A&A 547, A106 (2012)
DOI: 10.1051/0004-6361/201118412

Astronomy & Astrophysics

Activity and the Li abundances in the FGK dwarfs⋆,⋆⋆

T. V. Mishenina[1,2], C. Soubiran[2], V. V. Kovtyukh[1], M. M. Katsova[3], and M. A. Livshits[4]

[1] Astronomical Observatory, Odessa National University, and Isaac Newton Institute of Chile, Odessa Branch, T.G. Shevchenko Park, 65014 Odessa, Ukraine
e-mail: tamar@deneb1.odessa.ua
[2] Université Bordeaux 1 – CNRS – Laboratoire d'Astrophysique de Bordeaux, UMR 5804, 33271 Floirac Cedex, France
e-mail: Caroline.Soubiran@obs.u-bordeaux1.fr
[3] Sternberg State Astronomical Institute, Lomonosov Moscow State University, 13, Universitetsky Av., 119991 Moscow, Russia
e-mail: maria@sai.msu.ru
[4] Pushkov Institute of Terrestrial Magnetism, Ionosphere, and Radio Wave Propagation of Russian Academy of Sciences (IZMIRAN), Troitsk, 142190 Moscow, Russia
e-mail: maliv@mail.ru

Received 7 November 2011 / Accepted 1 October 2012

ABSTRACT

Aims. The aim of the present study is to determine the Li abundances for a large set of the FGK dwarfs and to analyse the connections between the Li content, stellar parameters, and activity.

Methods. The atmospheric parameters, rotational velocities and the Li abundances were determined from a homogeneous collection of the echelle spectra with high resolution and a high signal-to-noise ratio. The rotational velocities $v \sin i$ were determined by calibrating the cross-correlation function. The effective temperatures $T_{\rm eff}$ were estimated by the line-depth ratio method. The surface gravities $\log g$ were computed by two methods: the iron ionization balance and the parallax. The LTE Li abundances were computed using synthetic spectra method. The behaviour of the Li abundance was examined in correlation with $T_{\rm eff}$, [Fe/H], as well as with $v \sin i$ and the level of activity in three stellar groups of the different temperature range.

Results. The stellar parameters and the Li abundances are presented for 150 slow rotating stars of the lower part of the main sequence. The studied stars show a decline in the Li abundance with decreasing temperature $T_{\rm eff}$ and a significant spread, which should be due to the difference of age of stars. The correlations between the Li abundances, rotational velocities $v \sin i$, and the level of the chromospheric activity were discovered for the stars with $6000 > T_{\rm eff} > 5700$ K, and it is tighter for the stars with $5700 > T_{\rm eff} > 5200$ K. The target stars with $T_{\rm eff} < 5200$ K do not show any correlation between $\log A$(Li) and $v \sin i$. The relationship between the chromospheric and coronal fluxes in active with detected Li as well as in less active stars gives a hint that there exist different conditions in the action of the dynamo mechanism in those stars.

Conclusions. We found that the Li-activity correlation is evident only in a restricted temperature range and the Li abundance spread seems to be present in a group of low chromospheric activity stars that also show a broad spread in the chromospheric vs. coronal activity.

Key words. stars: abundances – stars: activity – stars: late-type – stars: fundamental parameters – stars: rotation

1. Introduction

Li burns at temperatures of 2.5×10^6 K via α captures, which makes it a useful probe of the mixing in stars. The connection of the Li abundance with stellar activity has a long history (Herbig 1965; Pallavicini et al. 1987). It was soon realized that, like stellar activity, high Li abundance is found in young stars, although the Li abundance, by itself, is not sufficient to estimate the age of a star. Skumanich (1972) showed that both the chromospheric emission of the Ca II H and K lines and the rotational velocity decline as the square root of the age of stars (*the Skumanich law*). However, the Li abundance does not show a tight correlation with either (Duncan 1981; Duncan & Jones 1983; Soderblom et al. 1993a). Whether a tight relation exists between the Li abundance and the stellar mass, the spread, observed in the Li abundance owing to presence of spots on the star's surface (Soderblom et al. 1993a) or to the main-sequence (MS) depletion (Thorburn et al. 1993) is still an open question.

A spread of the Li abundance in the open cluster (OC) stars and binaries with the same mass and the Li depletion (Martin et al. 2002; King 2010), as well as higher Li abundance of rapidly rotating dwarfs (Cutispoto et al. 2003), are not corroborated by the theoretical predictions of the near-solar masses, in which the convection was only considered as a mixing mechanism (Randich 2010), and fast rotation intensifies the mixing process that leads to the Li destruction (e.g. Charbonnel et al. 1992).

The observation of the rotation and chromospheric emission in the F, G, and K dwarfs of the OC stars allowed a reliable age-rotation relationship to be established that is one of the bases of the method of estimating age depending on the level of activity, so-called gyrochronology (Soderblom et al. 1993b,c; Barnes 2003). That paradigm can serve as a basis for understanding the relationship of activity, the light elements content and rotation (Barnes 2003).

⋆ Based on the spectra collected with the ELODIE spectrograph using the 1.93-m telescope at the Observatoire de Haute Provence (CNRS, France).

⋆⋆ Full Table 3 is only available at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via http://cdsarc.u-strasbg.fr/viz-bin/qcat?J/A+A/547/A106

Analysis of the mechanisms that provided the Li overabundance was carried out for the stars of the RS CVn – type binaries with spots and a significant rate of rotation (Pallavicini et al. 1992; Pallavicini et al. 1993; Randich et al. 1993). In doing so, the moderate excess (overabundance) of Li compared to normal stars of the same spectral types was confirmed, and the correlation with the rotation parameter and the chromospheric fluxes was not discovered. The possibility of the Li enrichment, connected to the presence of spots and the production of additional Li in areas (Pallavicini et al. 1992), was not eliminated. The fresh isotopes of Li can be produced by the nuclear interactions of ions, accelerated at the surface of the flaring stars (see e.g. Canal et al. 1975; Livshits 1997; Tatischeff & Thibaud 2007). Only one observational result that attests to the Li growth in the stellar area was obtained by Montes & Ramsey (1998).

