

Rotation-induced lithium depletion of solar-type stars in open stellar clusters

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Abstract. We test the correlation between Li-abundance and rotation period for solar-type stars (spectral-type in G0–K0). The result is not unique. Stars in young open clusters (IC2391, IC2602, IC4665, α Per) show a clear correlation: the faster the stellar rotation the smaller the Li-depletion. For the Pleiades cluster this correlation is still present but weak. The use of inverse Rossby number does not change this result.

Key words: Stars: abundances – Stars: evolution – Stars: rotation

1. Introduction

There are observational indications that rapidly rotating stars preserve their lithium better than slowly rotating stars of the same mass (Balachandran et al., 1988, Soderblom et al., 1993, Jones et al., 1997, Krishnamurthi et al., 1998). This result was found by $v \sin i$ measurements as indicator for rotation. On the base of photometrically determined rotation periods (e.g., Prosser et al., 1993a; Prosser et al., 1993b; Allain et al., 1996; Krishnamurthi et al., 1998; Barnes et al., 1998) the question is discussed if and which kind of the rotation parameter might give the proper physical influence to lithium depletion in solar-type stars.

The theoretical background of the present study is the following. In solar-type stars the Li-burning becomes significant in view of the solar age at about 2.6 Mio K which temperature is realized at a depth denoted with R_0 in Fig. 1. So the lithium must be transported from the convection zone (with its bottom R_i) to this layer. There is a gap of about 20.000...40.000 km between R_i and R_0 (Fig. 1). The question is how the chemicals are crossing this gap. The first possibility is by overshooting convection (Ahrens et al. 1992; Blöcker et al. 1999) and the second one is by (highly) anisotropic turbulence stabilized by the radial temperature gradient (Zahn 1992, 1993; Vincent et al. 1996). In both cases the anisotropies are quite opposite and so does the influence of the basic stellar rotation. By Rüdiger et al. (1999) the rotational influence is computed for the case of

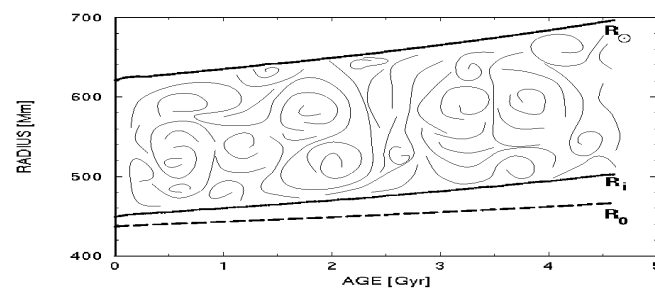


Fig. 1. The outer structure of the Sun during its main-sequence life. R_i limits the unstably stratified outer convection zone while R_0 displays the lithium burning zone with temperature of 2.6 Mio K. After Stix & Skaley (1990)

a turbulence field without any radial component. Only due to the Coriolis force the flow pattern obtains radial components in correlation with the horizontal intensities. The model calculations lead to the overall result that the Li-transport through the layer below the convection zone (the ‘tachocline’) is the *less* effective the *faster* the stellar rotation is.¹ The effect shall be probed here with sample of stars of the same age and the same chemical constitution but with different rotation rates, i.e. G-type stars of young open clusters.

2. Observational basis

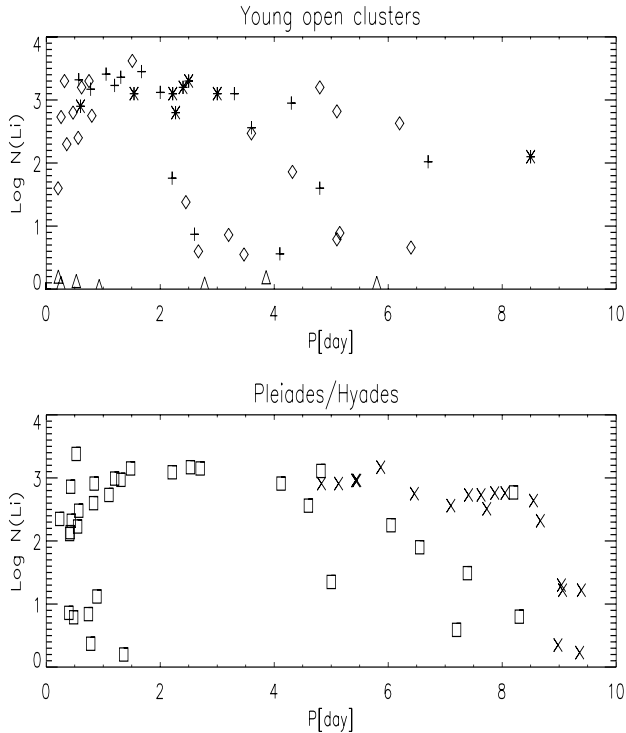
Table 1 gives the numbers of stars with known rotation period and Li-abundance available from the Prosser-Stauffer archive of stars in open clusters.

