}$ resonance doublet upon which most abundance measurements are based. Table 1 gives a summary of these observations, listing clusters, ages and distances (from the Lyngå 1987 catalogue – treat with extreme caution!), the number and spectral-types of (main-sequence [MS] or pre-main sequence [PMS]) stars surveyed, with references.

| Cluster   | Log Age (yr) | Distance (pc) | No. | Types  | Refs.                                           |
|-----------|--------------|---------------|-----|--------|------------------------------------------------|
| IC 2602   | 7.00         | 155           | 25  | FGKM   | Randich et al. 1997, A&A, 323, 86;              |
| IC 2602   | 7.00         | 155           | 26  | GKM    | Meola et al. these proceedings                  |
| NGC 2264  | 7.30         | 750           | 6   | FG     | King 1998, AJ, 116, 254;                        |
| IC 2391   | 7.56         | 140           | 10  | FGKM   | Stauffer et al. 1989, ApJ, 342, 285;            |
| IC 2391   | 7.56         | 140           | 22  | GKM    | Meola et al. these proceedings                  |
| IC 4665   | 7.56         | 430           | 14  | GKM    | Martín & Montes 1997, A&A, 318, 805              |
| Blanco 1  | 7.70         | 190           | 39  | FGK    | Panagi & O’Dell 1997, A&AS, 121, 213;            |
| Blanco 1  | 7.70         | 190           | 17  | GK     | Jeffries & James 1999, ApJ, 511, 218             |
| Alpha Per | 7.71         | 170           | 5   | F      | Boesgaard et al. 1988, ApJ, 327, 389;           |
| Alpha Per | 7.71         | 170           | 3   | M      | Garcia-Lopez et al. 1994, A&A, 282, 518;        |
| Alpha Per | 7.71         | 170           | 29  | FGK    | Balachandran et al. 1996, ApJ, 470, 1243;       |
| Alpha Per | 7.71         | 170           | 18  | KM     | Randich et al. 1998, A&A, 333, 591               |
| NGC 2547  | 7.76         | 400           | 34  | KM     | Jeffries et al. these proceedings               |
| Pleiades  | 7.89         | 125           | 17  | F      | Boesgaard et al. 1988, ApJ, 327, 389;           |
| Pleiades  | 7.89         | 125           | 95  | FGK    | Soderblom et al. 1993, AJ, 106, 1059;           |
| Pleiades  | 8.00         | 440           | 24  | FGK    | Soderblom et al. 1993, AJ, 106, 1059;           |
| Pleiades  | 8.00         | 440           | 13  | K      | Garcia-Lopez et al. 1994, A&A, 282, 518;        |
| Pleiades  | 8.00         | 440           | 15  | KM     | Jones et al. 1996, ApJ, 112, 186;                |
| Pleiades  | 8.00         | 440           | 8   | GK     | Russell 1996, ApJ, 463, 593;                    |
| NGC 2516  | 8.03         | 440           | 24  | FGK    | Jeffries et al. 1998, MNARS, 300, 550            |
| NGC 1039  | 8.29         | 440           | 34  | FGK    | Jones et al. 1997, AJ, 114, 352;                 |
| NGC 6475  | 8.35         | 240           | 35  | FGK    | James & Jeffries 1997, MNARS, 292, 252           |
| Coma Ber  | 8.60         | 86            | 16  | F      | Boesgaard 1987, ApJ, 321, 967;                   |
| Coma Ber  | 8.60         | 86            | 5   | FG     | Soderblom et al. 1990, AJ, 99, 595;             |
| Coma Ber  | 8.60         | 86            | 15  | FGK    | Soderblom et al. 1999, MNARS, 304, 821          |
| Coma Ber  | 8.60         | 86            | 5   | FGK    | Soderblom et al. 1999, MNARS, 304, 821          |
| Hyades    | 8.82         | 320           | 21  | FGK    | Jeffries 1997, MNARS, 292, 177                  |
| Hyades    | 8.82         | 320           | 21  | FGK    | Jeffries 1997, MNARS, 292, 177                  |
| Hyades    | 8.82         | 48            | 32  | F      | Boesgaard 1987, PASP, 99, 1067;                  |
| Hyades    | 8.82         | 48            | 32  | F      | Boesgaard & Budge 1988, ApJ, 332, 410;           |
| Hyades    | 8.82         | 48            | 23  | FG     | Soderblom et al. 1990, AJ, 99, 595;             |
| Hyades    | 8.82         | 48            | 23  | FG     | Soderblom et al. 1990, AJ, 99, 595;             |
| Hyades    | 8.82         | 48            | 68  | FGK    | Thorburn et al. 1993, ApJ, 415, 150              |
| Hyades    | 8.82         | 48            | 12  | K      | Soderblom et al. 1995, AJ, 110, 729             |
| Hyades    | 8.82         | 48            | 7   | K      | Barrado & Stauffer 1996, A&A, 310, 879          |
| Praesepe  | 8.82         | 180           | 63  | FG     | Soderblom et al. 1993, AJ, 106, 1080            |
| NGC 752   | 9.04         | 400           | 19  | FG     | Hobbs & Pilachowski 1986, ApJ, 311, L37;         |
| NGC 752   | 9.04         | 400           | 6   | F      | Hobbs & Pilachowski 1988, PASP, 100, 336         |
| NGC 3680  | 9.26         | 800           | 16  | FG     | Pasquini et al. 1998, CSSS10, CD-947            |
| M67       | 9.60         | 720           | 7   | FG     | Hobbs & Pilachowski 1986, ApJ, 311, L37;         |
| M67       | 9.60         | 720           | 6   | F      | Spite et al. 1987, A&A, 171, L1;                |
| M67       | 9.60         | 720           | 14  | FG     | Pasquini et al. 1997, A&A, 325, 535;            |
| M67       | 9.60         | 720           | 27  | FG     | Barrado et al. 1997, MSAI, 68, 939              |
| M67       | 9.60         | 720           | 25  | FG     | Jones et al. 1999, AJ, 117, 330                  |
| NGC 188   | 9.70         | 1550          | 7   | F      | Hobbs & Pilachowski 1988, ApJ, 334, 734          |