The chromospheric and coronal activities of late-type stars have been studied more in past decades (Guedel 2004; Guinnan & Enge 2009; Katsova & Livshits 2011). Katsova & Livshits (2011) find that the ideas about the gyrochronology (Mamajek & Hillenbrand 2008) is valid for the stars that are hotter than the Sun (with $T_{\rm eff} > T_{\rm eff\odot}$), but for the late-type dwarfs stars (with $T_{\rm eff} < T_{\rm eff\odot}$), whose convection zones are thicker than the solar ones, the activity evolves in time apparently according to the other law. Studing those stars that are both hotter and cooler than the Sun, can clarify the understanding of the features and causes of activity of the FGK dwarfs, as well as the real relation between the enhancement of Li and activity.

In this study we aim at finding some observational evidence of the Li abundance – activity behaviour in the stars in the lower part of the MS, that are the slow rotating dwarfs with masses close to the solar one.

The paper is divided as follows. The observational data are described in Sect. 2; Sect. 3 is devoted to the description of the levels of activity of the investigated stars; the methods and errors in determining of the rotational velocities, atmospheric parameters and the Li abundances are presented in Sects. 4–6, respectively. In Sect. 7, the Li abundance behaviour is considered in relation with the stellar and activity parameters. Conclusions are drawn in Sect. 8.

2. Observations and the spectral processing

The spectra of 150 stars were obtained using the 1.93 m telescope at the Observatoire de Haute-Provence (OHP, France), equipped with the échelle type spectrograph ELODIE (Barrane et al. 1996) which provides a resolving power of $R = 42\,000$. Most of the target stars, 126 stars on the lower part of the MS that are examined in the present study, were taken from our previous paper Mishenina et al. (2008, M08). Some stars from M08 were eliminated from the analysis because it was impossible to estimate the Li abundances owing to distortions of the spectra in the Li line region. A set of 24 stars was added with spectra that were previously analysed by Mishenina et al. (2004) or retrieved from the ELODIE archive (Moultaka et al. 2004). All 150 spectra were processed homogeneously using the same methods.

The extraction of the 1D spectra and measurement of the radial velocities were performed with the standard on-line ELODIE reduction software, while the deblazing and removal of cosmic particles were carried out following Katz et al. (1998). Further processing of spectra (the continuous spectrum level set up and measurement of the equivalent widths) was conducted using the DECH20 software package (Galazutdinov 1992). Figure 1 shows the Li region in the spectra for some target stars.

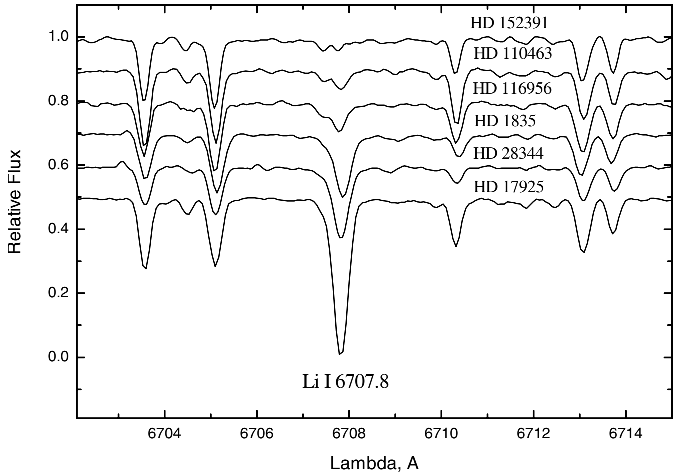

Fig. 1. The spectra in the Li 6707 Å line region for some of the target stars.

Table 1. Comparison of the $\log R'_{\rm HK}$ obtained by Wright et al. (2004) and from other sources.

$\Delta\log R'_{\rm HK}$	σ	N	Sources
0.00	±0.09	6	Henry et al. (1996)
0.01	±0.04	7	Baliunas et al. (1995)
–0.01	±0.07	7	Hall et al. (2007)

3. Levels of activity of the investigated stars

In M08, we investigated the difference between the elemental abundances in active and inactive stars. We labelled as active those stars of the BY Dra type, RS CnV type, and flare Fl stars according to SIMBAD. We also classified six variable stars as active that showed evidence of the chromospheric activity in their Ca II and H_α lines (see details in M08). In the present study, we also considered active those with a high level of activity, as discussed below.

As an indicator of the level of the chromospheric activity we examined the corresponding index $\log R'_{\rm HK}$ that measures the chromospheric emission in the cores of the broad photospheric Ca II H and K absorption lines, normalized to the underlying photospheric spectrum. For a part of the target stars with $T_{\rm eff} >$ 4800 K, we found the $\log R'_{\rm HK}$ values in Wright et al. (2004). We also used the data from the studies by Henri et al. (1996); Hall et al. (2007); Baliunas et al. (1995); and Maldonado et al.(2010). A total of 84 different stars were retrieved from those catalogues. The values of $\log R'_{\rm HK}$ by Wright et al. (2004) are compared to those from different studies (Table 1), and agreement is good. For some stars where the $\log R'_{\rm HK}$ index was not detected, we determined it on the base of the correlation between the chromospheric and the X-ray (Mamajek & Hillenbrand 2008). The X-ray was taken from the ROSAT All-Sky Survey (Voges et al. 1999).

