Lithium abundances of the local thin disc stars

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ABSTRACT

Lithium abundances are presented for a sample of 181 nearby F and G dwarfs with accurate *Hipparcos* parallaxes. The stars are on circular orbits about the Galactic centre and, hence, are identified as belonging to the thin disc. This sample is combined with two published surveys to provide a catalogue of lithium abundances, metallicities ([Fe/H]), masses, and ages for 451 F–G dwarfs, almost all belonging to the thin disc. The lithium abundances are compared and contrasted with published lithium abundances for F and G stars in local open clusters. The field stars span a larger range in [Fe/H] than the clusters for which $[Fe/H] \simeq 0.0 \pm 0.2$. The initial (i.e. interstellar) lithium abundance of the solar neighbourhood, as derived from stars for which astration of lithium is believed to be unimportant, is traced from $\log \epsilon(\mathrm{Li}) = 2.2$ at $[Fe/H] = -1$ to $\log \epsilon(\mathrm{Li}) = 3.2$ at $+0.1$. This form for the evolution is dependent on the assumption that astration of lithium is negligible for the stars defining the relation. An argument is advanced that this latter assumption may not be entirely correct, and, the evolution of lithium with [Fe/H] may be flatter than previously supposed. A sharp Hyades-like Li dip is not seen among the field stars and appears to be replaced by a large spread among lithium abundances of stars more massive than the lower mass limit of the dip. Astration of lithium by stars of masses too low to participate in the Li dip is discussed. These stars show little to no spread in lithium abundance at a given [Fe/H] and mass.

Key words: stars: abundances – galaxies: stellar content.

1 INTRODUCTION

Astrophysicists continue to find excitement in studying – observationally and theoretically – stellar abundances of lithium. Lithium abundances offer insights into a wide variety of problems, principally those related to the nucleosynthesis of lithium at an assortment of sites and to the astration of lithium by stars. The aim of our survey of lithium abundances in main sequence F–G stars was to document the astration of lithium as a function of stellar mass, age, and metallicity. We do this by assembling lithium abundances for a sample of 451 F and G disc stars, including 157 stars for which lithium abundances are presented for the first time. We compare and contrast the lithium abundances of these field stars with the abundances reported for similar stars in local open clusters. Our sample complements the clusters in that it extends to lower metallicity. It is not our intent to confront the abundances with theoretical projections and predictions.

Throughout the paper, we assume that the observed Li I 6707 Å resonance doublet and the derived lithium abundance refer to the isotope ^{7}Li with a negligible contribution from the isotope ^{6}Li. There are two strong reasons for our assumption. First, all but one proposed mode of lithium synthesis makes ^{7}Li with no or negligible

coproduction of ^{6}Li. Coproduction of both Li isotopes occurs in the interstellar medium between relativistic cosmic rays and ambient nuclei, as in collisions between protons and oxygen nuclei providing ^{6}Li, ^{7}Li as well as ^{9}Be, ^{10}B, and ^{11}B as fragments of the ^{16}O nucleus. Yields of ^{6}Li and ^{7}Li by this process may be assessed from measurements of ^{9}Be abundances for which spallation reactions are considered to be the sole mode of synthesis. This assessment shows the ^{6}Li abundance expected of disc main-sequence stars to be negligible. Secondly, astration of atmospheric lithium by mixing with the interior is driven by proton capture with a capture cross-section for ^{6}Li that is about a factor of 80 larger than the cross-section for ^{7}Li. Thus, except in very special or contrived circumstances even mild loss of surface lithium by mixing and proton capture leads to complete astration of ^{6}Li. Note that not all proposed theories of the Li dip (or general astration) invoke destruction of surface lithium. Theories ascribing the Li dip to a diffusion of Li out of the atmosphere may predict an alteration of the isotopic ratio. Even in these cases, the lithium abundance is probably dominated by ^{7}Li.

2 STELLAR SAMPLES AND LITHIUM ABUNDANCES

Our investigation is based on lithium abundances of 451 F and G nearby main-sequence stars drawn from three surveys. Table 1

Table 1. The catalogue. Sample lines of the table are shown here. The complete table is available from http://www.blackwellpublishing.com/products/journals/suppmat/MNR/MNR7557/MNR7557sm.htm

HD	[Fe/H]	T_{eff} (K)	$\log g$	M_v	Mass ($M_\odot$)	Age (Gyr)	$\log \epsilon(\text{Li})$	Source
101	−0.29	5826	4.36	4.55	0.88	12.5	2.21	LR
153	−0.11	5791	3.80	2.89	1.32	3.44	<0.69	LR
330	−0.27	5775	3.84	3.10	1.19	4.60	2.48	LR
400	−0.32	6096	4.16	3.61	1.05	6.46	2.25	CB
693	−0.48	6132	4.12	3.51	1.04	6.11	2.39	CB
912	−0.26	6011	3.82	2.92	1.22	4.12	<1.01	LR
1671	−0.09	6471	3.84	3.51	1.25	2.59	2.88	B
2454	−0.37	6418	4.09	3.26	1.20	3.50	<1.60	LR
2630	−0.17	6685	4.17	2.21	1.58	1.66	2.83	B
…	…	…	…	…	…	…	…	…

Note – LR: Lambert & Reddy (this study); B: Balachandran (1990); C: Chen et al. (2001); LRB, LRC or BC: identify stars in common to two surveys.

provides the HD number and basic information for each star. The majority of the sample has evolved off the zero-age main sequence. This condition reflects the selection criteria used by the surveyors. For stars included in two or more of the surveys, we have adopted a mean lithium abundance, and mean estimates for the important atmospheric parameters including the effective temperature and the metallicity.

With the exception of a few stars from Chen et al.'s (2001) sample, all of the stars belong to the local thin disc, i.e. they move about the Galactic centre in a roughly circular orbit at the Sun's Galactocentric distance. The Galactic thick disc and halo are very poorly represented in the combined sample. Thin disc stars of the same metallicity ([Fe/H]) have the same chemical composition to within a narrow range, i.e. [X/Fe] is the same for stars of the same [Fe/H], and [X/Fe] changes only slightly with [Fe/H] (Reddy et al. 2003). The three surveys excluded spectroscopic binaries where previously known or detected in the course of the survey, but a few surely remain undetected. It is unlikely, however, that Table 1 includes tidally locked binaries, which may defeat the usual processes of astration of lithium.

2.1 Reddy et al. (2003)

Reddy et al. (2003) reported abundance analyses of 181 F and G stars based on high-resolution, high signal-to-noise ratio optical spectra and model atmospheres. These field stars span the temperature range $5550 \leqslant T_{eff} \leqslant 6500$ K and metallicities $-0.80 \leqslant [\text{Fe/H}] \leqslant +0.20$ with an emphasis on the sub-solar metallicities. These stars, all belonging to the Galactic thin disc, were largely chosen to lie off the zero-age main sequence in order that an evolutionary age could be determined.

Lithium was not among the 27 elements considered. For this paper, we extended the analysis to lithium using the 6707 Å Li I resonance doublet. Selection of models and atmospheric parameters are discussed by Reddy et al. Basic atomic data for the 6707 Å doublet are taken from Reddy et al. (2002). The LTE Li abundances were corrected for non-LTE effects using Carlsson et al.'s (1994) recipe; the corrections are small, attaining only 0.10 dex in the most extreme cases. Lithium abundances obtained for 137 of the 181 stars and upper limits to the abundance for the other 44 stars are expected to be accurate to about ±0.1 dex with the uncertainty (±100 K) in the effective temperature as a leading source of error. The ±0.1 dex

is negligible with respect to the 2 dex or more depth of the Li dip, small with respect to the intrinsic scatter outside the dip, and much less than the apparent 1 dex growth of the lithium abundance from $[\text{Fe/H}] = -1$ to $[\text{Fe/H}] = 0$.