2. Models of Li Depletion

Figure 2 in the review of Pinsonneault (1997) gives an overview of the Li depletion predictions of standard stellar evolution models, where convection (and some convective overshoot) is the only mixing mechanism. Quantitatively, models produced by various groups depend upon the details of the adopted convective
Figure 1. Li abundances for members of the Pleiades (crosses) and Hyades (dots). The solid lines are standard model predictions of PMS Li depletion for two compositions (from Pinsonneault 1997).

3. The Pleiades and Hyades

The two best studied open clusters are the Pleiades and Hyades, with ages of \( \approx 100 \) and 600 Myr, and consistently determined spectroscopic iron abundances of \([\text{Fe/H}] = -0.034 \pm 0.024\) and \(+0.127 \pm 0.022\) (Boesgaard & Friel 1990, Friel...
Boesgaard 1992). Figure 1 shows Li abundances (determined using the same temperature scale and curves of growth) for these clusters using data on single stars gleaned from the sources in Table 1. Also shown are standard Li depletion models for two mean metallicities. The general pattern of Li depletion in the Pleiades is modelled reasonably well. The Hyades is more metal rich than the Pleiades, so we expect more PMS Li depletion, although not nearly as much as is observed. Two classes of solution can be put forward to explain this discrepancy. (a) Swenson, Stringfellow & Faulkner (1990) show that increasing interior opacities by modest amounts could bring standard models into agreement with the Hyades data. Such arguments do not explain why short-period, tidally locked binary systems in the Hyades are much less Li depleted than their single counterparts (Thorburn et al. 1993, Barrado y Navascués & Stauffer 1996). (b) Extra mixing whilst on the MS, driven by rotation and angular momentum loss seems capable of providing the additional Li depletion with a natural explanation for why the Li depletion in tidally locked binaries might be different (Chaboyer et al. 1995).

Standard models also struggle to explain spreads in Li abundance among late G and K-type Pleiades stars. The scatter appears to be correlated with rotation, although a more detailed consideration (e.g. Randich et al. 1998) shows that the correlation in both the Pleiades and α Per clusters is driven largely by the fact that fast rotating stars have suffered little Li depletion, whereas slowly rotating stars can have either high or low Li abundances (see Figure 2). There are some indications that this dispersion may decrease again at surface temperatures below 4500 K (Jones et al. 1996). One interpretation would be to invoke non-standard mixing during the PMS phase and the disk coupling paradigm for early angular momentum evolution (Bouvier et al. 1997). Slow rotators might suffer little extra mixing because they are born slow rotators and lose little angular momentum, or they could be born as fast rotators and lose considerable angular momentum by coupling to a long-lived circumstellar disk and consequently undergo greater mixing and Li depletion. Stars which are still fast rotators on the ZAMS would have been only briefly coupled to a disk, would not have lost significant angular momentum and suffered less internal mixing. The problem with this explanation may be that insufficient extra mixing associated with angular momentum can take place on the PMS, and that fast rotators in the Pleiades have Li abundances that lie above even the standard model predictions.

