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Hα emission fluxes and lithium abundances of low-mass stars in the young open cluster IC 4665*

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Abstract. As part of a long term effort to understand pre-main sequence Li burning, we have obtained high resolution spectroscopic observations of 14 late type stars (G0–M1) in the young open cluster IC 4665. Most of the stars have Hα filled-in and Li I absorption, as expected for their young age. ¿From the equivalent widths of Hα emission excess (obtained using the spectral subtraction technique) and the Li I λ6708 feature, we have derived Hα emission fluxes and photospheric Li abundances. The mean Li abundance of IC 4665 solar-type stars is log N(Li)=3.1; the same as in other young clusters (α Per, Pleiades) and T Tauri stars. Our results support the conclusions from previous works that PMS Li depletion is very small for masses $\sim$ 1 $M_\odot$. Among the IC 4665 late-G and early K-type stars, there is a spread in Li abundances of about one order of magnitude. The Li-poor IC 4665 members have low Hα excess and vsin$i \leq$10. Hence, the Li-activity-rotation connection which has been clearly established in the Pleiades also seems to hold in IC 4665. One M-type IC 4665 star that we have observed does not show Li, implying a very efficient Li depletion as observed in α Per stars of the same spectral type.

The level of chromospheric activity and Li depletion among the low-mass stars of IC 4665 is similar to that in the Pleiades. In fact, we note that the Li abundance distributions in several young clusters (α Per, Pleiades, IC 2391, IC 4665) and in post T Tauri stars are strikingly similar. This result suggests that Hα emission and Li abundance not well correlated with age for low-mass stars between 20 and 100 Myr old. We argue that a finer age indicator, the "LL-clock", would be the luminosity at which the transition between efficient Li depletion and preservation takes place for fully convective objects. The LL-clock could allow in the near future to derive the relative ages of young open clusters, and clarify the study of PMS evolution of cool stars.

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Key words: stars: abundances, activity, pre-main sequence – clusters: open: IC 4665

1. Introduction

This paper is the continuation of an ongoing project aimed at understanding pre-main sequence (PMS) Li burning. In previous works we have studied Li in different types of PMS stars: Martín et al. (1992) obtained Li abundances for 5 post T Tauri secondaries of early-type stars. Martín & Rebolo (1993) studied the PMS secondary of the eclipsing binary EK Cep and derived its Li abundance. Martín et al. (1994) presented Li abundances for 53 "weak" T Tauri stars (WTTS) in Taurus. They found a narrow peak in the Li distribution centered at log $N(Li)_{NLTE}$=3.1, which is the initial Li content of newly formed stars. They also found that PMS Li depletion is a strong function of mass and luminosity. García López et al. (1994) derived Li abundances for 24 Pleiades stars and confirmed the presence of a Li-rotation connection (see also Soderblom et al. 1993) among the late-G and early K-type stars, but not among the late-K and early-M stars. Such connection has been studied theoretically by Martín & Claret (1996), who showed that rotation lowers the temperature at the base of the convection region and hence reduces the efficiency of PMS Li depletion. Finally, Zapatero-Osorio et al. (1996) performed a search for Li in very low-mass (M3–M6) α Per stars with no positive Li detection.

The IC 4665 open cluster offers the possibility of testing our current ideas about PMS Li burning because it may have an age of only $\sim$35 Myr (Mermilliod 1981, but see the discussion in Sect. 4.2). Its coordinates (17h40m, +5^o) make it a suitable target from northern hemisphere observatories. Its distance ($\sim$350pc) is almost a factor of 3 farther than the Pleiades, and thus the cluster members are relatively faint. Nevertheless, a list of reliable low-mass members with V-magnitudes in the range 12–14 has been released from proper motion and radial velocity studies (Prosser & Giampapa 1994). We selected for spectroscopic observations the 13 bona fide IC 4665 members

Table 1. Observing log

Star	V	Date	Tel.	Disp. (Å pix^{-1})	Texp (s)
P12	12.72	Aug 6, 1995	INT	0.53	1200
P27	12.65	Aug 6-9 1995	INT	0.53-0.84	3300*
P60	13.43	Aug 9, 1995	INT	0.53	900
P71	13.68	Aug 6, 1995	INT	0.53	1600
P75	13.70	Jul 17, 1995	Calar	0.91	1000
P94	14.26	Aug 8, 1995	INT	0.84	1200
P100	14.37	Aug 7, 1995	INT	0.84	900
P107	12.94	Aug 8, 1995	INT	0.84	900
P146	14.19	Aug 6, 1995	INT	0.53	1800
P150	13.08	Aug 7, 1995	INT	0.84	600
P155	13.52	Aug 7, 1995	INT	0.84	900
P165	13.40	Aug 8, 1995	INT	0.84	900
P166	13.79	Aug 8, 1995	INT	0.84	900
P309	16.80	Aug 7-8, 1995	INT	0.84	3000