2.2 Chen et al. (2001)

Chen et al. surveyed the lithium abundance in 185 main-sequence stars sampling the interval $5600 \leqslant T_{eff} \leqslant 6600$ K and $-1.4 \leqslant [\text{Fe/H}] \leqslant +0.2$. A major fraction, 133 of 185 stars, was drawn from an earlier paper: Chen et al. (2000) had given abundances for a mix of elements but not including lithium. The remaining fraction came from a reanalysis of stars analysed by Lambert, Heath & Edvardsson (1991). The stars in the survey lie off the zero-age main sequence so that evolutionary ages may be estimated from stellar evolutionary tracks.

The method of abundance analysis chosen by Chen et al. (2000) and Chen et al. (2001) resembles ours and included non-LTE corrections from Carlsson et al. (1994). Reddy et al. (2003) compare elemental abundances for stars in common with Chen et al. (2000) and find very good agreement, also for the derived atmospheric parameters including the effective temperature and the metallicity. This agreement extends to the lithium abundances for 24 stars in common with Chen et al. (2001). The mean difference in abundance (us minus them) is a mere 0.03 ± 0.04 dex. For four stars, the difference in abundances is quite large, that is 0.2 to 0.6 dex, and traceable to differences in the equivalent width of the 6707 Å line. In particular, the 0.6 dex difference arises for a star with a very weak lithium line. Given this level of agreement, we merge the two samples without adjustments to the lithium abundances, the effective temperatures, and metallicities. For stars in common, we adopt the average of the two lithium abundances, effective temperatures, and [Fe/H] determinations.

2.3 Balachandran (1990)

Balachandran (1990) determined lithium abundances for nearly 200 field F stars. She sampled the temperature range $7000 \leqslant T_{eff} \leqslant 6000$ K with most stars having metallicities in the range [Fe/H] from −0.6 to +0.2. In contrast to the preceding three samples which were restricted to sharp-lined stars, Balachandran explicitly included broad-lined stars in order to investigate the effect of rotation on lithium surface depletions. Her sample comprised stars on and off the zero-age main sequence.

Four of Balachandran's stars are in our sample. Judged by these common stars, there is no significant difference in the lithium abundances from Balachandran and ourselves: the mean difference (us minus Balachandran) is -0.1 ± 0.06 dex. There are 10 stars that are common to Chen et al. and Balachandran. The mean differences (Chen minus Balachandran) in atmospheric parameters, and the Li abundances are very small: $\Delta T_{eff} = -27 \pm 76$ K, $\Delta \log g = -0.13 \pm 0.08$, $\Delta[\text{Fe/H}] = 0.08 \pm 0.08$, and $\Delta \log \epsilon(\text{Li}) = -0.04 \pm 0.09$. These comparisons show no systematic differences either in atmospheric parameters or in Li abundances between the three samples. Thus, we have simply adopted Balachandran results, after correction for the small non-LTE effects.

3 STELLAR LUMINOSITIES, MASSES AND AGES

Interpretation of the lithium abundances in terms of Galactic chemical evolution and stellar astration is helped greatly by examining the

abundances as a function of stellar mass, composition and age. The composition (here, [Fe/H]) is taken from the surveys. To determine mass and age, we compare the stars in Hertzsprung–Russell (H–R) diagrams against a set of theoretical stellar evolutionary tracks for the same metallicity. This comparison calls for the absolute visual magnitude M_V, effective temperature T_{eff} and metallicity [Fe/H] of each star. As our choice of evolutionary tracks, we use the set provided by Girardi et al. (2000).

The M_V for a star in our or Balachandran's sample is computed using the parallax and the apparent magnitude listed in the *Hipparcos* catalogue. For Chen et al.'s (2001) stars, we adopt their M_V, also computed from the *Hipparcos* parallax. Interstellar extinction is ignored for these stars which are within 150 pc of the Sun. As noted above, the published T_{eff} and [Fe/H] are adopted.

Given M_V, T_{eff} and [Fe/H] for a star, its mass and age were estimated by interpolation among the evolutionary tracks provided by Girardi et al. at 0.01 $M_{\odot}$ steps in mass and 0.01-dex steps in [Fe/H]. Chen et al. (2000) give masses and ages for their stars derived from evolutionary tracks computed by VandenBerg et al. (2000). We have rederived these quantities using the Girardi et al. tracks and find only slight differences. The interpolation is accurate to 0.005 $M_{\odot}$ in mass almost independently of age and [Fe/H] provided that the star does not lie near the hook in the tracks. In the case of the few stars that fall near the hook in the evolutionary tracks, there is an ambiguity of about 0.1 $M_{\odot}$. We assign higher weight to the track region where evolutionary rate is slower.

For most of the sample, the uncertainty in T_{eff} translates to an error in age but not a significant error in mass; a star evolves approximately at constant M_V. An error in [Fe/H] of about 0.2 dex translates to one in the derived mass of about 0.05 $M_{\odot}$. The uncertainties in the measured [Fe/H] should be much smaller than this illustrative estimate and, hence, the associated error in the derived mass may be ignored. The principal effect of an error in M_V is an error in the derived mass. On the assumption that the parallax is the sole source of uncertainty: $\Delta M_V = 2.2\Delta\pi/\pi$. In our sample, 448 stars or 95 per cent have a parallax accurate to 10 per cent or better or $\Delta M_V < 0.22$ which translates to a mass uncertainty of about 0.05 $M_{\odot}$. Our acceptance limit for a parallax was $\Delta\pi/\pi = 0.2$, which corresponds to a mass uncertainty of about 0.1 $M_{\odot}$.

4 SETTING THE STAGE WITH OPEN CLUSTERS

By way of an introduction to the discussion of the lithium abundances, we show in Figs 1 and 2 a series of H–R diagrams for stars in narrow intervals of [Fe/H]. The lithium abundances span at least two dex from a maximum of about $\log\epsilon(\mathrm{Li}) = 3.0$ to upper limits of $\log\epsilon(\mathrm{Li}) < 1.0$. On these two figures, the size of the symbol denotes the lithium abundance; measured abundances are shown by open symbols and limits by the filled symbols. Girardi et al.'s evolutionary tracks are plotted. An alternative representation of the data is shown in Fig. 3 where we plot the lithium abundances against the inferred stellar mass with each panel again showing stars within a narrow range in [Fe/H].

Before discussing our sample of field stars, we look at available data on lithium abundances for main sequence F–G stars in open clusters in the solar neighbourhood. There is now a quite considerable collection of clusters for which lithium abundances have been measured for F–G–K stars from clusters with pre-main-sequence stars to clusters older than the Sun. In a review of embedded clusters in molecular clouds, Lada & Lada (2003) suggest that most field stars originate from disrupted embedded clusters, and that

open clusters are the small fraction of surviving embedded clusters. We supplement this suggestion with the assumption that field and cluster stars having the same basic parameters (mass, age, and composition) share a common initial lithium abundance. Recent reviews on lithium abundances of stars in open clusters include those by Deliyannis (2000), Jeffries (2000) and Pasquini (2000).

Unfortunately, the available cluster data do not sample the full range of metallicities and ages of the field stars. The ([Fe/H], *t*) plane is sparsely covered by the clusters. With one exception, the open clusters for which lithium abundances have been reported cover the narrow range in [Fe/H] from +0.2 to −0.2, ages from pre-main-sequence to about 5 Gyr, and are at the Sun's Galactocentric distance within about 0.5 kpc. The exception is the metal-poor ([Fe/H] = −0.5; Hill & Pasquini 2000) cluster NGC 2243 at about 2 kpc in the anticentre direction. This is not a representative of the solar neighbourhood. We have taken lithium abundances directly from the published papers on clusters and made no attempt to make a uniform reanalysis of the observations. Use of different temperature scales and consideration or neglect of non-LTE effects may have introduced systematic differences of, perhaps, 0.2–0.3 dex between different papers.