Adherents to the standard models could appeal to small metallicity variations between cluster stars or to the possibility that atmospheric inhomogeneities such as plages or starspots could cause a scatter in the equivalent widths of Li i lines at a given $B-V$ value. This latter explanation has been reviewed by Stuik, Bruls & Rutten (1997), who make a plausible case for considering such effects and point out that the similarly formed K i 7699Å line shows a nearly equivalent scatter in Pleiades stars. As K abundance variations are not expected, then the scatter in K i equivalent widths at a given colour means that it is premature to ascribe the apparent Li abundance variation in late-type Pleiads to non-standard processes.
Figure 2. The Li16708Å line EWs for members of the Pleiades (dots) and α Per (circles) as a function of rotation period. Li measurements are from sources in Table 1. A narrow colour range of $0.81 < B - V < 1.07$ was chosen for the Pleiades and $0.88 < B - V < 1.13$ for α Per. Rotation periods are from O’Dell et al. (1995, and references therein) and Krishnamurthi et al. (1998).

4. Metallicity, age and Li depletion

A natural question to ask is whether the Li depletion pattern in the Hyades when it was younger, looked like that in the Pleiades now? Standard models predict that the Hyades would look about the same as they do now because all the depletion occurred during PMS evolution (for $T_{\text{eff}} \geq 5000$ K). Non-standard models predict a level of Li depletion somewhere between the present day Hyades and Pleiades levels, due to 500 Myr of non-standard MS mixing. Similarly, non-standard models predict that if the Pleiades were aged to about 600 Myr, the Li depletion pattern should lie between the present day Pleiades and Hyades because of reduced PMS Li depletion in the metal-poor Pleiades, followed by somewhat less efficient MS Li depletion than in the Hyades because of shallower CZs at a given $T_{\text{eff}}$. These are very clear predictions. To test them simply requires Li abundance measurements in the G and K stars of a cluster at the age of the Hyades, but with the metallicity of the Pleiades, and vice-versa. These data now exist in the form of Li abundances in the Blanco 1, and Coma Berenices open clusters.

4.1. Blanco 1

Jeffries & James (1999) present Li abundances for G and K stars in Blanco 1, a young cluster (age 70 Myr) with a spectroscopically determined iron abundance of [Fe/H]=+0.14, when derived using the same colour-$T_{\text{eff}}$ scale as used for other young clusters. Figure 3 presents the Li abundances of late-type stars in Blanco
1 compared with the Pleiades and Hyades. Clearly the Blanco 1 Li abundances are indistinguishable from those in the Pleiades and much higher than in the Hyades.

These observations present problems for both standard and non-standard Li depletion models. If the Hyades looked like Blanco 1 in the past then non-standard MS mixing and Li depletion is clearly indicated, because the stars in Blanco 1 should evolve to look like the Hyades in \( \sim 500 \) Myr, offering useful empirical constraints on the timescale for the mixing mechanisms. However, because non-standard models predict extra depletion compared with the standard models, an additional ingredient is required to explain why Blanco 1 has not suffered significantly more initial PMS Li depletion than the Pleiades, given it’s higher metallicity.

4.2. The Coma Berenices Open Cluster

The sparse Coma Berenices open cluster (age 500 Myr) has \([\text{Fe/H}] = -0.052 \pm 0.026\), determined in a rigorously consistent way with that of the Pleiades and Hyades values already quoted (Friel & Boesgaard 1992). Li abundances for G and K stars are presented by Jeffries (1999) and supplemented with a few more observations by Ford et al. (1999 - A&A submitted). The data for single stars are also shown in Figure 3. The Li depletion pattern for Coma Ber is very similar to that in the Hyades, with perhaps a hint of less Li depletion for stars cooler than 5700 K. Again, both standard and non-standard models have problems explaining these observations. The standard models would have that the Li depletion in Coma Ber, which occurred during PMS evolution, should be similar to or even less than that in the Pleiades. The extra depletion observed could be supplied by non-standard mixing (on timescales that agree very well with the Hyades-Blanco 1 comparison), but it is then hard to see why Coma Ber and the Hyades should be so close at the present day, unless the PMS Li depletion was not metallicity dependent and both clusters started out on the ZAMS with similar depletion patterns – as indicated by the Pleiades and Blanco 1 datasets.