Of this sample we plot in Fig. 2 the lithium abundance as a function of rotation period P_{rot} (day) (the symbols refer to stars in different clusters; see caption). No definite correlation can be determined from this data set at all. However, a group of fast rotating stars in IC2391 and in Pleiades (Krishnamurthi et al., 1997) with small Lithium content is visible. We note the gap of rotation periods between 3 and 4 days for this sample in older clusters.

¹ due to the rotational quenching of the eddy diffusivity, see Boubnov & Golitsin 1995

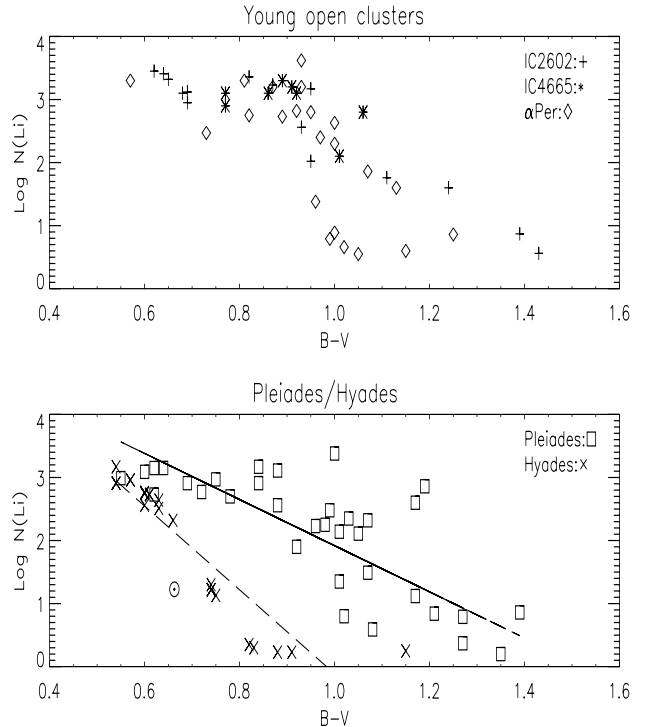
Table 1. Properties of open clusters. Last column gives the number of stars with known rotation period and Li-abundance

Cluster	Fe/H	E(B-V)	d(pc)	Age(My)	number
IC2602	0.0	0.04	150	30	15
IC4665	0.0	0.18	350	30	8
α Per	0.05	0.1	165	50	22
Pleiades	0.034	0.04	127	80 - 100	36
Hyades	0.127	0.0	42	600	23

**Fig. 2.** Li-abundance versus B-V for stars in open clusters with known rotation period and lithium abundance. Top: young open clusters (30 - 50 Myr), bottom: older clusters (100 - 600 Myr). Symbols used are: Top, IC2602 +, IC2391 Δ , IC4665 *, α Persei \diamond ; bottom, Pleiades \square , Hyades \times

In Fig. 3 we plot the relation between Li-abundance and color. It reproduces the two essential, well known facts, namely, *i.*) the dependence of lithium content of a star (surface value) on its color, i.e. on effective temperature and mass, respectively and *ii.*) the spread of Li-abundance, especially for colors of $B-V \sim 1$ in α Persei and in Pleiades stars. The spread at a given B-V indicates that mass, metallicity and age do not uniquely determine the surface lithium abundance. Therefore, an additional parameter must influence the evolution of stars (e.g., Pinsonneault, 1997). We note the red color of the IC2391 stars (besides SHJM6 all stars have $B-V > 1$). In Pleiades the group of fast rotators ($P_{\text{rot}} < 1.5$ days) with small Li-content ($\text{Log } N(\text{Li}) < 1$) have spectra between K4 - K8. We note the measured error of lithium abundance is approximately 0.1 dex.