4.1 Initial lithium abundance at [Fe/H] ∼ 0

In the youngest clusters, the lithium abundance is constant down to a mass of slightly less than 1 $M_{\odot}$. The sample of such clusters includes these with pre-main-sequence stars: NGC 2264 (King 1998; Soderblom et al. 1999) with $\log\epsilon(\mathrm{Li}) = 3.2$, and the Orion Association (King 1993; Cunha, Smith & Lambert 1995) also with $\log\epsilon(\mathrm{Li}) = 3.2$. Young clusters with ages of about 40 to 100 Myr show a gradual decrease in lithium abundance with decreasing mass beginning at about the solar mass. The lithium abundance of the stars more massive than a solar mass is independent of mass and the same in each cluster: IC 2602 and IC 2391 (Randich et al. 2001), IC 4665 (Martín & Montes 1997), α Persei (Balachandran, Lambert & Stauffer 1988, 1996; Boesgaard, Budge & Ramsay 1988b), Blanco 1 (Jeffries & James 1999) and the Pleiades (Boesgaard et al. 1988b; Jones et al. 1996). This abundance is in the range $\log\epsilon(\mathrm{Li}) = 3.0$ to 3.2.

A remarkable, unanticipated, and unexplained illustration of astration is the Li dip discovered by Boesgaard & Tripicco (1986a) among main-sequence stars of the Hyades cluster. Cluster stars in a narrow temperature range centred on $T_{eff} = 6600$ K show lithium depletions of up to 2.0 dex relative to stars with $T_{eff} > 6400$ K and $T_{eff} < 6200$ K. The Li dip discovered in the Hyades cluster of age $t = 660$ Myr is detected among members of the U Ma group at $t = 300$ Myr (Boesgaard, Budge & Burck 1988a; Soderblom et al. 1993b) and M34 at $t = 200$ Myr (Jones et al. 1997). An absence of the dip in NGC 2516 at $t = 150$ Myr (Jeffries, James & Thurston 1998), M35 at 175 Myr (Barrado y Navascués, Deliyannis & Stauffer 2001), and NGC 6475 at $t = 220$ Myr (James & Jeffries 1997; Sestito et al. 2003) possibly indicates that the dip is not present for stars younger than about 200 Myr but it has to be noted that the absence may be a consequence of inadequate or no coverage of the T_{eff} range of the dip. The lithium abundance on the high temperature side of the Li dip is indistinguishable from the abundance seen in the youngest clusters: $\log\epsilon(\mathrm{Li}) = 2.9$ (NGC 2516), 2.9 (M34), 2.8 (M35), 2.9 (NGC 6475), and 3.0 (U Ma). On the hot side of the Li dip there may be a star-to-star scatter in the Li abundances which may cause estimates of the initial Li abundance of a cluster to be lower than the true value – see our later discussion of the field stars, especially Fig. 4.
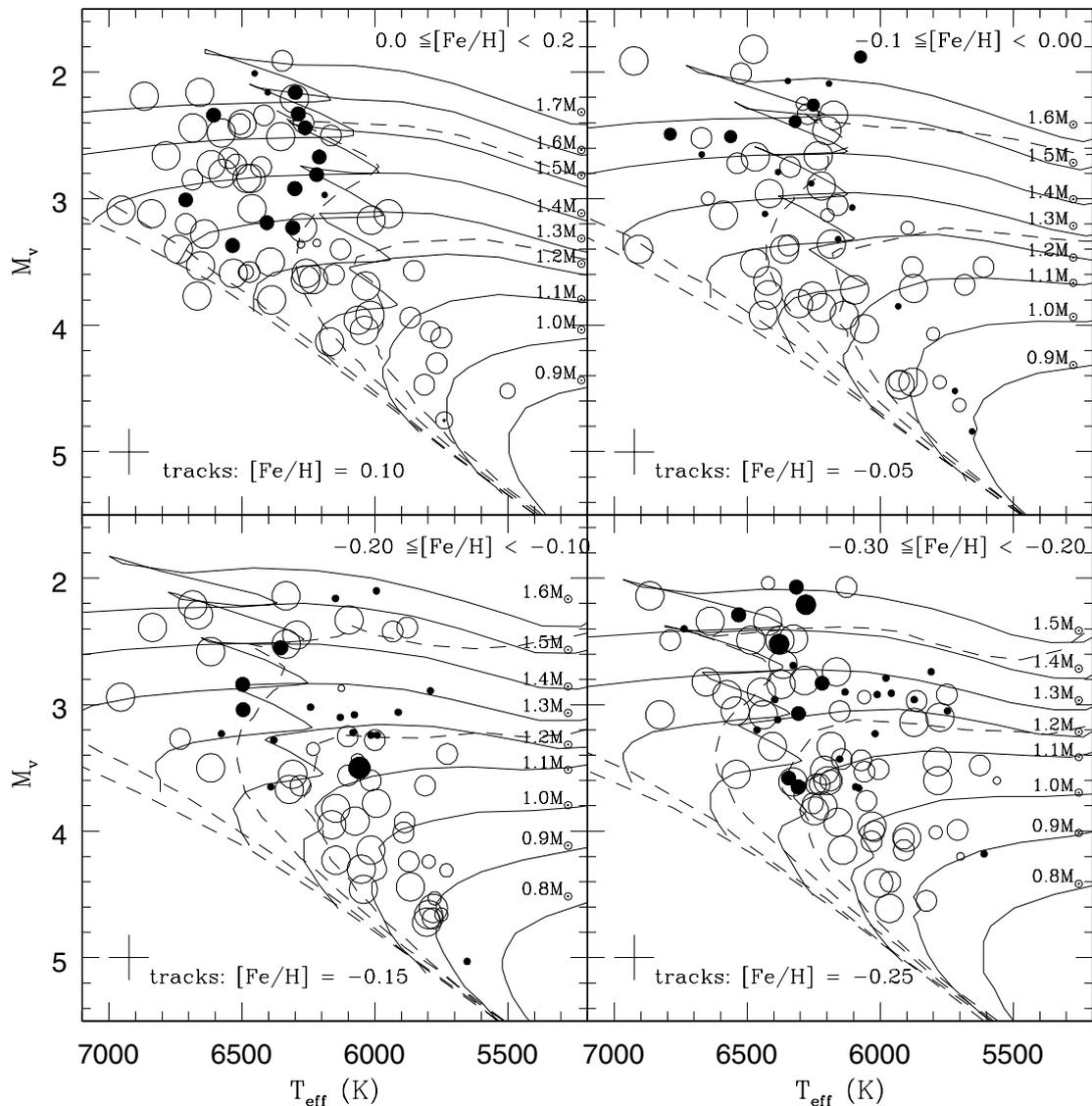
Figure 1. H–R diagrams showing the stars from Table 1 for the top four metallicity bins. Evolutionary tracks (solid lines), and isochrones (broken lines) for 100, 700, 2500, and 4500 Myr from Girardi et al. (2000) are shown for the mean [Fe/H] of a bin. Filled circles denote stars with no detected lithium, and open circles denote stars with detectable lithium. The symbol size represents the magnitude of the lithium abundance (or upper limit). Four sizes are used. In order of decreasing symbol size, the abundance intervals are: $\log \epsilon(Li) \geqslant 2.50$, $2.0 \leqslant \log \epsilon(Li) < 2.5$, $1.5 \leqslant \log \epsilon(Li) < 2.0$, and $\log \epsilon(Li) < 1.5$.