4.3. Other clusters

To these two examples could be added Li abundance datasets for IC 2391/2602, \( \alpha \) Per, IC 4665 and NGC 2516 (see Table 1). These clusters are either a little younger or a little older than the Pleiades and probably have a wide (albeit ill determined) range of metallicities. Yet the G and K stars in these clusters have Li depletion patterns very close to that in the Pleiades. Similarly, Praesepe and NGC 6633 have ages close to that of the Hyades, probably lower metallicities, yet show almost the same Li depletion pattern as the Hyades. There is perhaps some evidence in NGC 6633 that the K stars have not suffered quite as much depletion as in the Hyades, but they are significantly more depleted than the Pleiades (Jeffries 1997). There are also clusters with intermediate ages (NGC 1039, NGC 6475, 200-300 Myr) which show intermediate Li depletion patterns.

The global cluster dataset is clearly telling us that metallicity is not an important parameter in determining the amount of PMS Li depletion, which flatly contradicts the predictions of standard models. Non-standard mixing processes acting during MS evolution are required in order to rank the cluster Li depletion patterns according to age. Their appear to be no significant exceptions to
this trend. The only ways of rescuing the conventional view of standard models are to either abandon the idea that one cluster is representative of clusters at the same age and composition, or assume that $[\text{Fe/H}]$ is not representative of the overall metallicity of these clusters. Swenson et al. (1994) have shown that abundances of elements such as O and Si are important in determining CZ depth and PMS Li depletion. Detailed abundance analyses of key clusters are required to check that we are not seeing the effects of drastically non-solar abundance ratios, however this explanation would seem to require an unlikely conspiracy of circumstances, given the number of observed clusters.

For clusters with greater than solar metallicity, arriving on the ZAMS with similar Li depletion patterns to the Pleiades, a mechanism is indicated that severely reduces the predicted efficiency of Li depletion on the PMS. This requirement can be extended to lower metallicity clusters and is even more extreme if standard models incorporating the full spectrum of turbulence convection model are considered (Ventura et al. 1998). It has been suggested that structural changes associated with rapid rotation might do this job (Martín & Claret 1996) and at the same time, explain the Li abundance scatter in late-type Pleiades stars. Recently, Mendes, D’Antona & Mazzitelli (1999) have shown that the effects of rapid rotation might actually be in the opposite sense required and in any case, even the slow rotators in Blanco 1 have similar Li abundances to analogous stars in the Pleiades. Ventura et al. (1998) hypothesize that dynamo generated magnetic fields could steepen the adiabatic temperature gradient sufficiently to alter CZ properties and significantly diminish Li depletion. Stronger magnetic fields and less Li depletion would be expected in fast rotators, possibly matching observations in the Pleiades, Blanco 1 and other ZAMS clusters. At
present this model is very crude, but the work of Ventura et al. shows that
the size of the effect might certainly be enough to explain the lack of PMS Li
depletion and its near independence of metallicity.

5. Older clusters

As the case for non-standard Li depletion has been made convincingly for younger
clusters it is natural to ask how observations of older clusters might delineate
the mechanisms and timescales responsible for the extra mixing. The Hyades-
Blanco 1 and Pleiades-Coma Ber comparisons indicate a Li depletion rate of
about 300-500 Myr per dex for ZAMS K-stars, and perhaps a factor $\sim 2 - 3$
slower in G-stars. If the Sun were taken as representative for a star of it’s age,
the depletion rate in early G stars must average out to $\simeq 2$ dex of depletion in
4 Gyr.

Li abundances in a good sample of old open clusters would constrain these
timescales. Unfortunately old open clusters are relatively rare and tend to be
distant. Furthermore, the K-stars have probably depleted Li beyond detection
(although strong upper limits would be useful). Table 1 summarises the observa-
tional state of play. The best studied old open cluster is the solar-age M67.
The data presented in Jones, Fischer & Soderblom (1999) and Pasquini, Randich
& Pallavicini (1997) show an order of magnitude scatter in the Li abundances
of solar-type stars at this age, and significant depletion with respect to stan-
dard model PMS Li depletion predictions. The solar Li abundance is positioned
towards the lower end of the distribution.