Note: the exposure time for P27 is the sum of 4 individual exposures. This star is a spectroscopic binary.

with colors (B-V)>0.75, i.e. spectral type G0 and later, given by Prosser & Giampapa. We added to this sample one early M-type photometric member from Prosser (1993).

Our spectra contain not only the Li I λ6708 feature, but also Hα . The Hα emission excess is a fairly good indicator of chromospheric activity (Pasquini & Pallavicini 1991, Montes et al. 1995a), which in turn is connected to rotation via the dynamo mechanism. In the Pleiades cluster the fast rotators present both high Li abundance and high level of chromospheric activity (Soderblom et al. 1993, García López et al. 1994). Hence, there is a Li-activity connection induced by rotation. We have tested if such connection also holds for the IC 4665 stars.

2. Spectroscopic observations

All the programme stars, except P75, were observed at the 2.5m Isaac Newton telescope (INT) with the Intermediate Dispersion Spectrograph (IDS) during a four night run in August 1995. We used the 235mm camera, AgRed collimator, gratings R1200Y and H1800V and a TEK 1124x1124 CCD detector. For each star we give in Table 1 the Prosser (1993) number and V-magnitude, date of the observation, dispersion (resolution ∼ 2 pixels), and exposure time. One of the stars was observed with the 3.5m telescope at Calar Alto observatory, using the TWIN spectrograph, T06 grating in the red arm and a TEK chip.

Each spectrum was reduced by a standard procedure using IRAF[1], which included debias, flat field, optimal extraction and wavelength calibration using CuNe arc lamps. Fig. 1 displays the full range of the final spectra.

[1] IRAF is distributed by the National Optical Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

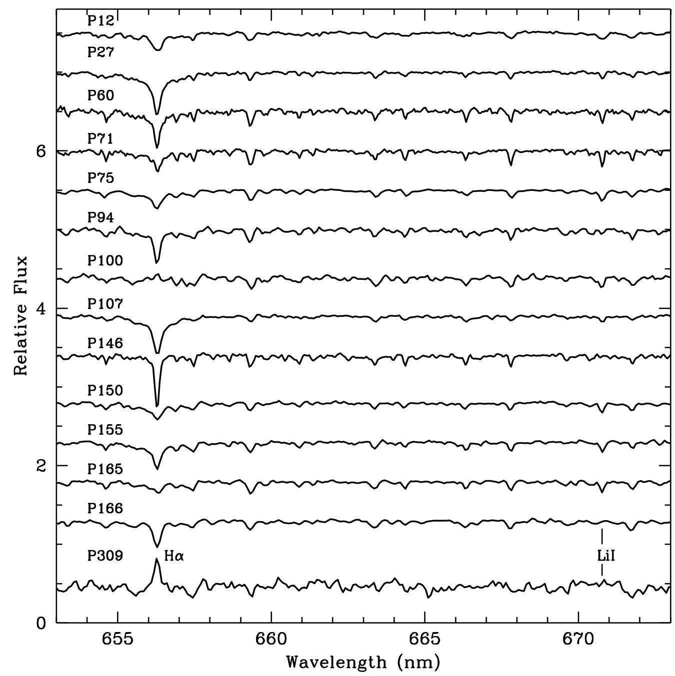

Fig. 1. Spectra of 14 late-type stars in the open cluster IC 4665. The positions of Hα and Li I λ6708 are marked.

3. Analysis

The Li abundances for our programme stars have been derived from the Li I λ6708 resonance line. We have measured the equivalent widths of the Li feature by direct integration and gaussian profile fitting. Both authors of this paper measured the equivalent width independently and we took the mean as the final value. Typically, the standard deviation of different measurements was ∼ 15 mÅ, which is the value that we took as error bar. We used NLTE curves of growth for the Li I line from Martín et al. (1994). The validity of these curves has been confirmed by the more recent work of Pavlenko et al. (1995). Effective temperatures for the IC 4665 stars were derived by two different methods: a calibration of B-V colour vs. T_{eff} (Arribas & Martinez Roger 1988), and a calibration of spectral type vs. T_{eff} (de Jager & Nieuwenhuijzen 1987). The B-V colours were taken from Prosser (1993) and they were corrected by the average cluster colour excess of E(B-V)=0.18. The spectral types were derived from comparison of our spectra with a battery of standards observed with the IDS (Montes et al. 1995b). We estimate that our spectral types are accurate to about half a spectral subclass. The temperature of P309 was estimated from the spectral type only, because the B-V calibration of Arribas & Martinez Roger did not include M-type stars.