In clusters with ages from about 300 Myr to about 2 Gyr, a signature of the Li dip is present. No single cluster provides an adequate number of stars to affirm that the lithium abundance of the hot stars is independent of mass. This abundance seems, however, to be very similar from one cluster to the next and identical to within the errors with that from the youngest clusters: $\log \epsilon(Li) = 3.1$ (Hyades – Boesgaard & Tripicco 1986a; Thorburn et al. 1993; Balachandran 1995), 3.2 (Praesepe – Boesgaard & Budge 1988; Soderblom et al. 1993a; Balachandran 1995); 3.0 (NGC 6633 – Jeffries 1997; Jeffries et al. 2002), 3.1 (NGC 752 – Hobbs & Pilachowski 1986; Pilachowski & Hobbs 1988; Balachandran 1995), 3.2 (NGC 3680 – Pasquini, Randich & Pallavicini 2001). Observations of the Coma Berenices cluster (age 400–500 Myr) provide just one star on the hot side of the Li dip (Ford et al. 2001). This star with the abundance $\log \epsilon(Li) = 2.8$ may be on the shoulder of the dip. The similar maximum lithium abundance in the youngest clusters and in these slightly older clusters implies that F main-sequence stars experience

very little depletion of lithium up to ages of about 1 Gyr. The G and K stars do experience astration which is more severe the lower the mass of the star. Previous lithium detectives have noted the uniformity of the maximum lithium abundance in local open clusters and suggested that it represents the interstellar lithium abundance of the natal clouds of the clusters (e.g. Pilachowski & Hobbs 1988). The uniformity implies little to no evolution of the lithium abundance in the local interstellar medium over the last several Gyr. The interstellar Li abundance is possibly slightly less than the solar system abundance ($\log \epsilon(Li) = 3.3$), a difference that may reflect a systematic error in the lithium abundance analysis of early F stars (i.e. classical atmospheres ignore stellar granulation).

4.2 The Li dip at [Fe/H] $\sim$ 0

As noted above, the dip is seen only in clusters older than about 300 Myr. In clusters older than about 2–3 Gyr, the dip is not seen
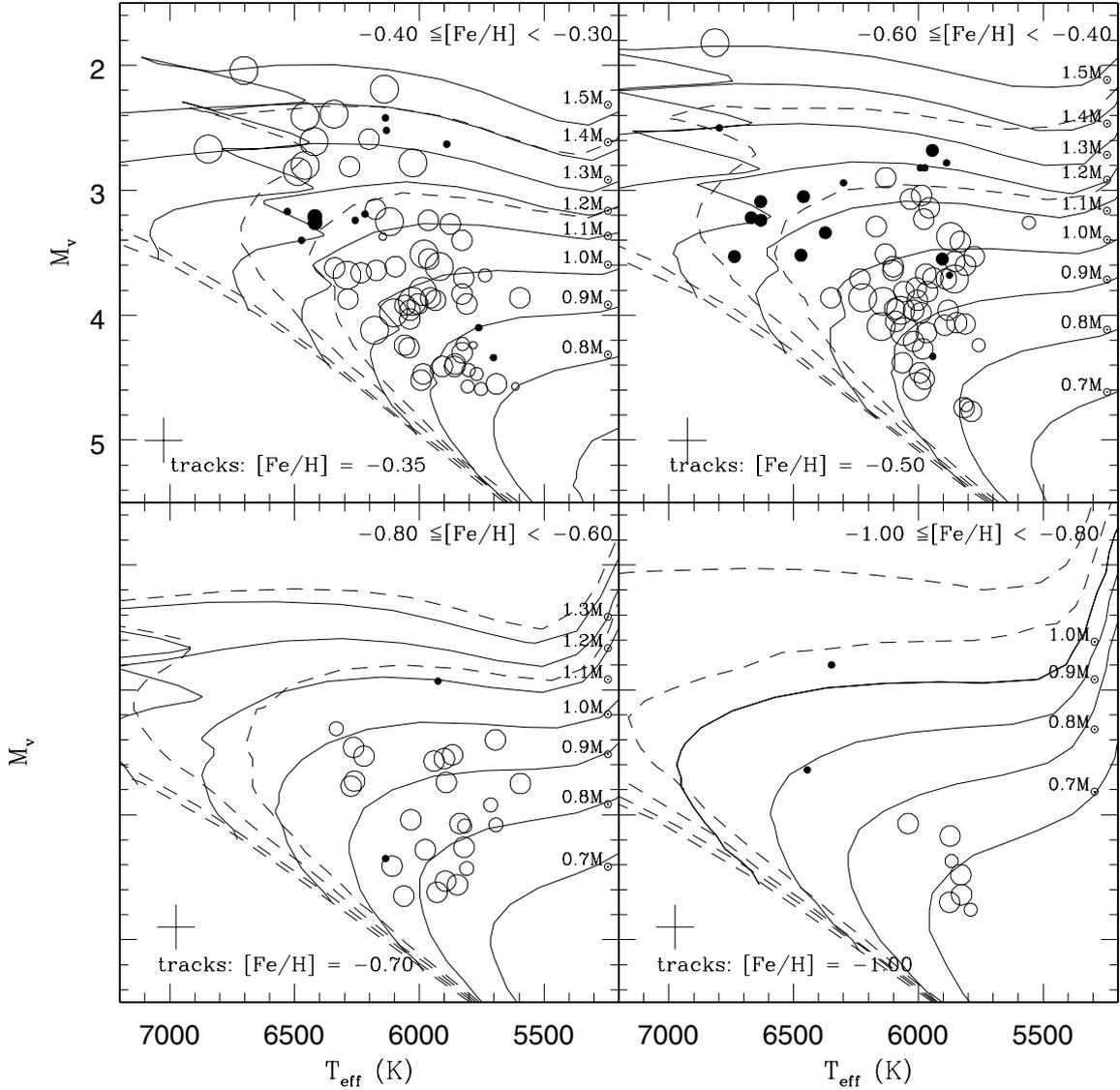
Figure 2. H–R diagrams showing stars from Table 1 for the four bottom [Fe/H] bins. See caption to Fig. 1 for further explanation.

among the main-sequence stars because stars susceptible to the responsible processes have evolved off the main sequence. The few well observed clusters between these age limits show the Li dip. (In our view, the Hyades Li dip is the sole convincing example of a dip with well defined steep sides. Other clusters clearly have Li-poor stars at the temperature of the Hyades dip but the $T_{\rm eff}$ dependence of a dip cannot be defined clearly.)

A uniform analysis of observations of the Li dip was reported by Balachandran (1995) for the Hyades, Praesepe, NGC 752, and M67. (In the case of M67, the Li dip is not a main-sequence phenomenon but is inferred from lithium abundances of subgiants.) A conclusion from this work is that over the limited metallicity range represented by the Hyades, Praesepe and NGC 752 (+0.12 to −0.15 in [Fe/H], according to Balachandran), the dip occurs at the same effective temperature for the zero age main-sequence stars ($T_{\rm eff} \simeq 6500$K), which implies that the corresponding mass is metallicity-dependent ($M/{\rm M}_\odot \sim 1.3 + 0.5$ [Fe/H]). Among additional conclusions drawn by Balachandran are the following: lithium in stars of the dip is destroyed within the stars; all main-sequence stars within the temperature range that defines the Li dip experience astration. These

conclusions and the mass dependence are potentially examinable using samples of field stars. In particular, the greater [Fe/H] range covered by field stars may allow for the mass–metallicity relation to be extended to lower [Fe/H]. Balachandran's conclusions about the shape of the Li dip are likely too subtle to be checked using field stars.