On having applied this index, it was necessary for us to pick out its value, corresponding to the "section boundary" between active and inactive stars. It should be noted that the values of indices themselves differ from each other in various studies. The discussion for some of these stars can be seen in the appendix.

We accepted that the transition between active and inactive stars occurs at $\log R'_{\rm HK} \sim -4.75$. As indicated by Lovis et al. (2011) "this value corresponds to active stars according to the

Table 2. Comparison of our $v \sin i$ values with those of other authors.

$\Delta v \sin i$	σ	n	Source
–0.15	±1.33	83	Nordström et al. (2004)
–0.37	±1.18	67	Valenti & Fisher (2005)
–0.70	±2.00	26	Tokovinin (1992)
–0.29	±0.71	25	Fuhrmann (2008)
0.13	±0.96	14	Benz & Mayor (1984)
–0.56	±0.67	12	Gaidos et al. (2000)

Notes. The mean difference and standard deviation are presented.

limit given by the Vaughan-Preston gap (Vaughan & Preston 1980)". Moreover, a close value of $\log R'_{\rm HK} \sim -4.80$ was declared in the study by Jenkins et al. (2011) and Katsova & Livshits (2011).

4. Rotational velocities

We measured the rotational velocities ($v \sin i$) of the target stars with a relation calibrated by Queloz et al. (1998), giving $v \sin i$ as a function of σRV, the standard deviation of the ELODIE cross-correlation function, approximated by the Gaussian. The relation is the following:

$$v \sin i = 1.90 \sqrt{\sigma_{\rm RV}^2 - \sigma_0^2}.$$

The parameter σ_0 represents the mean intrinsic width for the non-rotating stars. It was calibrated by Queloz et al. (1998) as a function of $(B - V)$:

$$\sigma_0 = 0.27(B - V)^2 + 4.51.$$

This $v \sin i$ calibration is valid for the stars in the colour range $0.7 \leq B - V \leq 1.4$, with slow and moderate rotation rates ($\leq$40 km s^{-1}) and the solar metallicities that are consistent with our stars.

We compared our values of $v \sin i$ with the results of determinations by other authors (Table 2). The comparison of our $v \sin i$ determinations with six other studies shows good compliance. The low values of $v \sin i$ are the upper limits of the projection of the rotational velocity definition. The obtained values of $v \sin i$ are given in Table 3.

5. Atmospheric parameters

We defined parameters ($T_{\rm eff}$, $\log g$, [Fe/H]) just for several newly included stars and for the others we used the determinations by Mishenina et al. (2004) and M08. The effective temperatures $T_{\rm eff}$ were estimated by the line-depth ratio method (Kovtyukh et al. 2004). The surface gravity $\log g$ was computed by two methods: the iron ionization balance $\log g_{\rm IE}$ and the parallax $\log g_{\rm P}$. The results of applying of those two methods are in good compliance (M08). For cooler stars, which are short in the Fe II lines, the parallax was the only method used. The microturbulent velocity $V_{\rm t}$ was derived by considering that the iron abundance $\log A$(Fe), obtained from the given Fe I line, is not correlated with the equivalent width (EW) of that line. The adopted metallicity [Fe/H] is the iron abundance, which was determined from the Fe I lines.

The comparison of the obtained atmospheric parameters with those by the other authors is given in Table 4. As is evident, there is no significant difference between various determinations. The errors of the obtained temperature determinations are given for each star, once determined by the line-depth ratio method. For $\log g$, $V_{\rm t}$, and [Fe/H], we estimated the errors to be 0.2 dex, 0.2 dex, and 0.05 dex, respectively.

6. Determination of the Li abundance

We used the grid of the stellar atmosphere models under the overshooting approximation from Kurucz (1993) to compute the abundances of Li and metallicity [Fe/H]. The Li abundances in the investigated stars were obtained by fitting the observational profiles to the synthetic spectra that were computed by the STARSP LTE spectral synthesis code, developed by Tsymbal (1996). Considering the wide temperature and metallicity ranges of the target stars, we made every effort to compile the full list of the atomic and molecular lines close to the ^{7}Li 6707 Å line (Mishenina & Tsymbal 1997). Calculating the synthetic spectra, we used the values of vsini, obtained with the relation calibrated by Queloz et al. (1998) described above. The stellar parameters and the Li abundances, measured in the present study, as well as the basic stellar characteristics are presented in Table 3.

Table 5 shows the example of three stars with different parameters: the error determination for some typical models of the investigated stars, for strong lines with EW_1 = 100 mÅ and for weak lines with EW_2 = 5 mÅ with $\Delta T_{\rm eff}$ = +100 K (Col. 1); $\Delta \log g = -0.2$ (Col. 2); $\Delta V_{\rm t}$ = +0.2 km s^{-1} (Col. 3); ΔEW_1 = ±3 mÅ (Col. 4); and ΔEW_1 = ±2 mÅ (Col. 5). The total error is given in Col. 6. As seen in Table 5, the total uncertainty grows for the stars with decreasing temperatures and depends on the EW lines. It reaches 0.10–0.14 dex in the abundance determination for strong lines (near 100 mÅ) and 0.18–0.20 dex for weak lines (near 5 mÅ).

The comparison of the stellar parameters and the Li abundance with the results by other authors is given in Table 6. In Table 7 we compared our Li abundances with those in some papers, which have only one common star with our work. The parameters and the Li abundance, determined by us, are mainly in good compliance with the determinations of other authors. The comparison was made for the precise determinations of the Li content, but not for the estimations of the upper limits of the Li abundance. As marked in the study by Lubin et al. (2010), which collected the determinations of the Li abundance, made in thirty studies by different authors and for various objects, for $\log A$(Li) > 1.5 there is a relatively small dispersion in the Li abundance detections among various measurement programmes, while the scattering increases for lower $\log A$(Li). The difference in $\log A$(Li) is about 0.5–1 dex.