The differences in the T_{eff} obtained from (B-V) and spectral type ranged from 30 to 310 K, with an average of 147 K. For the star P12 we found an anomalous large discrepancy between the colour and the spectral type. This star was classified by Prosser & Giampapa (1994) as G0V and they also gave a $v\sin i$ =10km s^{-1}. In contrast, we find a spectral type of K0V and a

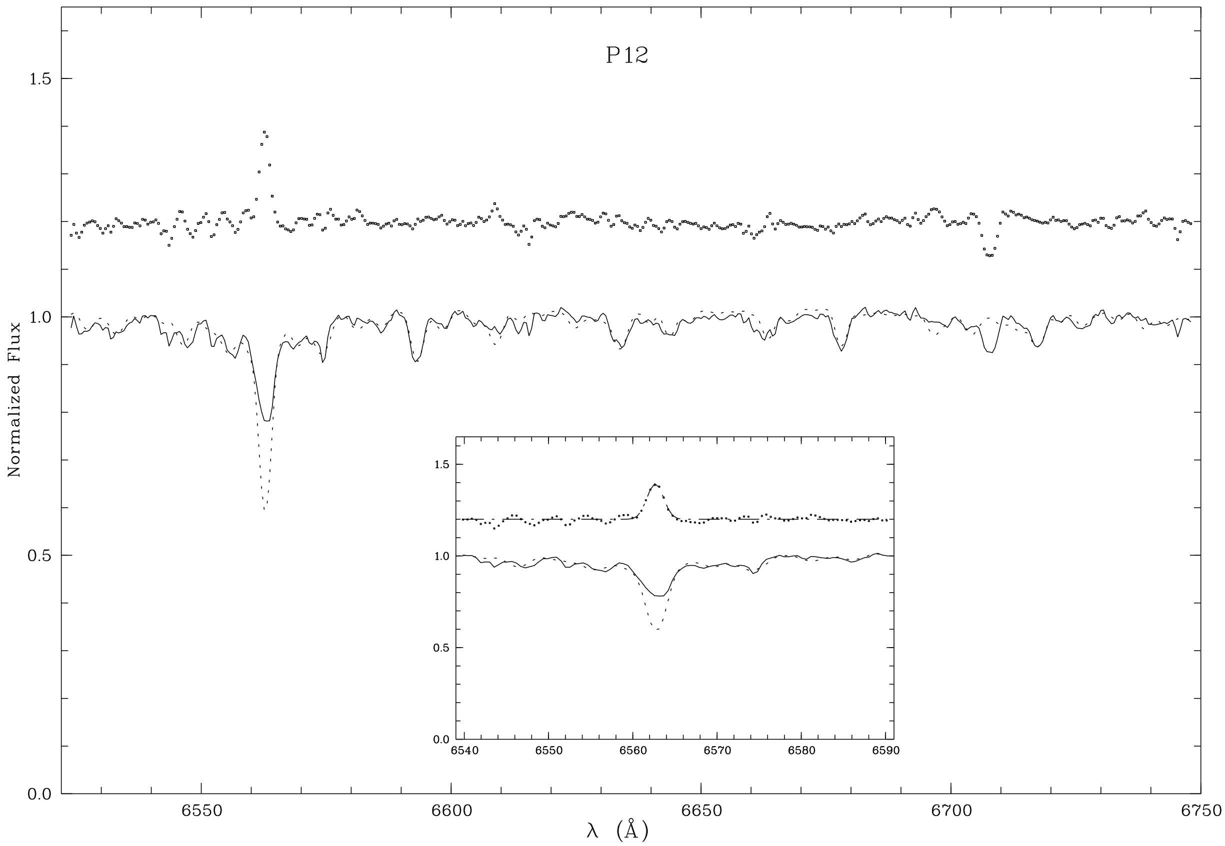

Fig. 2. One example of the spectral subtraction technique. The upper spectrum is the subtracted spectrum. The lower spectra are the observed IC 4665 star (solid line) and superimposed the reference spectrum (dashed line). In the small window we show a zoom of the Hα region. The upper spectra are the subtracted spectrum (dotted line) and a Gaussian profile fit (dotted-dashed line). The lower spectra are the IC 4665 star (solid line) and the standard (dashed line).