4.3 General astration at [Fe/H] ∼ 0

The Hyades stars show a monotonic decrease of lithium abundance for masses below the dip, and no star-to-star scatter in abundance at a fixed mass. The few well observed clusters of similar or older age to the Hyades show a lithium abundance versus mass relation not remarkably different from the Hyades. Balachandran (1995) compares Hyades with Praesepe (also 600–700 Myr), NGC 752 (1100 Myr), and M67 (4000 Myr). Randich, Sestito & Pallavicini (2003) compare Hyades and NGC 188 (7000 Myr). At fixed mass rather than a common $T_{\rm eff}$, the run of the maximum lithium abundance with mass is very similar across this age range, as noted by Randich et al. who, however, use $T_{\rm eff}$ rather than mass for the comparison. On the
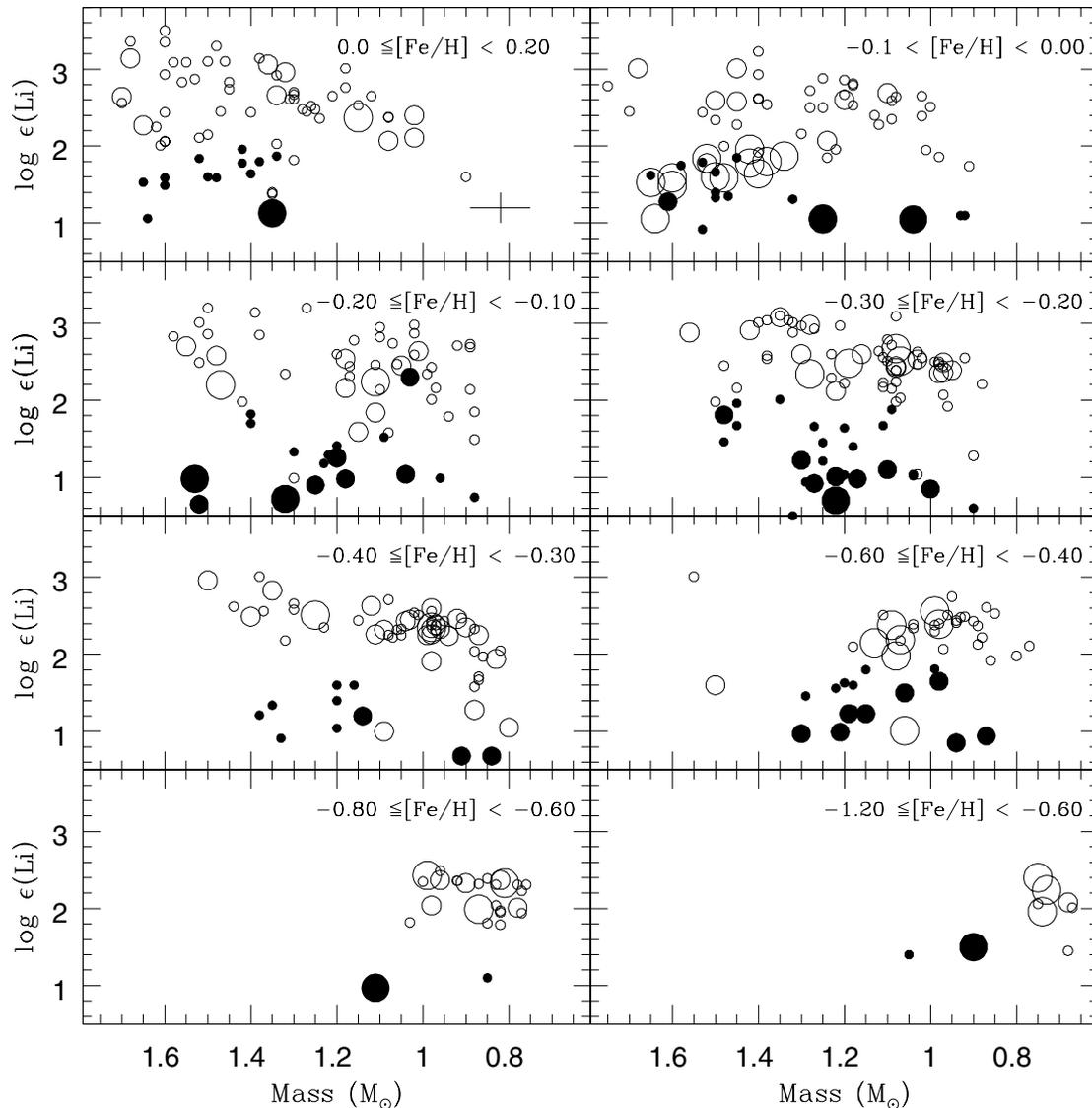
Figure 3. Li abundance versus stellar mass in eight different [Fe/H] bins. Filled circles denote upper limits to the lithium abundance. Open circles refer to measured abundances. The three sizes for the circles identify the accuracy of the *Hipparcos* parallax, a major influence on the derived mass. Stars with a parallax error $\geqslant 10$ per cent are assigned the biggest circle. Stars with an error of 5 to 10 per cent are shown with the middle-sized circle. Those stars with a 5 per cent or smaller error are given the smallest circles.

assumption that the initial lithium abundances were very nearly alike and the assumption that astration is composition-independent, this implies that the additional astration is slight above ages of about 600 Myr. It is well known that astration from birth to the age of the Hyades is significant – approximately 1.0 dex at 1 M$_\odot$ (see above cited reviews). The growth of the astration–mass relation to the levels shown by the Hyades and older clusters is traceable from the cluster analyses cited above. Since low-mass stars younger than the Hyades are not well represented in our sample, we refrain from commenting further on these younger clusters, the growth of the lithium–mass relation for low-mass stars, and the scatter in lithium abundances at a fixed mass.

Scatter in lithium abundances exists among low-mass stars in at least one old cluster. Main-sequence stars of M67 show a star-to-star scatter of at least 1 dex (Jones, Fischer & Soderblom 1999, and references therein) with about two-thirds showing a (maximum) lithium abundance consistent with that of other clusters (see above) and the majority of the other one-third showing no detectable lithium

or an abundance limit about 1 dex below the lithium-rich stars. In sharp contrast is NGC 188 for which Randich et al. (2003) find 'virtually no scatter' in the lithium abundance of solar-type stars, and an abundance consistent with that of other old clusters (and the Hyades) including that of M67's Li-rich two-thirds. Randich et al. further remark that 'M67 remains so far the only old cluster for which a dispersion [in lithium abundances] among solar-type stars has been confirmed', but the fact is that few old clusters have been observed for lithium and in those few the sample of examined stars is small.

A curiosity is that the Sun's lithium abundance [log ε(Li) = 1.0 – Müller, Peytremann & de la Reza 1975] appears to fall by more than 1 dex below the trend defined by the field stars (see Fig. 3). If placed among NGC 188's stars, the Sun would be deemed very Li-poor. Among M67's stars, the Sun would be one of the most Li-poor stars. This hint that the Sun may be 'peculiar' as regards the depletion of lithium weakens its value as a calibrator for prescriptions of non-standard modes of lithium astration.
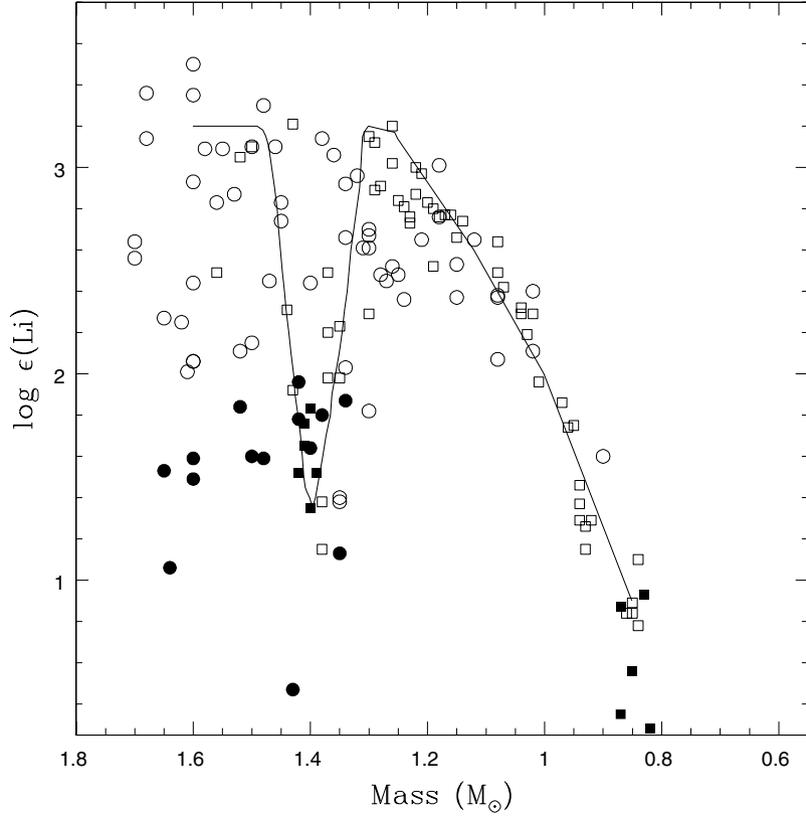
Figure 4. Lithium abundance versus stellar mass for the Hyades members (open squares) and field stars with [Fe/H] in the range 0.0 to +0.2 (circles). Filled symbols denote upper limits to the lithium abundance. The solid line is the mean relation for the Hyades stars with the Li dip prominent at about $M = 1.4 \, \mathrm{M_\odot}$.