7. Lithium, stellar parameters, and activity

Our target stars have been selected as the stars belonging to the lower part of the MS upon photometric criterion ($M_v - (B - V)$), where $M_v = V + 5 + 2.5 \log \pi$ (M08). Figure 2 shows the positions of the investigated stars at the luminosity $\log L/L_\odot$ against the effective temperature $\log T_{\rm eff}$ diagram where $\log L/L_\odot = 0.4(4.75 - M_{\rm bol})$, and $M_{\rm bol} = M_v + {\rm BC}$ (the bolometric corrections BC were taken from Flower 1996) and the evolutionary tracks by Girardi et al. 2000. Those stars are the FGK spectral type ones, and as can be seen from Fig. 2, they are almost evenly distributed over the effective temperature and have masses of about the solar one (from 0.7 to 1.1 $M_\odot$). They have the average value of gravity $\langle \log g \rangle$ equal to 4.45 ± 0.16 and metallicity $\langle$[Fe/H]$\rangle$ = −0.01 ± 0.17. The rotational velocities of the

Table 3. Stellar parameters, determined in the present study.

HD	$T_{\rm eff}$	log *g*(1)	log *g*(2)	[Fe/H]	*v* sin *i*	Object type	$R_{\rm x}$	log $R'_{\rm HK}$	Ref	log *A*(Li)	Class
166	5514	4.6	4.6	0.16	4.0	BY	–4.31	–4.33		2.24	A
1835	5790	4.5	...	0.13	6.51	BY	–4.58	–4.44	W04	2.45	A
3651	5277	4.5	4.5	0.15	0.0	V	–6.07	–5.02	W04	<–0.52	wA
4256	5020	4.3	4.3	0.08	1.5	...	...	...		<–0.40	...
4628	4905	4.6	...	–0.21	1.5	...	–5.93	–4.85	H96, B95	<–0.45	wA
4635	5103	4.4	4.4	0.07	1.4	...	...	–4.67	W04	<0.15	A
4913	4342	4.4	...	0.05	2.15	...	...	...		<–0.90	...
6660	4759	4.6	...	0.08	2.5	...	...	...		<–0.50	...
7590	5962	4.4	4.4	–0.10	6.7	BY	–4.69	–4.53	W04	2.73	A
7924	5165	4.4	4.4	–0.22	1.1	...	–5.71	–4.83	W04	<–0.30	wA
...	...	...	...	...	...	...	...	...	...	...	...

Notes. log *g*(1): spectroscopic, log *g*(2): astrometric, object type from SIMBAD, Rx adopted from the ROSAT catalogues or estimated from the ROSAT archive data, indices log $R'_{\rm HK}$ retrieved from different sources, the measured Li abundance, and the class of activity. The log $R'_{\rm HK}$ values, taken from Wright et al. (2004) are marked by W04; from Henri et al. (1996) – marked by H96; from Hall et al. (2007) – by H07; from Baliunas et al. (1995) – by B95, from Maldonado et al. (2010) – by M10. The stars with weak levels of the solar-type activity are marked by wA; the stars with high levels of the solar-type activity are marked by A in the last column.

Table 4. Comparison of atmospheric parameters obtained by us with those by other authors.

$\Delta T_{\rm eff}$	Δlog *g*	Δ[Fe/H]	*n*	Source
16 ± 68			32	Masana et al. (2006)
–8 ± 63	–0.14 ± 0.18	–0.03 ± 0.08	67	Valenti & Fisher (2005)
42 ± 36	–0.07 ± 0.15	0.00 ± 0.05	26	Fuhrmann (2008)
1 ± 73	–0.01 ± 0.17	–0.03 ± 0.04	14	Gaidos & Gonzalez (2002)

Table 5. Influence of stellar parameters on Li abundance determination.

Parameter deviations					Total error	
$\Delta T_{\rm eff}$ –100 K	Δlog *g* –0.2	$\Delta V_{\rm t}$ +0.2	*EW* = 100 mÅ +3 mÅ	*EW* = 5 mÅ +2 mÅ	strong lines	weak lines
$T_{\rm eff}$ = 5800, log *g* = 4.5, $V_{\rm t}$ = 1.0 km s^{-1}, [Fe/H] = 0.0						
0.095	0.001	0.009	0.03	0.15	0.10	0.18
$T_{\rm eff}$ = 5000, log *g* = 4.5, $V_{\rm t}$ = 1.0 km s^{-1}, [Fe/H] = 0.0						
0.113	0.003	0.006	0.03	0.15	0.12	0.19
$T_{\rm eff}$ = 4600, log *g* = 4.5, $V_{\rm t}$ = 1.0 km s^{-1}, [Fe/H] = 0.0						
0.141	0.000	0.008	0.03	0.15	0.14	0.20

Table 6. Comparison of atmospheric parameters and Li abundance with those obtained by other authors.

$\Delta T_{\rm eff}$	Δlog *g*	Δ[Fe/H]	*A*(Li)	*n*	Source
67 ± 137	0.23 ± 0.11	0.11 ± 0.08	–0.01 ± 0.10	3	Chen et al. (2001)
76 ± 69			0.09 ± 0.14	3	Favata et al. (1997)
29 ± 67	0.06 ± 0.17	0.03 ± 0.06	–0.08 ± 0.12	10	Takeda et al. (2005, 2007)
24 ± 51	0.11 ± 0.15	0.04 ± 0.09	0.00 ± 0.04	5	Luck & Heiter (2006)

investigated stars generally do not exceed 6 km s^{-1} (Fig. 3, upper panel). The X-ray flux distribution has just one peak and the average value equals –4.58 ± 0.58; however, the distribution of the intensities of the H and K Ca ii emission lines in the chromospheres has two peaks that are separated by value log $R'_{\rm HK}$ = –4.75 (Fig. 3, bottom panel), which correspond to the values adopted by us (Sect. 3). Comparison of this histogram with similar distributions for active late-type stars (see, for instance, Katsova & Livshits 2011) shows that our set of stars is characterized by relatively moref stars with the higher activity.

