

AGE SPREADS IN STAR-FORMING REGIONS: THE LITHIUM TEST IN THE ORION NEBULA CLUSTER¹

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ABSTRACT

We present the initial results of a study of the surface lithium abundance in a sample of low-mass members ($M_* \sim 0.4\text{--}1.0 M_\odot$) of the Orion Nebula Cluster (ONC) that provide an independent clock to estimate stellar ages. We report the discovery of a significant depletion of lithium in four stars with estimated masses of $\sim 0.4 M_\odot$ and ages ~ 10 Myr. Comparison with the predictions of numerical and analytical models shows excellent agreement between the isochronal age and lithium depletion timescale for two objects, the first such case for lithium-poor pre-main-sequence stars. Our results bear on the issue of the real age spread in the ONC and hence on the overall duration of the star formation process, indicating that the stellar population did not come into existence in a single, rapid burst.

Subject headings: open clusters and associations: individual (Orion Nebula Cluster) — stars: abundances — stars: formation — stars: pre-main-sequence

1. INTRODUCTION

Stars form from the gravitational collapse of dense cores within molecular cloud complexes. Whether such clouds can sustain the production of stars for an extended period of time ($t_{\text{cl}} \approx 10^7$ yr) longer than the typical free-fall time ($t_{\text{ff}} \approx 10^6$ yr) is still unknown and critically debated (e.g., Mac Low & Klessen 2004; Tassis & Mouschovias 2004). Empirical information on the duration comes from studies of the evolution of the gas in molecular cores (the stellar progenitors) and of the stellar population associated with young clusters and associations. As to young stars, the reconstruction of the history of stellar births can be obtained from the isochronal ages using the H-R diagram. Application to several nearby clusters and associations has shown a common behavior in which stars begin to form at modest levels roughly 10 Myr in the past, and then at an accelerating rate with typical e -folding times of 1–3 Myr. In the case of the Orion Nebula cluster (ONC), detailed studies of the optically visible population have revealed that the period of most active formation is confined to a few million years and has recently ended, with the dispersal of the remnant molecular gas from the winds and UV radiation of the massive Trapezium stars (Hillenbrand 1997, hereafter H97; Palla & Stahler 1999, hereafter PS99; Muench et al. 2002; Flaccomio et al. 2003).

In addition to providing an average age for the ONC, the pattern of stellar births has revealed another important aspect regarding its *age spread*: the existence of a small but statistically significant population of older stars with estimated isochronal ages in excess of ~ 5 Myr (see also Slesnick et al. 2004). Since the existence of older stars in young clusters bears directly on the issue of the duration of star formation, the identification of such a population requires careful examination. In this Letter, we present the initial results of a study aimed to determine the age spread of the ONC using measurements of the lithium abundance in stars of a selected mass range by means of the Li I 670.8 nm doublet.

The Li test rests on the ability of stars to deplete their initial Li content during the early phases of pre-main-sequence (PMS) contraction. It has been shown that the physics required to study the depletion history as a function of age has little uncertainty, since it depends mostly on effective temperature (T_{eff}) for fully convective objects (Bildsten et al. 1997). Detailed numerical models show that stars in the range $0.5\text{--}0.2 M_\odot$ start to deplete Li after about 5–10 Myr and completely destroy it after an additional ~ 10 Myr (e.g., Baraffe et al. 1998; Siess et al. 2000). The first evidence for complete Li depletion in a PMS star was reported by Song et al. (2002) in the case of the HIP 112312 binary system. Similarly, the spectra of both components of the spectroscopic binary system St 34, a candidate member of the Taurus-Auriga association, show no Li absorption line (White & Hillenbrand 2005). In both instances, the Li depletion timescale inferred from stellar models turns out to be larger than the isochronal age. Significant Li depletion was also found in several T Tauri stars at levels inconsistent with their relatively high luminosities—that is, young ages (Magazzù et al. 1992; Martín et al. 1994).

Despite these sparse results, the Li test has never been tried systematically in young clusters, on the assumption that sub-solar members would have not had time to significantly deplete their initial Li content. However, in the case of the ONC the presence of a number of older stars in the H-R diagram suggests that the opposite might be true. To verify this, we have selected a sample of 84 low-mass stars in the range $\sim 0.4\text{--}1.0 M_\odot$ and with isochronal ages greater than ~ 1 Myr (PS99), drawn from the H97 survey with membership probability greater than 90%, based on various proper-motion studies. Their distribution in the H-R diagram is shown in Figure 1, together with the region of partial (*light shading*) and full (*dark shading*) depletion predicted by stellar evolution models (Siess et al. 2000).