5 LITHIUM ABUNDANCES OF THE FIELD STARS

The field star sample is sorted into eight metallicity bins. In the H–R diagrams (Figs 1 and 2) for the eight bins, the size of the open circle denotes the magnitude of the measured lithium abundance and upper limits are represented by a filled circle of the appropriate size. The lithium abundance versus mass plots are shown in Fig. 3 with the size of the symbol denoting the accuracy of the *Hipparcos* parallax, again open circles refer to measured lithium abundances and filled circles to upper limits. The parallax error is the principal contributor to the precision with which the stellar mass may be estimated from a given set of evolutionary tracks.

Quite independently of the lithium abundance, one fact stands out from inspection of the HR diagrams (Figs 1 and 2) and the lithium–mass plots (Fig. 3): the absence of the higher mass stars in the lower [Fe/H] bins. Contrast, for example, the panels in Fig. 3 for $-0.4 <$ [Fe/H] > -0.3 and $-0.6 <$ [Fe/H] -0.4. The former panel is representative of the higher [Fe/H] bins: the maximum mass in a bin increases with increasing [Fe/H]. (A mass of about 1.6 $\mathrm{M_\odot}$ is about the mass at which a main-sequence star is so hot that the Li I resonance doublet is undetectable. Lithium is traceable in higher mass stars when, as subgiants, they evolve across the Hertzsprung gap as subgiants.) The latter panel is almost devoid of stars with $M > 1.2 \, \mathrm{M_\odot}$, and the maximum mass seen in the panels decreases with decreasing [Fe/H]. This correlation probably reflects the form of the age–metallicity relation displayed by the field stars (Edvardsson et al. 1993; Chen et al. 2000; Reddy et al. 2003).

The age–metallicity relation for local field stars, as first clearly expressed by Edvardsson et al., exhibits scatter at a fixed age. In the

(age, [Fe/H]) plane, the stars are bounded at the upper end at [Fe/H] $\sim +0.2$ at all ages, but at the lower end by a trend of decreasing [Fe/H] with increasing age. For example, at [Fe/H] $= -0.5$ there are very few field stars (at least, in these surveys) younger than about 4 Gyr, and, as a result, the H–R diagrams and the low [Fe/H] bins in Fig. 3 lack the more massive stars. This interpretation is independent of the origins of the scatter in the age–metallicity relation. A search for field stars more massive than those represented in Fig. 3 would be of interest.

5.1 The maximum lithium abundance

The maximum lithium abundance in each [Fe/H] bin is taken to be the mean of the six highest lithium abundances in that bin. Table 2 shows this abundance and the corresponding mean mass. Selected stars are members of the thin disc. Only in the lowest metallicity

Table 2. Mean Li abundances calculated from the six most Li-rich stars in each [Fe/H] bin.

[Fe/H]	$\log \epsilon$(Li)	$\langle m/m_\odot \rangle$
0.2 to 0.0	3.33 ± 0.16	1.52 ± 0.12
0.0 to -0.1	3.03 ± 0.14	1.40 ± 0.16
-0.1 to -0.2	3.10 ± 0.06	1.31 ± 0.17
-0.2 to -0.3	3.09 ± 0.04	1.31 ± 0.11
-0.3 to -0.4	2.86 ± 0.14	1.34 ± 0.14
-0.4 to -0.6	2.64 ± 0.07	1.03 ± 0.26
-0.6 to -0.8	2.39 ± 0.06	0.91 ± 0.06
-0.8 to -1.2	2.15 ± 0.15	0.71 ± 0.04

bin would thick disc stars be members of the richest sextet. The two thin disc stars in this bin have abundances of $\log \epsilon(\text{Li}) = 2.40$ and 1.96 for a mean of 2.18, a value equivalent to the mean of 2.15 from the entire sextet. For the three bins which overlap the [Fe/H] range of the clusters, the lithium abundances in Table 2 are identical to the maximum abundances from the clusters. We identify this abundance with that of the interstellar gas from which the clusters and field stars formed. The lithium abundance seems to have increased by only about 0.2 dex as [Fe/H] increased from -0.35 to $+0.15$.

At metallicities [Fe/H] < -0.4, the maximum lithium abundance is provided by stars of about 1 $M_\odot$ or less, a lower mass than provides the maximum abundance for more metal-rich stars. Astration of lithium in the latter stars seems unlikely from Fig. 3 and the data on open clusters discussed above. But, the question arises: is the maximum lithium abundance for the [Fe/H] < -0.4 bins reduced from the initial abundance by astration? Inspection of the data in the $-0.4 <$ [Fe/H] $- 0.3$ bin shows the lithium abundance falling steadily with decreasing mass. If a similar relation, as seems plausible, applies to the adjacent bin for $-0.6 <$ [Fe/H] < -0.4, the maximum abundance attributed in Table 2 to the bin must be increased by about 0.5 dex, as indicated by the outlier at $M \simeq 1.55\ M_\odot$. Then, the entry in Table 2 for the bin would be $\log \epsilon(\text{Li}) \simeq 3.1$ leading to the implication that the lithium abundance was constant as the [Fe/H] of the thin disc increased from -0.5 to $+0.1$.

If astration is ineffective in the contributing stars, the lithium abundances in Table 2 map the evolution of lithium with [Fe/H]. The orthodox consider that the floor to the tabulated data be set at the lithium abundance [$\log \epsilon(\text{Li}) \simeq 2$] of the Spites' plateau of the halo stars (Spite & Spite 1982). An allowance for astration, as suggested by Fig. 3 and the bins for [Fe/H] > -0.4, would seem to imply that the the lithium abundance has evolved little over the lifetime of the thin disc. In that case, how should one match a near uniform abundance of $\log \epsilon(\text{Li}) \simeq 3.1$ for the thin disc to the halo abundance of $\log \epsilon(\text{Li}) \simeq 2$? Perhaps one should contemplate models in which the gas providing the earliest generations of thin disc stars is enriched in lithium from sources other than the big bang. The unorthodox view of the Spites' plateau is that the big bang lithium abundance was greater than the present plateau; lithium has been depleted over the life of the halo stars defining the plateau. This view encourages the speculation that the lithium abundance of the disc may have evolved only slightly above the big bang value. In this connection, we note that a standard big bang model with the Ω_b estimated from the cosmic microwave background (CMB) fluctuations and the cosmological D/H ratio implies a lithium abundance of $\log \epsilon(\text{Li}) \simeq 2.6$ (Kirkman et al. 2003), a value which would merge smoothly with the entries in Table 2 for the more metal-rich bins. This scenario supposes that lithium is astrated in the low mass metal-poor stars comprising the Spites' plateau and, by extension, also in the stars contributing to the entries for the lowest two bins in Table 2.