The Li is detected in 43 stars among 69 stars with a high level of the chromospheric activity, while it is detected in ten stars among 31 dwarfs with weak level of the solar-type activity, i.e. in about 62% and 31%, respectively. We have confirmed our previous result (M08) that the frequency of stars with the observed Li abundance is higher in active stars.

7.1. *Lithium abundance behaviour in relation to $T_{\rm eff}$ and metallicity*

The obtained Li abundances log *A*(Li) are presented as a function of the effective temperature $T_{\rm eff}$ in Fig. 4. Our set of stars showed a typical decrease of the Li abundance with decreasing temperature as predicted by the theoretical calculations (e.g.

Table 7. Comparison of the parameters and the Li abundance for some stars

HD	$T_{\rm eff}$	$\log g$	$\log A$(Li)	
17925	5225	4.56	2.68	this work
	5235	4.66	2.82	Takeda et al. (2005)
	5012	4.60	2.45	Christian et al. (2005)
30495	5820	4.40	2.35	this work
	5880	4.67	2.45	Israelian et al. (2004)
190406	5905	4.30	2.28	this work
	5797	4.38	2.26	Chen & Zhao (2006)
219623	5949	4.20	2.60	this work
	6103	4.18	2.76	Takeda et al. (2005)
	6130	4.21	2.68	Lambert et al. (1991)

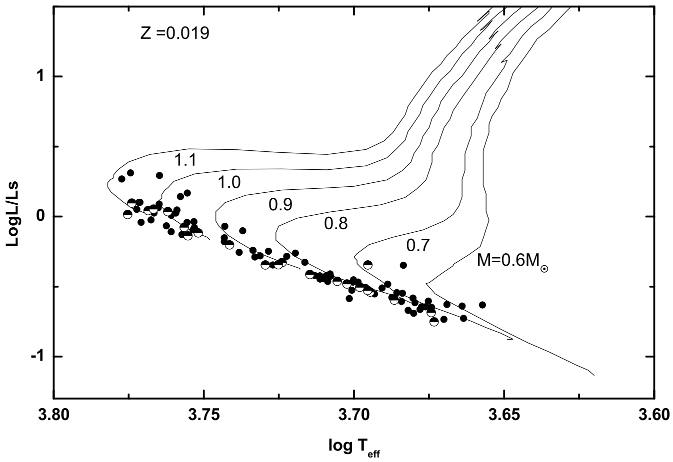

Fig. 2. Position of our target stars in the $\log L/L_{\odot}$ vs. $\log T_{\rm eff}$ diagram. Evolutionary tracks were taken from Girardi et al. (2000), the stars of the BY Dra types are marked as semi-full circles, the other stars as full circles.

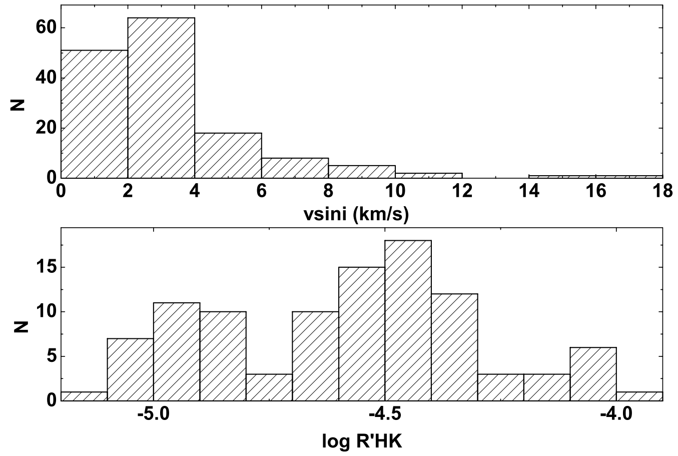

Fig. 3. The distribution of $v \sin i$ and $\log R'_{\rm HK}$ of our target stars.

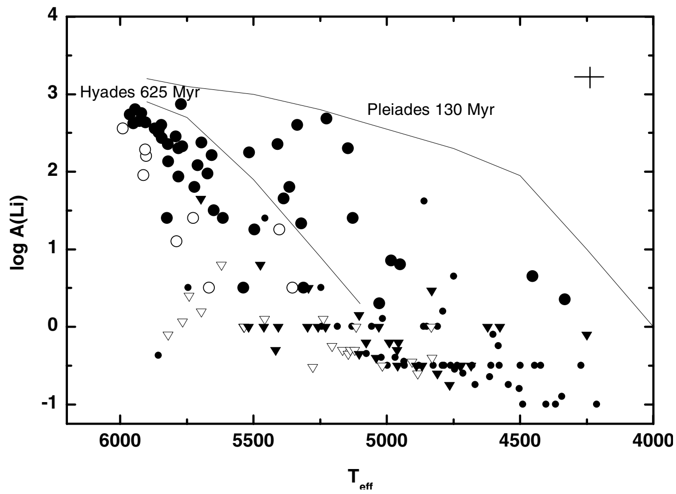

Fig. 4. Lithium abundances vs. $T_{\rm eff}$. The medium trend of the Pleiades and the Hyades is represented according to Soderblom et al. (1993a) and Thorburn et al. (1993), respectively. The stars with a high level of the chromospheric activity ($\log R'_{\rm HK} > -4.75$) are marked as full circles, those with a weak level of activity ($\log R'_{\rm HK} < -4.75$) as open circles. Triangles denote the upper limits of the Li determinations. The stars, for which $\log R'_{\rm HK}$ are not defined, are marked as small full circles.