That Li is detected at all in 4.5 Gyr old solar-type stars probably indicates
that Li depletion slows from an initially higher rate on the ZAMS. This would
certainly be expected for mixing mechanisms that were driven by a slowly de-
clining rate of rotation and angular momentum loss. Jones et al. (1999) ascribe
the spread in Li abundances to non-standard mixing in stars with a spread in
initial ZAMS rotation rates. The abundance spread must develop over several
Gyr, because the Pleiades and Hyades G stars show only marginal signs of this
spread at younger ages (Thorburn et al. 1993). The stars with initially higher
rotation rates would then be those with the lowest Li abundances in M67 and
vice-versa (reversing the trend seen in Pleiades K stars!). The circumstantial
evidence for this, is that the proportion of low and high Li abundances in M67
approximately matches the proportions of fast and slow rotators in the Pleiades.

This intriguing notion needs bolstering with measured rotation rates in M67
(although rotation rates may well have converged to be indistinguishable). If the
scenario could be confirmed, then Jones et al. (1999) speculate that the low Li
abundance of the Sun indicates that is was rapidly rotating on the ZAMS. This
may still be premature because M67 has a slightly sub-solar metallicity. We lack
the evidence to say by how much metallicity affects non-standard mixing on long
timescales, but if higher metallicities enhance MS Li depletion, then the Sun may
yet turn out to have a high Li abundance for its age. This could be addressed by
observations of several older clusters and would be important in understanding
how much prior depletion has occurred in very metal-poor Population II stars.
6. Conclusions

I end by attempting to briefly answer the original questions in the abstract. It is clear from the evidence reviewed that standard stellar evolution models struggle to explain the patterns of Li depletion seen in open clusters. Furthermore, observations of clusters with different metallicities provide difficulties for current non-standard models. There are strong indications that PMS Li depletion is not as strong as predicted in either class of model. This has not yet been widely recognized and hence explanations are so far rather speculative.

There are many pieces of evidence that non-standard mixing and Li depletion are important during MS evolution. These include the Hyades-Blanco 1 and Pleiades-Coma Ber comparisons, where the confounding factor of metallicity dependent PMS Li depletion has been removed, the general ordering of cluster Li depletion according to age and the strong depletion seen among older clusters and the Sun. The timescales for MS Li depletion are longer than PMS Li depletion timescales but are still uncertain. The current observational evidence suggests that the MS depletion timescales are shorter for K stars than G stars and may get longer as stars spin down.

Metallicity appears not to play a great role in PMS Li depletion, contradicting expectations. Abundance analyses are required for O and Si to see whether CZ depth is affected by non-solar abundance ratios, although the number of clusters in the extant dataset makes this possibility unlikely. If metallicity is not important for PMS Li depletion, then one of the major uncertainties in using Li abundances to date young stars is removed. The other is the scatter in abundances seen at a given age, which inevitably introduces uncertainties that can be well quantified by comparison with cluster datasets. Thus although using Li abundances to age young stars might be relatively inaccurate, depending on the spectral-type of star considered, the uncertainties can at least be empirically determined. It is very difficult however to date older stars using Li abundances because (a) they also show a scatter in Li abundance that develops with age, (b) stars cooler than G-type won’t have detectable Li once older than ∼ 1 Gyr and (c) we still don’t know whether metallicity greatly affects the efficiency of MS Li depletion.

New observations could be made which would clarify a number of these issues. Detailed abundance analyses could be performed for all the key open clusters to check for non-solar abundance ratios. Li abundance measurements in several more old open clusters might betray any metallicity dependence of MS depletion timescales. Measuring rotation periods in many more cluster stars with Li abundances, including the slower rotators in older clusters where these measurements tend to be much more difficult, would allow further investigation of how depletion timescales depend on rotation rates. The connection between Li depletion and rotation in cool ZAMS stars is still far from resolved and may yet turn out to be problems in our understanding of inhomogeneous stellar atmospheres. In that respect, the connection between rotation, surface inhomogeneities, Li i, and K i equivalent width spreads needs to be carefully investigated, possibly using doppler tomographic techniques (e.g. Hussain, Unruh & Collier-Cameron 1998).
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