$v\sin i$ =70km s^{-1}. Our high $v\sin i$ is consistent with the short rotational period found by Allain et al. (1996) of 0.60 days. We believe that there is a problem with the photometry and spectroscopy given by Prosser (1993) and Prosser & Giampapa (1994) for this star. Hence, we chose to ignore the photometry and used only our spectral type for deriving its T_{eff} .

Taking into account the maximum uncertainties in T_{eff} (±150 K) and Li I equivalent widths (±15 mÅ), they lead to an error bar in the Li abundances of ± 0.3 dex. This is similar to previous works on Li abundances in other clusters (e.g. García López et al. 1994). In Table 2 we give the NLTE Li abundances of our programme stars in the customary scale of log N(H)=12.

The Hα emission excess was measured using the spectral subtraction technique. Reference spectra were constructed for all the IC 4665 stars using main-sequence standards of the same spectral type, which were rotationally broadened and doppler shifted to give as good match as possible. We subtracted the reference spectra from the IC 4665 spectra and obtained the chromospheric contribution of Hα . For more details on this technique see Montes et al. (1995a). In Fig. 2 we display one example (P12) of the spectral subtraction method. In the subtracted spectra Hα shows up in emission and Li I in absorption, whereas the other photospheric lines are canceled. The equivalent width of Hα in emission were converted to flux using: a calibration of B-V vs. surface flux in the Hα region (Hall 1996); and a calibration of V-R vs. surface flux in the Hα region (Pasquini & Pallavicini 1991). We obtained the B-V and V-R colours from our spectral types and from dereddening the B,V photometry of Prosser (1993). The results obtained from both colours agreed quite well, and the final values adopted are given in Table 2. We note that for P27 the radial velocity changed from night to night and we also noticed variations in the Hα emission from logF(Hα)=5.63 to log F(Hα)=5.86. In all our spectra of P27 the Li I equivalent widths were similar except in that with the largest Hα emission, which presented a shallower Li I feature (equivalent width 110 mÅ). We suggest that P27 deserves monitoring of radial velocity, Hα and Li variations.

4. Discussion

4.1. Chromospheric activity and Li depletion in IC 4665

We have found a large spread in Hα chromospheric fluxes and photospheric Li abundances among the IC 4665 stars. Fig. 3 displays the temperature dependence of Hα and Li. They show

Table 2. Hα fluxes and Li abundances of IC 4665 stars

Star	B-V	SpT.	T_{eff} (K)	$v\sin i$ (km s^{-1})	EW Hα (Å)	log F(Hα) (erg cm^{-2} s^{-1} $Å^{-1}$)	EW Li I (mÅ)	log N(Li) ±0.3 dex
P12	0.77	K0	5150*	70	0.475	6.36	270	2.9
P27	0.77	G0	5900	33	0.076	5.78	140	3.1
P60	0.88	G7	5440	13	0.261	6.20	215	3.0
P71	0.92	G8	5340	17	0.602	6.54	260	3.1
P75	0.89	G9	5345	16	0.592	6.51	320	3.3
P94	1.01	K0	5135	10	0.198	5.99	90	2.1
P100	1.06	K0	5070	21	1.184	6.72	277	2.8
P107	0.84	G1	5745	27	0.044	5.51	156	3.0
P146	1.12	K0	5000	<10	∼0.0		<40	<1.6
P150	0.86	G7	5470	25	0.721	6.65	235	3.1
P155	0.91	G7.5	5365	17	0.415	6.39	264	3.2
P165	0.90	G9	5330	40	0.794	6.63	253	3.1
P166	0.97	K0	5190	<10	0.328	6.20	<35	<1.4
P309	1.62	M1	3660*	<20	1.439	6.00	<170	<0.5

Note: * effective temperature derived only from the spectral type (see text for remarks on P12).