D'Antona & Mazzitelli 1997), but with a rather wide spread. The active stars have higher values for the Li abundance than the usual dwarfs at any given temperature.

The excess of Li may be explained, in particular, by the production of additional Li in the flares. To refine that assumption, it is necessary to study the isotopic ratio ^{6}Li/^{7}Li, which requires spectra with resolution better than 100 000 and a signal-to-noise ratio greater than 400. That is beyond the scope of the present study.

This spread is unlikely owing to the difference in metallicity, because Fig. 5 with $\log A$(Li) vs. [Fe/H] shows evidence of the fairly compact distribution of metallicity around the solar value for active stars.

Then, we compared the Li abundance behaviour with "the middle course of the Li trend" for several OCs of different ages (in Fig. 3 the trends are given schematically). We can see in Fig. 3, the Li abundance spread is due to different ages of stars. Younger stars have higher Li abundance, but, at the same time, they are actually active stars.

7.2. Relationship between the Li abundance, rotation, and the chromospheric activity index

Below we consider the dependencies of the Li abundance on other parameters, including the activity indices, for the stars of three different temperature ranges: the first group with $6000 > T_{\rm eff} > 5700$, the second group with $5700 > T_{\rm eff} > 5200$, and the third group with $T_{\rm eff} < 5200$ K.

Those dependencies are quite clearly expressed for the first two groups of stars: both the Li abundance and the chromospheric activity grow for the faster rotators. The values of $\log A$(Li) are higher for the solar-type stars than for the stars cooler than the Sun (i.e. the late-type G stars). The spread of these parameters in Figs. 6a, b and 7a, b is somewhat greater for the first group of stars than for the second one.

Those results can be seen more evidently we compare the Li abundance with the chromospheric activity (Fig. 8). It is also clear that the $\log A$(Li) values are greater for the stars in the first group than in the second one. The correlation coefficient is 0.64 for the solar-type stars, and 0.77 for the stars cooler than the Sun. The spread of values of $\log A$(Li) is less for the stars of the second group

For a few stars with $T_{\rm eff}$ lower than 5200 K, a detectable value of the Li abundance was obtained. Those stars (see Fig. 6c) demonstrate the absence of the correlation practically between $\log A$(Li) and $v \sin i$ and there are some outliers with high

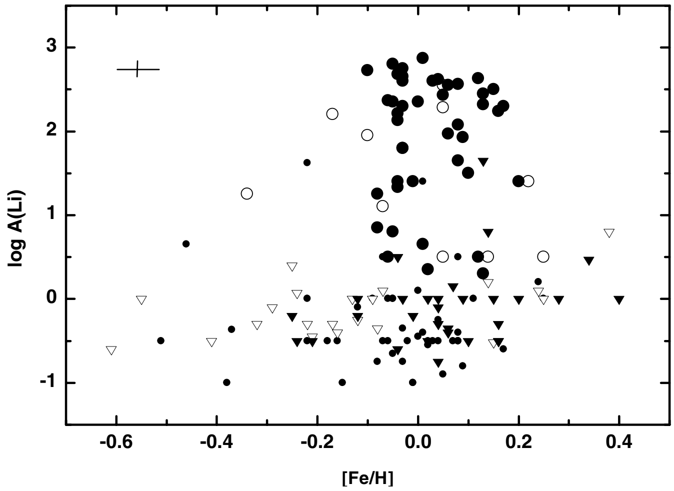

Fig. 5. The Li abundances vs. [Fe/H], the notation is the same as in Fig. 4.

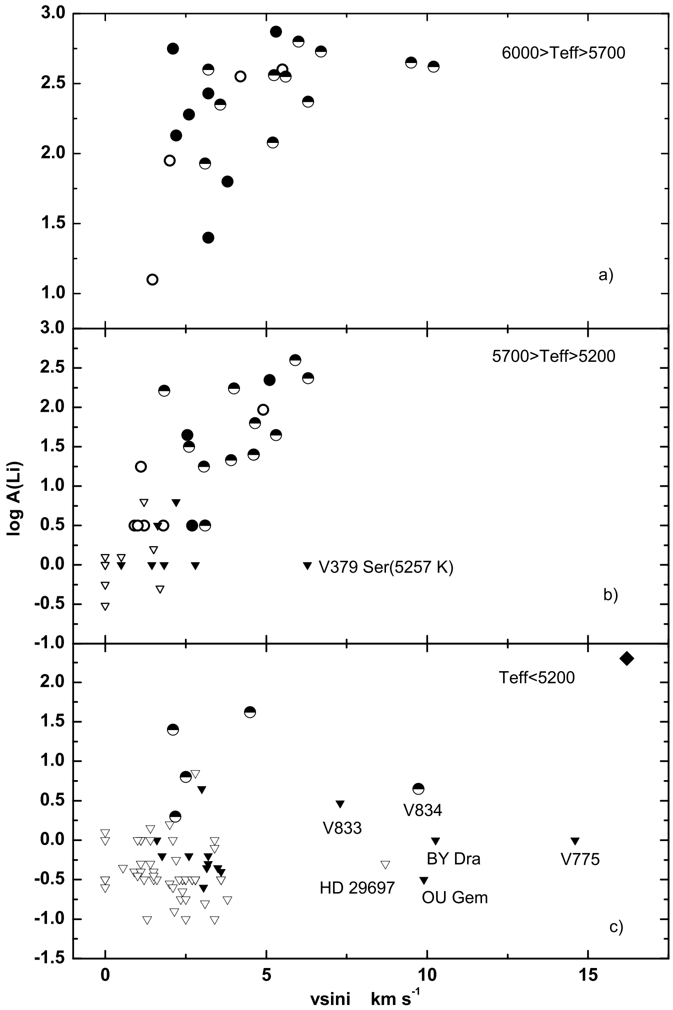

Fig. 6. Dependence of the Li abundance on $v \sin i$.

velocities and low Li abundances. Those stars, except HD 29697, are known stars of the BY Dra type (namely, V833 Tau, V834 Tau, BY Dra, OU Gem, and V775 Her) binaries, stars with low temperatures and very weak lines of Li in the spectra of the main component.