2. OBSERVATIONS AND DATA REDUCTION

The observations were carried out on 2004 February 14 as part of the Ital-FLAMES Consortium Guaranteed Time Observer program “Multiobject Spectroscopy of Galactic Open

¹ Based on data collected at the ESO Very Large Telescope, Paranal Observatory, Chile [program 072.D-0019(B)].

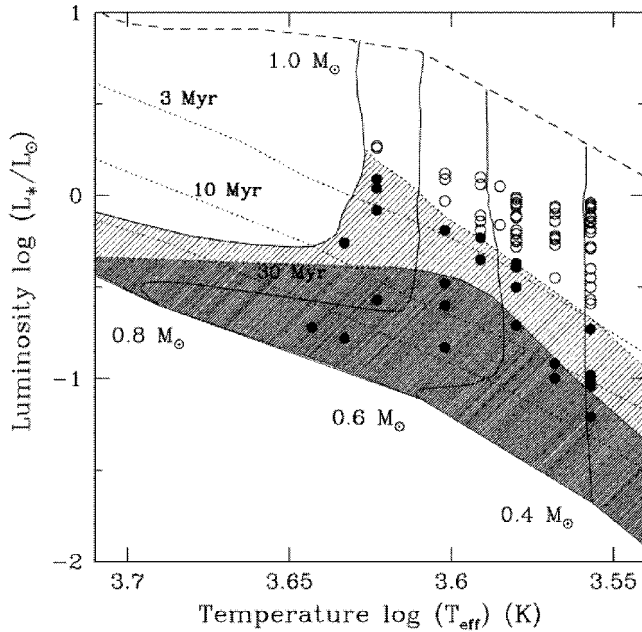


FIG. 1.—Distribution of the sample stars in the H-R diagram. The shaded regions indicate different levels of predicted Li depletion: up to a factor of 10 (light gray) and more (dark gray) below the initial value according to the models of Siess et al. (2000). Selected masses and isochrones are indicated. Open and filled circles are for theoretically expected undepleted and depleted stars, respectively. (Adapted from Stahler & Palla 2004, p. 600.)

Clusters of Different Ages and Metallicities” using FLAMES, mounted on VLT-Kueyen (Unit Telescope 2). The Giraffe spectrograph and Medusa fiber system were used in conjunction with the 316 line mm^{-1} grating and order-sorting filter 15, yielding a nominal resolving power $R = 19,300$ and spectral coverage from 660.7 to 696.5 nm, which includes the Li I 670.8 nm line. We observed the same fiber configuration centered at R.A. = $05^{\text{h}}35^{\text{m}}16^{\text{s}}.0$ and decl. = $-05^{\circ}24'20''$ (J2000) in three separate 1 hr exposures. Typical signal-to-noise ratios range between ~ 230 and 35 pixel^{-1} for the brightest ($I \sim 13.5$) and faintest ($I \sim 17$) objects, respectively.

Data reduction was done using the Giraffe BLDRS pipeline,² following the standard procedure and steps (Blecha & Simond 2004). Sky subtraction was performed separately using the method employed by Jeffries & Oliveira (2005). We obtained a good sky continuum subtraction, while the subtraction of the very strong emission lines due to the nebular emission in the ONC was rather poor. However, this does not affect the measurement of the equivalent widths (EWs), since all the lines used in this study are far enough in wavelength from sky emission. A sample of spectra in the vicinity of 671 nm is displayed in Figure 2 for five stars of the same spectral type (M1) but different luminosity. Note the large variation of the Li I 670.8 nm line from star to star, which, in some cases, corresponds to a Li abundance lower than the interstellar value, as we now show.

3. DERIVED LITHIUM ABUNDANCES

Our spectra are severely affected by spectral veiling, which needs to be corrected before determining Li abundances from the measured $\text{EW}(\text{Li})$. Given r , the ratio of the excess to the photospheric continuum, the relationship between the true and

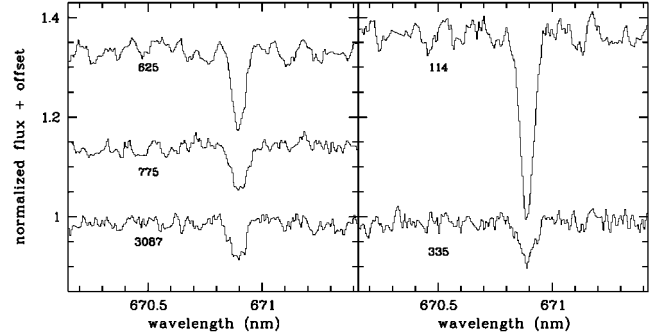


FIG. 2.—Portion of the VLT Giraffe spectra in the vicinity of the Li I 670.8 nm line of the five faintest and coolest stars of the ONC sample (see Fig. 1). Numbers refer to the optical star designation in H97.