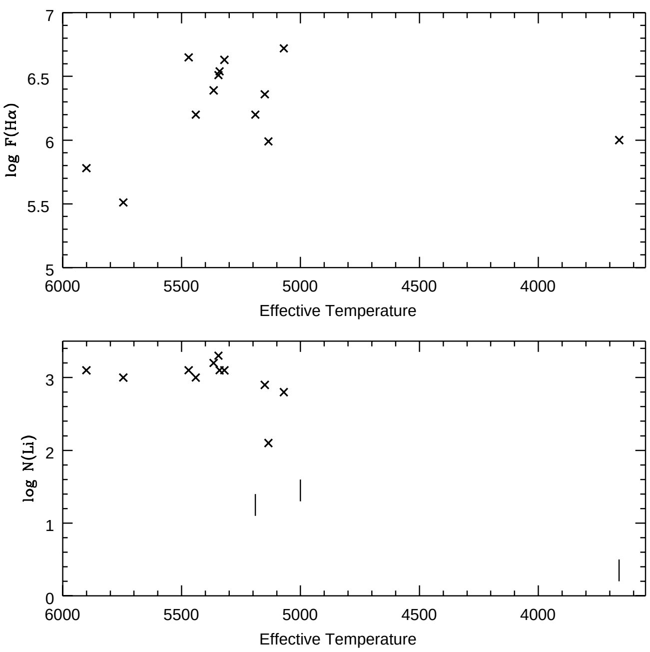

Fig. 3. Upper panel: Excess Hα emission fluxes for the IC 4665 stars versus T_{eff} . The star P146 is not plotted because it did not show a measurable Hα excess. Lower panel: Li abundances for the IC 4665 stars versus T_{eff} .

different behaviours: Hα emission tends to increase towards cooler T_{eff} , whereas Li decreases. Both effects can be qualitatively explained by the increase in the depth of the convection region towards cooler stars. Note that the spread both in Hα and Li appears to increase for T_{eff} <5500 K.

In order to place our results in a wider context we have compared the IC 4665 stars with the well-studied Pleiades cluster. Fig. 4 shows our Li abundances together with those of Soderblom et al. (1993) and García López et al. (1994) for the Pleiades. The patterns are very similar. Broadly speaking we can distinguish three groups of stars:

i) early G-type (6000 K–5300 K) stars have quite uniform abundances, with a mean value of log N(Li)=3.1, which is the same as in WTTS (Martín et al. 1994) and the interstellar medium. Hence, these stars have retained their initial Li abundance.

ii) late-G and early-K stars (5300K–4500K) present a broad range of abundances, which in the Pleiades was clearly shown to be related to chromospheric activity and rotation (Soderblom et al. 1993; García López et al. 1994). Such effect could be caused by the effect of rotation on the temperature at the base of the convection zone (Martín & Claret 1996). We only have six stars in this group: P12, P100 and P165 with high Li abundances and high Hα excesses, and P94, P146 and P166 with low abundances and low excesses. In Fig. 5, we have plotted the IC 4665 stars from this work, and the Pleiades stars from Soderblom et al. (1993) with T_{eff} in the range 5300K–4900K in a Li vs. Hα diagram. We converted our Hα fluxes to flux ratios ($R_{H\alpha}=F_{H\alpha}/\sigma T_{eff}^{\ 4}$) in order to compare with Soderblom et al. In the stars of both clusters there is a similar correlation of Li with Hα excess. The stars P146 and P166 have very small Hα excesses (we could not measure any excess in the first one and it is not included in Fig. 5) and we could not detect Li. The comparison with the Pleiades suggests that such Hα activity and Li are very unusual and it may indicate that these stars are in fact not cluster members. However, we hesitate to discard P146 and P166 as cluster members because their radial velocities match the cluster mean (Prosser & Giampapa 1994). We note that if these stars were non-members, the correlation between Li and Hα flux does not disappear, but the specimens with low Li and low Hα excess are reduced to only one (P94). Hence, it is important to find more low-mass IC 4665 members in which we can test better the Li-activity connection in this cluster.

Prosser & Giampapa (1994) and Allain et al. (1996) obtained v sin*i* and photometric rotation periods, respectively, for