In a second step we select from our sample solar-type stars, i.e. stars within the spectral range of G0 - K0. Known binaries

**Fig. 3.** Lithium versus B-V. Samples of stars and notation as in Fig. 2

have been discarded. For IC2391 only one star remains which we do not include in further discussion.

At 30 Myr, the G stars have just arrived on the Zero Age Main Sequence (Prosser, 1992; D'Antona & Mazzitelli, 1994). Their Li-abundance should be the result of PMS processes only.

Table 2 contains data of these stars according to their membership of the young open clusters IC2602, IC4665, α Per and of the older clusters, i.e. Pleiades and Hyades. Column 1 gives the V magnitude; column 2, the B-V color; column 3, measured rotation period; column 4 and column 5 the measured lithium abundance and $v \sin i$, respectively. Column 6 gives the name of the star. For the exact references of the values in Table 2 we refer to the Prosser-Stauffer archive.

With these data we plot Fig. 4 which shows the dependence of Li-abundance on rotation frequency $\Omega = 2\pi/P_{\text{rot}}$ of solar-type stars. The correlation for stars in young open clusters is evident: The faster the rotation the smaller the Li-depletion. In the Pleiades this effect is still present, but weak. Moreover, for Hyades the dependence is very strong. More observational information in this spectral range is needed, to decide whether it is a real evolutionary effect or not.

3. Rossby or not Rossby

The most important parameters in the interior of rotating stars are the inverse Rossby number and the depth of convection zone. The inverse Rossby number Ro^{-1} (the ratio of turnover time for convection to the rotation time for the star) determines the time-scale for Coriolis forces acting on the convectively streaming matter. An empirical relation for the turnover time

Table 2. Stars in open clusters with known P_{rot} and Li-abundance within the spectral range of G0 – K0. Spectra marked by * are derived from B–V values according to Allen, 1991; < indicates upper limits

V	B–V	P (days)	Log N(Li)	$v \sin i$ (km/s)	Sp	name
IC2602						
11.86	0.82	1.31	3.36	34	G8*	R59
10.60	0.95	6.7	2.02	10	G5	B134
10.52	0.65	0.57	3.31	93	G0	B102
11.07	0.68	3.3	3.10	12	G4*	R66
10.92	0.69	4.3	2.95	11	G4*	W85
10.89	0.64	1.05	3.41	49	G0	B120
10.70	0.62	1.67	3.45	30	G2*	R83
10.31	0.69	2.0	3.12	14	G4	B132
11.73	0.87	1.20	3.23	12	G9*	R95A
IC4665						
12.65	0.77	1.54	3.1	34	G0	P27
13.68	0.92	3.0	3.1	17	K0	P71
13.70	0.89	2.5	3.3	16	G8	P75
14.26	1.01	8.5	2.1	10	K0	P94
14.37	1.06	2.27	2.8	21	K0	P100
13.08	0.86	2.22	3.1	25	G5	P150
13.52	0.91	2.4	3.2	17	K0	P155
α Per						
11.69	0.79	0.60	3.05	87	G7*	HE520
11.43	0.73	3.6	2.47	15	G6*	HE601
11.66	0.82	19.3	2.75	61	G8*	HE622
10.59	0.57	0.75	3.30	71	g0*	HE684
12.08	0.87	4.8	2.89	<10	K0*	AP 97
12.06	0.81	0.32	3.30	160	G8*	AP118
12.38	0.89	0.26	2.73	170	K0*	APX158
Pleiades						
10.93	0.72	8.2	2.77	<7	G4	HII1512
10.73	0.69	4.12	2.91	<7	G1	HII152
9.57	0.62	2.70	3.15	13	G0	HII739
11.10	0.75	1.31	2.97	36	G8	HII1032
9.70	0.55	1.2	2.99	50	F9	HII727
10.13	0.62	1.1	2.73	45	F9	HII708
11.57	0.84	0.84	2.91	17	G8	HII345
12.18	1.00	0.524	3.38	68	G8	HII1136
12.69	1.19	0.428	2.86	94	K0	HII625
Hyades						
7.47	0.57	5.45	2.96		G0	VB31
7.85	0.61	7.41	2.73		G1	VA495
7.94	0.63	8.55	2.64		G1	VA748
8.12	0.66	8.67	2.32		G2	VA400
8.66	0.74	9.04	1.3		G8	VA692
8.63	0.74	9.39	1.22		G9	VB26
9.15	0.82	8.98	0.35		K0	VB21
8.96	0.83	11.38	-0.3		K0	VA547