In the simplest of thin disc models, one expects the lithium abundance to increase with time. The data for the individual stars contributing to Table 2 hint at such an increase, but we suspect that the biases in the samples comprising the three surveys are largely responsible for the trend, also seen in the [Fe/H]–age trend. The abundance ratio Li/Fe is remarkably constant across the bins: $\log \epsilon(\text{Li/Fe}) = -4.30 \pm 0.10$, -4.45 ± 0.11, -4.24 ± 0.06, -4.20 ± 0.06, -4.35 ± 0.18, -4.32 ± 0.16, -4.44 ± 0.04, and -4.41 ± 0.27 for the bins from the most iron rich to the most iron-deficient.

Previously, the evolution of lithium with [Fe/H] has been identified with the upper envelope of the points in a $\log \epsilon(\text{Li})$ versus [Fe/H] plot (see, for example, Rebolo et al. 1988; Lambert et al. 1991) without specific consideration of the mass of the stars and the

possible variation of the mean mass with [Fe/H] and its implications for astration. Our discussion based on Fig. 3 draws attention to this variation.

5.2 Star-to-star scatter?

If initial lithium abundance were coupled tightly to the [Fe/H] of a star, or astration at a fixed [Fe/H] were only a function of a star's mass and were completed before evolution off the main sequence, the lithium abundances in each panel of Fig. 3 would be a smoothly varying function of mass with no scatter about the mean trend except for that attributable to errors of measurement. This is not the case, an observation noted previously by Balachandran (1990) and Chen et al. (2001) from their samples of stars observed off the zero-age main sequence.

5.2.1 Field and cluster stars at [Fe/H] $\geqslant -0.3$

We begin examination of the field stars with the $0.0 \leqslant$ [Fe/H] $< +0.20$ bin and the Hyades stars. The comparison is shown in Fig. 4. The solid line is a mean line through the Hyades points taken from Balachandran (1995). The field stars at masses less than those of the Li dip trace the Hyades mean line with few stars showing a lower lithium abundance. The low-mass limit (red-edge) of the Hyades Li dip appears to mark the low-mass boundary of the large star-to-star scatter in Fig. 4. Our sample, however, contains few stars with $M < 1\ M_\odot$. Published surveys providing Li abundances for such stars indicate that scatter in lithium abundances exists for such stars (e.g. Pasquini, Liu & Pallavicini 1994, Mallik et al. 2003).

The field stars mapping the Hyades relation are much older than the cluster: the mean age of the field sample on the low-mass side of the Li dip is about 5 Gyr versus the cluster age of 660 Myr. At face value, the similar lithium abundances of field and Hyades stars of the same mass on the low-mass side of the Li dip would seem to confirm the suggestion from cluster analyses that the rate of astration is very slow in stars older than about the Hyades. There is, however, a systematic slight difference in the mean [Fe/H] of the field stars and the Hyades: [Fe/H] for the field is about 0.07 dex less than that of the cluster. Astration is predicted to be less severe in lower [Fe/H] stars (Chaboyer, Demarque & Pinsonneault 1995), and hence the field stars appear to have undergone more severe astration than the Hyades, say by about 0.3 dex in about 4 Gyr. This suggestion is not inconsistent with the indications from comparisons of the Hyades and older clusters.

Lithium abundances in field stars with masses greater than the value corresponding to the red edge of the Li dip show a range from the initial abundance of a star [$\log \epsilon(\text{Li}) \simeq 3.0$] to the detection limit for these warm stars, a limit of $\log \epsilon(\text{Li}) \leqslant 1.5$ or even less. The fact that the lower mass limit for severe scatter in the field sample coincides with the red edge of the Hyades Li dip is presumably not fortuitous but a reflection of a common cause. It is a well-known observation (Kraft 1987) and one that motivated Balachandran's selection of field stars that early-F stars include rapid rotators and the break in rotational speeds occurs at about the mass of stars belonging to the Li dip. We follow Balachandran in supposing that loss of angular momentum ('braking') has led to mixing and destruction of lithium. Given an initial distribution in angular momenta, it is easy to imagine how a spread in surface lithium abundances results after braking. Clearly, the Hyades Li dip is not simply replicated by the field stars. Field stars of normal lithium abundance occupy the mass range of the dip. Li-poor field stars are found at masses higher than

the central mass of the Hyades dip. The filling in of the Hyades dip by field stars may be due to errors in the assigned masses arising primarily from parallax and $T_{\rm eff}$ errors and the spread in the central mass of the dip resulting from its metallicity dependence and the 0.2 dex width in [Fe/H] of the bin.

Young well-sampled clusters (e.g. α Per and Pleiades) show neither the Li dip nor a spread in lithium abundances for stars with masses greater than the mass of the subsequent red edge of the Li dip. Clusters with a clear signature of the Li dip have very few stars more massive than those belonging to the Li dip, and generally few stars in the dip. Even the Hyades could be suspected of showing some scatter in lithium abundance in excess of observational errors for stars more massive than the mass of the centre of the dip. We venture to suggest that the large scatter shown by field stars is not contradicted by observations of open clusters. Given that the field stars are older than the cluster main-sequence stars of the same mass and that the time-scale for development of lithium astration may be comparable to or longer than the main-sequence lifetime, one can understand the possibly smaller scatter of the lithium abundances among the cluster.

Our diagnosis of Fig. 4 seems to apply to the other bins (Fig. 3) down to [Fe/H] = -0.3 with the proviso that the central mass of the Li dip moves to lower values with decreasing [Fe/H]. There is a suspicion that the $-0.2 \leqslant$ [Fe/H] < -0.1 bin shows appreciable scatter in the lithium abundances among stars to the low mass side of the Li dip. At [Fe/H] ~ -0.3, the distribution of the data points in Fig. 3 (also Fig. 2) changes from one dominated by scatter to one in which a clear trend emerges with a few points lying on the low lithium side of the trend.

In young clusters such as the Pleiades, a dependence of the lithium abundance on rotational velocity ($v \sin i$) is seen for stars of less than about 1 $M_\odot$ with higher lithium abundance tied to faster rotation. This dependence is not seen in the more massive Pleiades stars nor at all strongly in the low-mass stars of very young clusters (e.g. α Per). Also, the scatter in lithium versus mass relation is not seen among the low mass Hyades stars. Assuming that the Pleiades–Hyades difference is not a reflection of different initial conditions for the two clusters, it would seem that a different coupling of rotation and lithium operates at and below 1 $M_\odot$ than at the higher masses.

5.2.2 The Li dip

Observations of the Li dip in open clusters show that over a narrow range in metallicity centred on the solar value that the mass at which the Li dip occurs decreases with decreasing [Fe/H] (Balachandran 1995). An alternative description of the result is that the Li dip occurs at a similar effective temperature on the zero-age main sequence, which may be a clue to the dip's origin. The [Fe/H] dependence of the Li dip was anticipated from samples of field stars by Balachandran (1990) and echoed by Chen et al. (2001).

The Li dip is traceable in the H–R diagrams and the panels of Fig. 3. It is blurred on the high-mass side by scatter. An occasional lithium-poor star of low mass (a solar analogue?) is readily set aside. We estimate by inspection the mass of the Li dip by looking for the mass at which there is a concentration of Li-poor stars and a relative paucity of stars with a normal lithium abundance. This exercise is impossible for the bin with 0.0 < [Fe/H] < +0.2 and for bins with [Fe/H] < -0.6. With imagination, the mass might be considered to be 1.35 $M_\odot$, 1.25 $M_\odot$, 1.2 $M_\odot$, and 1.2 $M_\odot$ for the five bins between [Fe/H] = 0.0 and -0.4. In the bin for [Fe/H] from -0.4 to -0.6, the low mass side of a dip seems traceable and $M_\odot \geqslant 1.2$ is

suggested. Local clusters suggest that the mass of the dip decreases by about 0.05 $M_\odot$ for a 0.1 dex decrease in [Fe/H] (Balachandran 1995). This is not inconsistent with the above estimates for the five bins, the centres of which span 0.35 dex.