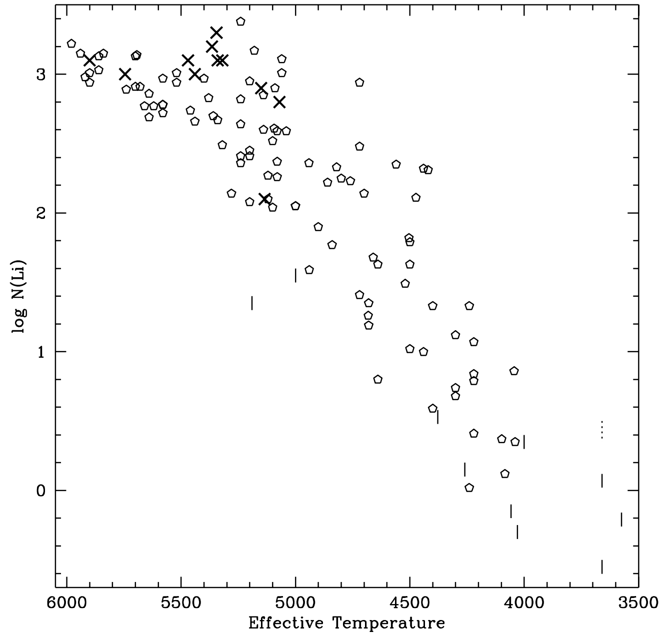

Fig. 4. Li abundances versus T_{eff} for stars in IC 4665 (diagonal crosses) and the Pleiades (empty pentagons). The four upper limits at $T_{eff} <$ 4000 K correspond to P309 (dotted trace) and 3 α Per stars observed by García López et al. (1994).

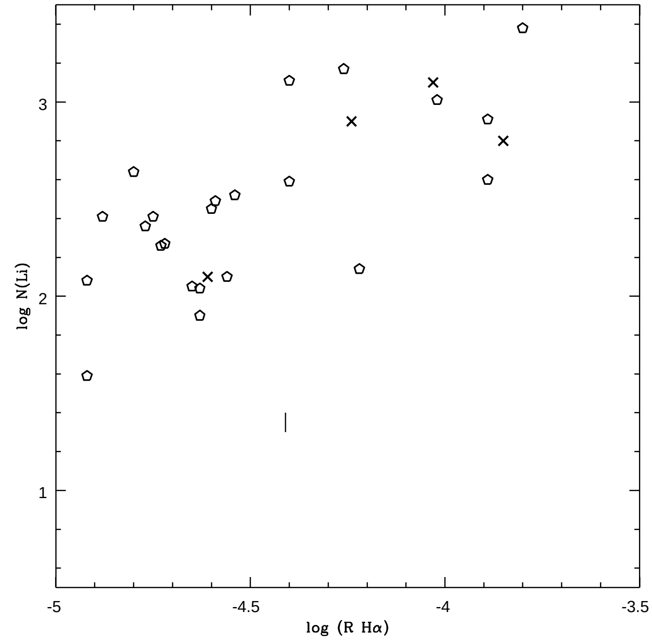

Fig. 5. Li abundances versus Hα excess emission ratios for stars in IC 4665 (diagonal crosses) and the Pleiades (empty pentagons) with T_{eff} in the range 5300 K – 4900 K.

several of our programme stars. The three stars with low Li and Hα excess (P94, P146 and P166) have vsin*i*≤10 km s^{-1}. Allain et al. could not detect any period in P94 and P146. On the other hand the three stars with high Li abundance and Hα excess have high vsin*i* (see Table 2). Interestingly, Allain et al. (1996) were able to derive rotation periods for P12 (0.6 days) and P100 (2.27 days). Therefore, there is a real difference between the equatorial velocities of these two stars of about a factor 5. The Hα emission level of P100 is a bit higher than that of P12, indicating that there is not a good one to one relationship between Hα and rotation, but both stars do have higher activity than the slow rotators (P94, P146, P166). The Li abundance of P12 is higher than that of P100, but the difference is only 0.1 dex which is within our error bars. With only these two stars it is not yet possible to test the models of Martín & Claret (1996), which predict that fast rotating stars deplete less Li than slow rotating stars during their PMS evolution.

iii) the late-K and early M stars (4500K–3500K) do not present the Li-activity-rotation connection in the αPer and Pleiades clusters (García López et al. 1994). We have only observed one M-type star in IC 4665, and we could not detect Li in it. The inferred upper limit to the Li abundance is shown in Figs. 3 and 4. Our result is consistent with the high efficiency of PMS Li depletion found for the stars of this group. The possibility that such property could be used for a fine dating of young open clusters is discussed in the following section.

4.2. The age of young clusters and the LL-clock

Mermilliod (1981) determined an age for IC 4665 of 36 Myr from empirical isochrone fitting of the upper main sequence, which is clearly younger than the ages he obtained for α Per (51 Myr) and the Pleiades (78 Myr). However, some of the stars used by Mermilliod have been shown to be binaries in later works, and Prosser (1993) revised the upper main-sequence fitting to yield an age of $\sim$ 50–70 Myr. Prosser concluded that IC 4665 is not younger than α Per and it might be as old as the Pleiades.