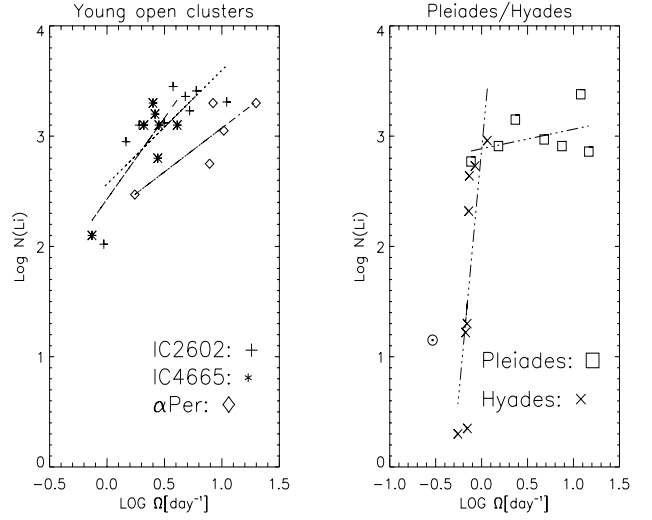


Fig. 4. Solar-type stars in open clusters with lithium abundance as a function of rotation frequency Ω (day^{-1}). Left: young clusters (30 – 50 Myr); right: cluster (100 – 600 Myr). Sun is indicated by solar symbol \odot

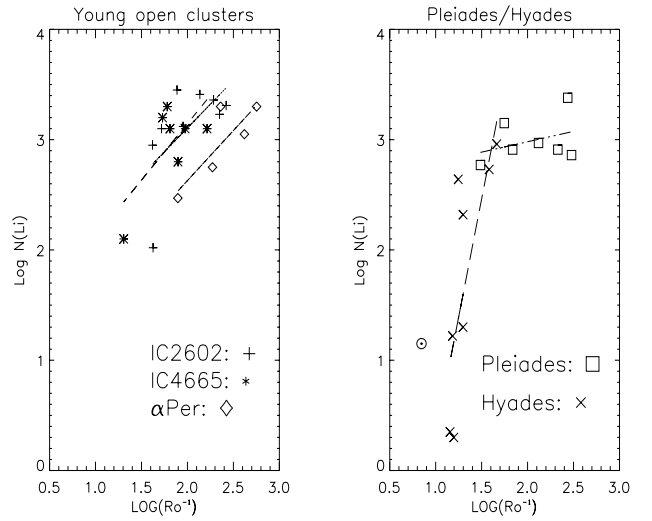


Fig. 5. Solar-type stars in open clusters with lithium abundance versus inverse Rossby number Ro^{-1} . Left: young clusters (30 – 50 Myr); right: older cluster (100 – 600 Myr). Sun is indicated by solar symbol \odot

τ_{corr} depending on the single parameter (B–V) was derived by Noyes et al. 1984,

$$\log \tau_{\text{corr}} = \begin{cases} 1.362 - 0.166x + 0.025x^3, & x > 0 \\ 1.362 - 0.14x, & x < 0, \end{cases}$$

where $x = 1 - (\text{B} - \text{V})$.

Using this relation we illustrate in Fig. 5 the dependency of Li-depletion on the inverse Rossby-number. The comparison with Fig. 4 does not give any remarkable difference. We conclude that the inverse Rossby number does not provide a proper parameter for a correlation of Li-abundance with rotation.

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