A key open question remains: is the Li dip preserved as the stars age? Data on clusters are too sparse to answer the question. Preservation of the dip would suggest that lithium in Li dip stars is destroyed and not merely hidden below the surface. A signature of a preserved Li dip would be a string of Li-poor stars along a track at a constant mass (Figs 1 and 2). This is seen for the bin with $-0.6 <$ [Fe/H] $<$ -0.4, but, in the more metal-rich bins, Li-poor and Li-rich stars are commonly juxtaposed.

This juxtaposition may have several origins and may not be in conflict with the idea that the Li dip is a permanent mark for a star until growth of the convective envelope dilutes the surface lithium abundance of all stars. Errors in the lithium abundance determination, the estimate of M_V, and the confusion arising from the hook in the evolutionary track, may all blur evidence for a Li dip confined to and a permanent feature of main-sequence stars in a narrow mass range. Yet, our assessment of these effects is that they may not fully account for the juxtaposition of Li-normal and Li-poor stars. We suspect that an additional mechanism is needed to account for the mixing of Li-rich and Li-poor stars.

For [Fe/H] < -0.3, the distribution of the data in Fig. 3 (also Fig. 2) changes from one dominated by scatter to one in which a clear trend emerges with a few stars on the low lithium side of the trend. A Li dip seems apparent for the bins with [Fe/H] between -0.3 and -0.6.

5.2.3 Scatter at $M \leqslant 1 M_\odot$

An intriguing result from open clusters is the contrast between the dispersion of 1 dex or more in lithium abundances among low-mass stars of the old cluster M67 and the uniformity of the abundances in a similarly old cluster NGC 188. In light of this, we comment on the scatter among the lithium abundances of the field stars on the low-mass side of the Li dip.

A M67-like scatter for low mass stars is seen in the bin covering [Fe/H] values from -0.1 to -0.2, and in the -0.2 to -0.3 bin. Pasquini (2000) speculates that the scatter for M67 is of a bimodal nature but this is not evident from Randich et al.'s (2003) presentation of the results (their Fig. 4). A bimodality is not evident in the metal-rich bins in Fig. 3. The scatter appears smaller in the two more metal-rich bins (Fig. 3), but we note that the number of stars in these two bins with a mass of about one solar mass is small. The scatter appears much reduced for the [Fe/H] < -0.3 bins. It is intriguing that the scatter at low masses may be correlated with that among stars more massive than the mass of the Li dip. This hints at a common underlying origin for the scatter – a spread in angular momenta of main-sequence stars that is large at high [Fe/H] and reduced or absent in low [Fe/H] stars? Our catalogue of field stars contains few stars with $M \leqslant 1 M_\odot$. Pasquini et al. (1994) find a M67-like scatter in this mass range from observations of field G stars. Favata, Micela & Sciortino's (1996) results for nearby G and K dwarfs may indicate a reduction of the scatter (see their Fig. 1) at about $M \simeq 0.8 M_\odot$ and lower masses. These G and K field stars are likely very old.

To search for an age dependence for astration, we selected narrow well-sampled mass intervals and plotted the lithium abundance versus the age. In these samples, almost all of the stars have evolved away from the zero-age main sequence. The spread in ages across

the sample is small relative to the total main-sequence lifetime. The lack of a dependence of lithium abundance on age is not, therefore, in conflict with the observed decrease of lithium with increasing age presented using the open clusters which span a larger age range than the field stars.

6 CONCLUDING REMARKS

Unravelling the web of factors that control the surface lithium abundance of main-sequence F and G stars has demanded extensive observations of lithium in stars in open clusters and the field. Our principal goal in this paper has been to present the first measurements of the lithium abundances in nearly 200 F and G field stars, and to combine our results with those of two earlier surveys (Balachandran 1990; Chen et al. 2001) to provide a catalogue of lithium abundances for 451 F and G field stars.

The field stars are presently residing in the immediate neighbourhood of the Sun, and most were likely born at about the Sun's Galactocentric distance. Distance and, hence, absolute magnitude M_V are rather precisely known thanks to the *Hipparcos* satellite. Since the three contributing samples include stars somewhat off the zero-age main sequence, it is possible with the theoretical evolutionary tracks and the measurements of M_V, $T_{\rm eff}$ and [Fe/H] to assign an evolutionary age to most stars. The sample of open clusters for which lithium abundances have been determined for F and G main-sequence stars are also residents of the solar neighbourhood, albeit at a mean distance from the Sun somewhat larger than the mean distance of the field stars. The environments in which field stars and open clusters are formed are unlikely to have differed greatly and one expects a field star and an identical cluster star to exhibit the same lithium abundance.

Lithium abundances of field and cluster stars share common aspects, and may point to some differences. One common aspect is that the inferred initial lithium abundance is the same over the age and metallicity range spanned by the open clusters. The initial or interstellar lithium abundance has been approximately constant in the solar neighbourhood for several Gyr and over the [Fe/H] range from about +0.2 to −0.2. The growth of the lithium abundance from the Spites' plateau to the present level is presently definable only through observations of field stars. Table 2 is our attempt to define that growth but it is based on the key assumption that the lithium of the defining stars is unaffected by astration. If the astration resembled that exhibited by the Hyades and other clusters, the lithium of the thin disc may have had an approximately constant abundance as [Fe/H] grew from −1 to 0.

Astration of lithium is not merely a function of a star's mass, age and composition. This was evident long ago. The difference between the low lithium abundance of the Sun and the much higher abundance exhibited by many field and cluster solar-like stars is one indication that other variables affect the surface lithium abundance. There is probably no convincing evidence yet that field and cluster stars of the same mass, age and composition differ in their star-to-star variation of the lithium abundances, a variation attributed to astration rather than a spread in the initial lithium abundances.

We have supposed that the scatter in lithium abundances among field stars with masses above the high-mass edge of the Li dip is due to differences in initial angular momentum and its loss (rotational braking). An apparent absence of scatter in lithium abundance among such stars of open clusters may be due to the fact that few cluster stars in this mass range present themselves for analysis. It appears that the astration responsible for the star-to-star scatter occurs in main sequence not pre-main-sequence stars.

Stars on the low-mass side of the Li dip experience astration which develops at an early age, i.e. it is evident in Hyades and younger clusters. Cluster and field stars show that additional astration beyond the age of the Hyades is slight. At [Fe/H] $\leqslant$ − 0.2, questions of lithium synthesis and astration must be answered from field stars; few clusters with [Fe/H] $\leqslant$ −0.2 are known. Only one (NGC 2243) has been examined for lithium (Hill & Pasquini 2000). The field stars suggest that the star-to-star variation in lithium abundance is much reduced at low metallicity with the exception of a few stars with an uncommonly low lithium abundance.

Despite intensive observing campaigns on open clusters and field stars there remain gaps in our knowledge about lithium abundances in the (mass, metallicity, age) space, and rotation should be an additional one or two dimensions to this space. Analyses of local field stars should be extended by making either more detailed studies of parts of the HR diagrams sampled by the three surveys used here or by extensions to new parts of the HR diagram, especially to lower masses.

We have noted several times that the local open clusters span a narrow range in [Fe/H]. To extend the work on clusters to lower [Fe/H], it will be necessary to seek distant clusters such as NGC 2243 in the anticentre direction – see, for example, the catalogue of open clusters compiled by Chen, Hou & Wang (2003). Thorough scrutiny of a Hyades-like cluster of [Fe/H] $\sim$ −0.5 or less would offer an empirical test of the variation of the mass dependence of astration with [Fe/H], a crucial test for establishing the growth of the lithium abundance in the local thin disc. The lack of metal-poor open clusters near the Sun and belonging to the thin disc is presumably due to the evaporation and dissolution of clusters. None the less, survival of old solar metallicity clusters like M67 and NGC 188 and the lack of (say) local [Fe/H] $\sim$ − 0.5 clusters seems odd. Certainly, these clusters appear to exclude a rapid recent increase in [Fe/H] to present values.

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