The distribution of Li abundances in the low-mass stars of IC 4665 and the Pleiades are quite similar (Fig. 4). However, this does not necessarily imply that both clusters have the same age. The distribution of Li is quite similar also in α Per (Balachandran, Lambert & Stauffer 1998, García López et al. 1994). With respect to Hα activity, in Fig. 6 we compare the IC 4665 stars with the Pleiades. The IC 4665 stars present the same level of Hα activity as the Pleiades.

Stauffer et al. (1989) gave Li I equivalent widths for 10 low-mass members of the IC 2391 cluster, but they did not derive Li abundances. This cluster is very interesting because according to Mermilliod (1981) it belongs to the same age group as IC 4665. We have applied the abundance analysis described in Sect. 3 to the IC 2391 stars. The effective temperatures were derived from the Arribas & Martinez-Roger relationship (1988) using the (B-V) colours given by Stauffer et al. (1989), dereddened by the mean E(B-V)=0.04 of the cluster. The Li abundances obtained are listed in Table 3.

The Li abundances of the IC 2391 stars fall within the range of abundances of the IC 4665 and Pleiades stars (Fig. 4). We

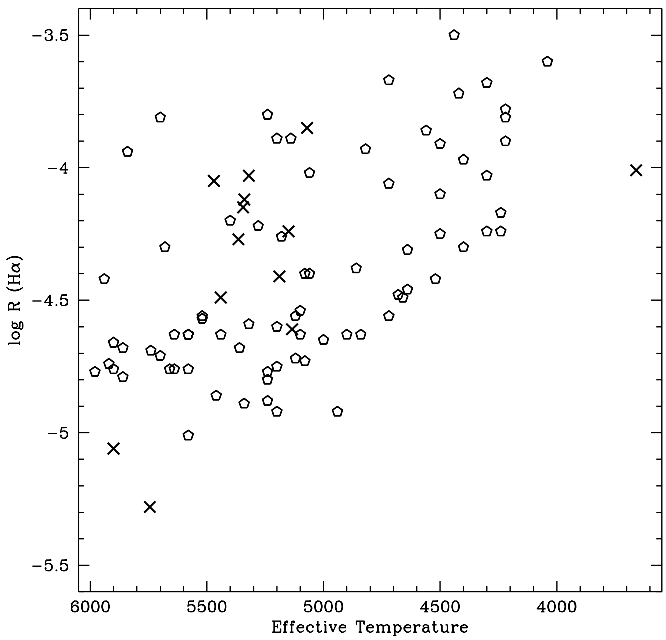

Fig. 6. Hα excess emission ratios for stars in IC 4665 (diagonal crosses) and the Pleiades (empty pentagons) versus T_{eff} .

Table 3. Li abundances for IC 2391 stars

Star	B-V	T_{eff} (K)	$v\sin i$ (km s^{-1})	EW Li I (Å)	log N(Li) ±0.3 dex
1	0.68	5685	34	0.16	3.0
2	0.57	6074	<15	0.14	3.2
3	1.00	4793	90	0.13	1.9
4	1.39	4023	<15	<0.05	<0.4
5	1.39	4023	150	<0.2	<1.2
6	0.84	5201	16	0.19	2.6
7	1.10	4568	<15	<0.05	<1.1
8	1.25	4269	18	0.09	1.0
9	1.25	4269	<15	0.10	1.0
10	1.44	3942	95	<0.1	<0.7

Note: the data was taken from Stauffer et al. (1989).

can also compare with the post T Tauri stars (PTTS) studied by Martín et al. (1992) and Martín (1993). The estimated ages of PTTS are 20–50 Myr, and the Li abundances for 9 PTTS are in the range log N(Li)=3.3 – 1.8, their T_{eff} ranging from 5900 K to 4400 K. The degree of Li depletion among the PTTS is similar to that among the IC 2391, IC 4665, α Per and the Pleiades stars, indicating that either the PTTS and the 4 open clusters share similar age distributions, or Li is not sensitive for ages in the range $\sim$ 20–100 Myr. The first interpretation would imply a rather large age spread within the low-mass population of open clusters. On the other hand, the strong correlation of Li with luminosity found by Martín et al. (1994) in WTTS, indicates that PMS Li burning is very efficient during a short timescale. It is conceivable that the observed pattern of Li abundances in PTTS and young clusters is formed quite rapidly through PMS convective mixing (timescale of a few Myr) at an age of $\sim$ 20 Myr. Theoretical models are qualitatively consistent with this scenario, because they predict a sudden drop in Li abundance when the bottom of the convection region reaches high enough temperature for Li burning, but as the star approaches the ZAMS, convection becomes shallower and Li depletion should slow down. However, it has been noted that theoretical models do not give yet a quantitative good description of the observed Li abundances among PMS stars (Martín et al. 1994, García López et al. 1994).