measured EW is $\text{EW}_{\text{true}} = \text{EW}_{\text{meas}}(1 + r)$. In order to estimate r , we have measured the EWs of three strong lines included in our spectral range (Ni I 664.36 nm, Fe I 666.34 nm, and V I 662.48 nm) in all target stars and compared them with those measured in the spectra of stars of similar temperature in IC 2391 and IC 2602 that are old enough (30–50 Myr; Randich et al. 2001) to ensure that their spectra are not affected by veiling. For each line and each star in the ONC, the quantity r was calculated from $\text{EW}_{\text{IC}}/\text{EW}_{\text{ONC}} - 1$, where EW_{IC} refers to the open clusters. Finally, the average value of the veiling from the three lines was computed. In a few cases it was not possible to measure the EWs of the three lines and the veiling was derived using one or two lines only.

Measured Li EWs were then corrected for veiling using the r -values determined as above. Corrected (true) EWs lie in the range 400–1000 mÅ. Finally, lithium abundances were derived using MOOG (Snedden 1973) and Kurucz (1993) model atmospheres, and assuming effective temperatures from the spectral types of H97 following Hillenbrand & White (2004). The resulting values of $\log n(\text{Li}) [\equiv N(\text{Li})/N(\text{H}) + 12]$ for the whole sample vary between 2.3 and 3.7, without considering upper limits, with a median value $n(\text{Li}) = 3.12$, very close to the lower limit of the initial interstellar value. Random errors in Li abundances include uncertainties in the correction for veiling, in the measurement of the EW, and in T_{eff} . We estimate that in most cases the total error in $\log n(\text{Li})$ does not exceed 0.3 dex. In order to estimate errors in the abundance scale, in particular for the coolest stars, we have also determined abundances using the curves of growth of Zapatero Osorio et al. (2002), which yield abundances systematically lower by ~ 0.15 dex.

Considering the subsample of stars with masses in the interval ~ 0.6 – $1.0 M_{\odot}$ (see Fig. 1), in all cases we do not find indication of Li depletion. Actually, the median abundance $[n(\text{Li}) = 3.28]$ is slightly higher than that of the whole sample. The fact that the four stars with isochronal ages greater than 10 Myr and masses between 0.7 and $0.8 M_{\odot}$ display no Li depletion is not too surprising given the uncertainties introduced by the rapidly developing radiative core, which make the analysis of Li depletion very sensitive to the detailed physics adopted (the convective-radiative boundary and mixing; see, e.g., Piau & Turck-Chièze 2002).

The situation improves for the subsample of stars with estimated masses below $\sim 0.6 M_{\odot}$. The derived Li abundances are displayed in Figure 3, where it can be seen that the younger ONC stars have maintained all the initial Li. The exception is star No. 73, for which we could only derive a lower limit since

² Version 1.08; see <http://girblhrs.sourceforge.net>.

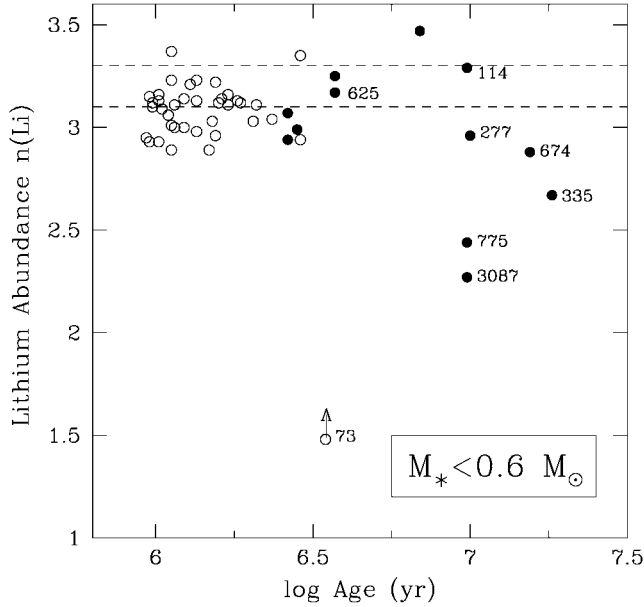


FIG. 3.—Li abundance vs. age for stars with mass below $0.6 M_{\odot}$. Symbols are the same as in Fig. 1. The dashed horizontal lines mark the region of the interstellar Li abundance (3.1–3.3). Typical errors in $n(\text{Li})$ are ± 0.3 dex. All labeled stars are discussed in the text.