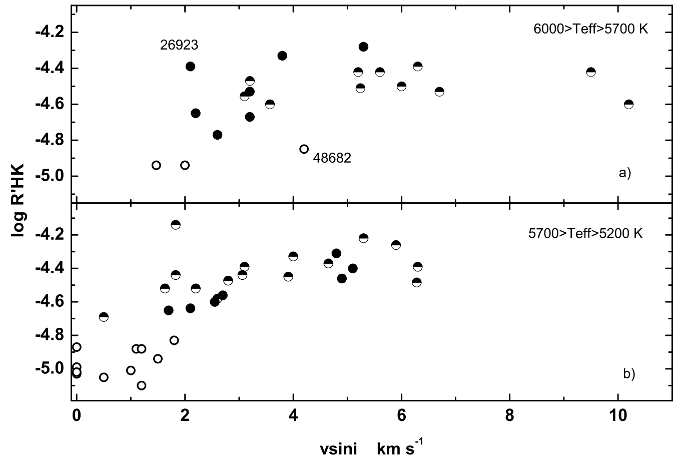

Fig. 7. Dependence of the $\log R'_{\rm HK}$ on $v \sin i$.

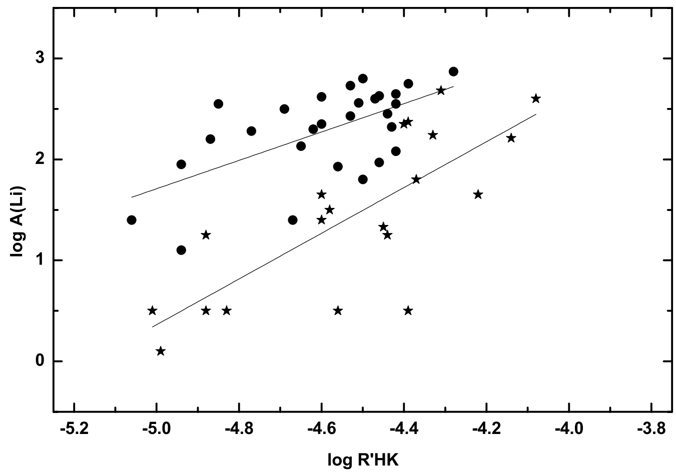

Fig. 8. Dependence of the Li abundance on $\log R'_{\rm HK}$ for the stars with $6000 > T_{\rm eff} > 5700$ (full circles) and with $T_{\rm eff}$ from 5700 to 5200 K (asterisks).

The lower abundances of Li for the later G stars are associated with the fact that the convection zones of those stars become deeper than that on the Sun. The decrease in the Li abundance must be observed at $T_{\rm eff} < 5800$ K where the bottom of the surface convection zone reached the regions where Li, Be, and B burn (e.g. Michaud et al. 2004) and the strong convection destroys Li at $T_{\rm eff} < 5400$ K (e.g. Iben 1965; D'Antona & Mazzitelli 1984, etc.).

Good correlations between $\log A$(Li) and $\log R'_{\rm HK}$ with $v \sin i$ for G-type stars are evidence that the rotation is a key factor in the physical processes that are responsible for the levels of the Li abundance and the chromospheric activity. Some distinctions of those dependences are due to the different role of the rotation rate in both processes. The Li abundance depends on the axial rotation rate indirectly through the age, while the dynamo process is a direct consequence of interaction between the rotation and the turbulent convection.

7.3. How can studying lithium help with understanding the general problems of stellar activity?

Up to now stellar activity has been studied for the young objects with activity close to saturation and less active stars observed during execution of exoplanet search programmes (for example, Wright et al. 2004; Martínez-Arnáiz et al. 2011). Previously, we

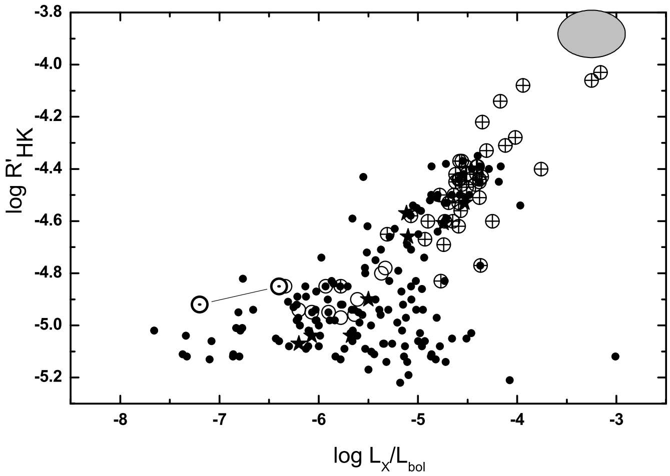

Fig. 9. Diagram of the chromospheric and coronal activity for the late-type stars. The stars of the basic data set are marked as dots. The corresponding references are given above, or the summary table see Katsova & Livshits (2011). The investigated stars with measured Li abundance and with direct measurements of the log $R'_{\rm HK}$ indices (from the studies mentioned above) are marked as crosses inside the circles. According to the type of a cycle, the stars of group "Excellent" are marked as circles, the stars of "Good" group are indicated as asterisks; the Sun at the maximum and at the minimum is denoted by its own sign and connected by the direct line.

studied the relationship between the coronal and chromospheric activity (Katsova & Livshits 2006, 2011). Here we also consider a set of stars that contains objects with a detectable Li line and with moderate activity levels. Data on the chromospheric activity indices are adopted from the papers cited in Sect. 3. The soft X-ray radiation of all those stars was adopted from the ROSAT data (Schmitt & Liefke 2004; Huensch et al. 1999) and the *XMM-Newton* observations (Poppenhaeger et al. 2010, 2011). The data for more than 50 stars with detected Li abundances allows us to fill up a gap between low- and saturated activity on the chromosphere-corona diagram constructed by Katsova & Livshits (2011) for 172 stars including the Sun. In this way, the whole set of stars includes stars with the low- and high activity levels.