In Fig. 4, it can be seen that below T_{eff} 4000 K, Li has not been detected in any star of the α Per and IC 4665 clusters. The upper limits imply very strong Li depletions. However, as we move to lower masses, the internal temperatures diminish and we should reach a point where they are not high enough for Li burning. Hence, we should see Li again in the very low-mass cluster members. This effect has been proposed as a test for distinguishing between stars and brown dwarfs (Rebolo et al. 1992; Magazzù et al. 1993). Very recently, Li has been detected in the coolest known members of the Pleiades (Basri et al. 1996, Rebolo et al. 1996). For the age of the Pleiades (70-120 Myr), theoretical models predict that only brown dwarfs preserve lithium (e.g. Magazzù et al. 1993), but for younger ages the very low-mass stars also start to preserve it because they require a long time to contract. Thus, we expect that in clusters younger than the Pleiades, the reappearance of Li should be shifted to higher masses. Such an effect provides a precision clock for dating clusters. D'Antona & Mazzitelli (1994) suggested on the basis of their theoretical isochrones of Li depletion that low luminosity stars could be used for dating open clusters. They also noted that the Li depletion is quite sensitive to input physics of the models which have considerable uncertainties (opacities, convection). Hence, it may be difficult to use Li to assign absolute ages to open clusters, but relative ages will probably be safe.

What we call in this paper "LL-clock" stands for Lithium-Luminosity clock. It is based on the high efficiency of Li depletion for fully convective low luminosity objects. The age of a young cluster will be given by the most massive objects among the very low-mass members in which Li is seen to re-emerge, after having been efficiently depleted by higher mass cluster members. In the Pleiades the Li destruction–preservation borderline has been found at luminosity around log L=-2.9 $L_\odot$ (Basri et al. 1996) according to the Li detection in the object PPl 15. The traditional method for dating open clusters, i.e. upper main-sequence turn off fitting, says that αPer is younger by $\sim$20 Myr than the Pleiades (Mermilliod 1981). If PPl 15 were 20 Myr younger, it luminosity would be about 0.12 dex larger (D'Antona & Mazzitelli 1994), and it should be slightly hotter and have higher Li abundance. Zapatero-Osorio et al. (1996) have reported a negative Li detection in AP J0323+4853, which has a luminosity around log L=-2.6 $L_\odot$. This result does not rule out that αPer is younger than the Pleiades, but it shows how close the observations are to telling us very interesting things about the relative ages of the young clusters. In IC 4665, it will be a little more difficult to investigate the very low-luminosity members, simply because of its larger distance, but if it is indeed younger than the Pleiades, we expect that Li should re-appear at higher luminosities.

5. Conclusions

We have obtained high resolution spectra of 14 cool stars (G0–M1) in the open IC 4665 cluster. Excess Hα emission and Li abundances have been derived from the data. We find a large spread in both parameters. The dependence of Hα and Li with T_{eff} in IC 4665 seems similar to that in the Pleiades. Two IC 4665 stars (P146 and P166) with lower Hα emission and Li abundance than Pleiades stars of the same T_{eff} are suspected of not being cluster members, although their radial velocities do indicate membership. The Li abundances of IC 4665 stars support previous conclusions on PMS Li burning (Martín et al. 1994; García López et al. 1994): solar type stars experience little PMS Li depletion; late-G and early-K stars present a large spread of Li abundances (about 1 dex), which is related to activity and rotation in the sense that fast rotators have higher Li abundance and chromospheric emission; late-K and early-M stars experience very efficient Li depletion, which is larger than a factor of 100 for $T_{eff} \leq 4000$ K.

The distribution of Li abundances in the low-mass stars of several open clusters (IC 2391, IC 4665, α Per, Pleiades), and in post T Tauri stars, are rather similar. There can be two reasons for that: (a) the stars in different clusters and the PTTS span the same range of ages, and (b) Li and Hα are not precise age indicators between $\sim$ 20 and 100 Myr. We argue that relative ages of young clusters may be obtained in the near future using the "LL-clock". This would certainly help to clarify the evolution of Li and chromospheric activity during late PMS evolution.

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