the poor signal-to-noise ratio did not allow a determination of veiling. In the case of stars with isochronal ages ≥ 3 Myr, four show significantly depleted Li abundances (up to a factor of 7 for star 3087), while the rest (eight objects) fall within the region of no depletion. Table 1 summarizes the properties of the depleted stars. We stress that these objects have 99% membership probability based on proper motion (H97), and the radial velocities derived by us (listed in Table 1) are consistent with that of the ONC ($V_r \approx 26.5 \text{ km s}^{-1}$; e.g., Sicilia-Aguilar et al. 2005). Given the significance of this finding, in the following we concentrate the analysis on this restricted group of stars.

4. COMPARISON WITH MODELS AND IMPLICATIONS

The existence of several Li-poor, low-mass stars in the ONC allows a direct comparison with both theoretical and analytical models of early nuclear burning. The mass and isochronal age for each star in Table 1 (labeled with subscript “HRD”) were determined using the PMS models of PS99. Errors on both quantities have been estimated from the uncertainties on luminosity (± 0.15 dex) and T_{eff} (roughly ± 80 K, corresponding to half a spectral class). The same values (to within a few percent) for the mass are obtained using the PMS models of Siess et al. (2000), while the ages differ by less than 10% (larger values for Siess et al.). Similar agreement is also found using D’Antona & Mazzitelli (1998) models, computed with a different treatment of convection. On the other hand, the models

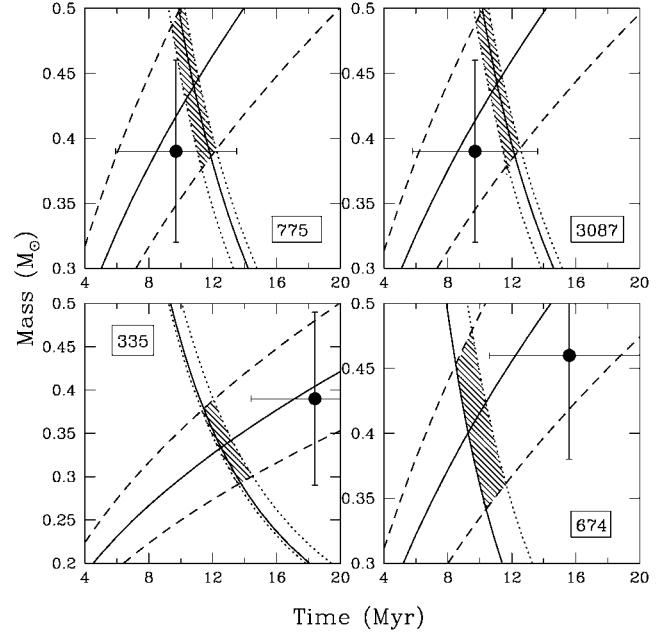


FIG. 4.—Mass vs. age plot for the four stars with evidence of Li depletion. For each star, we plot the luminosity curve (*positive slope*) and the Li abundance curve (*negative slope*) computed for the value of T_{eff} given in Table 1. The dashed curves give the uncertainty range in the observed L (± 0.15 dex; *long-dashed curve*) and in the measured $n(\text{Li})$ (± 0.3 dex; *short-dashed curve*). The hatched regions bound the values of M and t consistent with the observations. In each panel, the circle with error bars gives the mass and age from theoretical PMS tracks and isochrones (PS99).

of Baraffe et al. (1998) yield significantly higher mass, age, and depletion levels.

It is instructive to compare these results with the analytic estimates derived by Bildsten et al. (1997) that apply to the mass range considered here. For fully convective objects undergoing gravitational contraction at approximately constant effective temperature and assuming fast and complete mixing, Bildsten et al. derived simple and accurate (better than $\sim 20\%$) relations for the time variation of the luminosity (their eq. [4]) and for the amount of Li depletion at a given age (their eq. [11]). From the observed L and T_{eff} , one can then construct a plot of the mass depletion time relation that is bounded by the determination of the Li abundance. The results for the four depleted stars are shown in Figure 4. In this diagram, the observed luminosity is represented by a line with positive slope, while the depletion time is set by the observed Li abundance represented by a line with negative slope. The intersection of the two lines yields the combination of mass and age at the given T_{eff} . The last two columns of Table 1 list the derived values obtained in this manner. The hatched region in each panel represents the allowed region bound by the uncertainties in L and in $n(\text{Li})$ (± 0.3 dex).

TABLE 1
PROPERTIES OF THE LITHIUM-DEPLETED STARS

ID	$\log L$ (L_{\odot})	$\log T_{\text{eff}}$ (K)	V_r (km s^{-1})	$n(\text{Li})$	M_{HRD} (M_{\odot})	t_{HRD} (Myr)	M_{Li} (M_{\odot})	t_{Li} (Myr)
775	-1.006	3.557	31.6	2.44	0.39 ± 0.07	9.7 ± 3.9	0.44 ± 0.06	10.8 ± 1.5
3087	-1.014	3.557	27.5	2.27	0.39 ± 0.07	9.8 ± 3.8	0.44 ± 0.06	11.0 ± 1.5
335	-1.206	3.557	26.5	2.67	0.39 ± 0.07	18.4 ± 4.0	0.33 ± 0.06	$12.5^{+7.0}_{-1.4}$
674	-0.999	3.568	26.6	2.88	0.46 ± 0.08	15.6 ± 5.0	0.40 ± 0.07	$9.3^{+2.5}_{-1.4}$

Stars 3087 and 775 have almost identical values of T_{eff} and L and therefore occupy the same position in the plot. In both cases, we find excellent agreement between the observed and theoretical estimates: the stellar mass is well represented by the evolutionary tracks (to within 10%), while the isochronal age differs from the depletion age by 10%. To our knowledge, this is the first time that the two methods have given consistent results to such high accuracy. The agreement can be improved by considering that the age at a given depletion is quite sensitive to T_{eff} ($t \propto 1/T_{\text{eff}}^{3.4}$). Thus, a small variation of this quantity shifts the position of the hatched region. For example, using a hotter temperature scale (by ~ 50 K), the resulting difference between the isochronal and depletion ages would be reduced to less than 5%, while the mass would maintain the same consistency. Thus, our observations confirm that Li can serve not only as a powerful and highly accurate age clock in young clusters, but also as a test of PMS models.

The situation for the two other stars displayed in Figure 4 is not as favorable as in the previous case. In both stars 674 and 335, the derived values of $n(\text{Li})$ yield ages that are marginally inconsistent with the isochronal ones (at the 1σ level): these stars have experienced too little burning for the estimated ages. However, both objects are within the bounded region predicted by the Bildsten et al. analysis. A cooler T_{eff} , higher L , or both would help to reduce the discrepancy, thus allowing the stars to fall within (or very close to) the hatched regions.

We have already noted that other stars that should have shown some level of Li depletion actually do not pass the test (see Fig. 3). In particular, star 114 has $n(\text{Li}) = 3.18$ although its luminosity and effective temperature are almost identical to those of 775 and 3087. Less problematic is the case of star 625 [$n(\text{Li}) = 3.17$], with the same T_{eff} but higher luminosity ($\log L = -0.73$) that places it right at the boundary of the depletion region (cf. Fig. 1). Of the two stars with $\log T_{\text{eff}} = 3.568$ (spectral type M0.5), No. 277 shows only marginal Li depletion [$n(\text{Li}) = 2.96$] despite an isochronal age of ~ 10 Myr. Finally, the only object with mass $\sim 0.57 M_{\odot}$ that falls within the theoretical region of full depletion actually displays the

initial amount of Li. However, at this mass and age such an object has already developed a small radiative core, so again the negative result is not completely unexpected.

5. CONCLUSIONS

The initial study of the Li abundance in the ONC has uncovered four low-mass, bona fide members that show partial depletion at levels consistent with their age and mass. The derived ages of about 10 Myr indicate that the ONC does contain objects much older than the average age of the dominant population. The identification of such a group of stars has significant implications for the star formation history of the cluster, indicating that its duration extends long into the past, although at a reduced rate, in accordance with the empirical evidence found in the majority of nearby star-forming regions (Palla & Stahler 2000). We note that the presence of a population in the ONC with isochronal ages in excess of ~ 10 Myr has been independently inferred by Slesnick et al. (2004) in their study of the very low mass and brown dwarf members. However, this apparently old population could also represent a population of scattered-light objects due to disk occultation whose true luminosity has been underestimated. In our case, the consistency between the Li and isochronal age for the Li-depleted stars makes this interpretation unnecessary.

Finally, we emphasize that it is important to extend the present observations to lower mass members of the ONC, where the transition between depleted and undepleted stars should occur. The study of H97 allows us to probe the critical mass interval between ~ 0.4 and $\sim 0.2 M_{\odot}$, while lower mass objects would be too faint for high spectral resolution observations in the optical. However, considering that a $0.3 M_{\odot}$ star is expected to deplete half of its initial Li in more than 15 Myr, it is possible that the observations presented here might have uncovered the most Li-depleted stars of the ONC.

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