The results are presented in Fig. 9. Newly added stars with detected Li hardly deviate from the straight line by Mamajek & Hillenbrand (2008) corresponding to the linear regression between log $R'_{\rm HK}$ and log $L_{\rm X}/L_{\rm bol}$. Most stars of that group are hotter than the Sun. Since the activity level is associated with the age, displacement along this line describes an evolution in the activity of such stars. The activity of all late-type stars evolves quickly during the first 1–2 Gyr, then their paths diverge and the stars cooler than the Sun displace below this line. Only several stars with detected Li are among these objects, while the others, revealed earlier on the same kind of diagram by Katsova & Livshits (2011) are less active.

Physically, the change in the relationship between the chromospheric and coronal indices reflects the change in the properties of the activity. Probably, that can be due to various depths of the convection zone in those stars and the change in conditions for the dynamo mechanism. A broad spread in estimations of the ages of late G and K stars from their activity levels and from the Li abundance is due to that circumstance. We believe that Li may be a better indicator of the age than the activity. We point out that the stars, classified in the HK Project as stars with "Excellent" cycles, are located on the diagram outside the main group of the F and earlier G-stars because the formation processes of the stellar cycles can be related to the above problems.

8. Conclusion

The physical parameters, [Fe/H], and the Li abundances were determined homogeneously for a sample of 24 FGK dwarfs, and the behaviour of the Li abundance was analysed for 150 stars. For our sample of stars, including many BY Dra-type objects, the correlation between the chromospheric activity, measured by the log $R'_{\rm HK}$-index and rotation $v \sin i$ and between the Li abundance, rotation, and the log $R'_{\rm HK}$-index were considered for three groups of the stars with $T_{\rm eff}$ from 6000 to 5700 K, $T_{\rm eff}$ from 5700 to 5200 K and $T_{\rm eff} < 5200$ K. The high Li abundance was detected for a small number of the stars with $T_{\rm eff} < 5600$ K. We can make two main conclusions.

1. The correlation Li-activity is evident only in a restricted temperature range ($T_{\rm eff}$ from 5700 to 5200 K).
2. The Li abundance spread seems to be present in a group of low chromospheric activity stars that also show a broad spread in the chromospheric vs. coronal activity.

Acknowledgements. The authors thank the anonymous referee and Dr. Piercarlo Bonifacio, as referee, for the careful reading of the manuscript and the important remarks that enabled the work to be improved. T.M. thanks the Laboratoire d'Astrophysique de Bordeaux for their kind hospitality during the course of the present project. This study was conducted using the SIMBAD database, operated at the CDS, Strasbourg, France. It is based on the data obtained from the ESA Hipparcos satellite (Hipparcos catalogue). The present work was supported by the Swiss National Science Foundation, project SCOPES No. IZ73Z0-128180/1. M.K. and M.L. are grateful for the financial support within the framework of RFBR grant 12-02-00884, and RSS grant 2374.2012.2.

Appendix A

HD 139813 has both high X-ray emission ($R_{\rm x} = -3.75$) and log $R'_{\rm HK} = -4.40$ (Wright et al. 2004) that indicates it is an active star. Its SIMBAD object type is a star in a double system with high proper motion and IR source.

HD 185414 has log $R'_{\rm HK} = -4.83$ according to Baliunas et al. (1995). That star is in Takeda et al. (2010) where its measurements indicate moderate activity (HIP 96396, $r_0(8542) = 0.218$).

HD 208038 is in Wright et al. (2004), but its colour is outside the boundaries for the log $R'_{\rm HK}$ determination. Its GrandS value (0.533) indicates some Ca II emission, so, it can be considered as an active one.

We noted three stars with log $R'_{\rm HK}$ in the range –4.55 to –4.70 in Wright et al. (2004), but with no other indication of the activity (HD 4635, HD 105631, HD 184385).

References

Baliunas, S. L., Donahue, R. A., Soon, W. H., et al. 1995, ApJ, 438, 269
Baranne, A., Queloz, D., Mayor, M., et al. 1996, A&AS, 119, 373
Barnes, S. A. 2003, ApJ, 586, 464
Benz, W., & Mayor, M. 1984, A&A, 138, 183
Canal, R., Isern, J., & Sanahuja, B. 1975, ApJ, 200, 646
Charbonnel, C., Vauclair, S., & Zahn, J.-P. 1992, A&A, 255, 191
Chen, Y. Q., & Zhao, G. 2006, AJ, 131, 1816
Chen, Y. Q., Nissen, P. E., Benoni, T., & Zhao, G. 2001, A&A, 371, 943
Christian, D. J., Mathioudakos, J. D., et al. 2005, A&A, 632, L1237
Cutispoto, G., Tagliaferri, G., & de Medeiros, J. R., et al. 2003, A&A, 397, 987
D'Antona, F., & Mazzitelli, I. 1984, A&A, 138, 431
D'Antona, F., & Mazzitelli, I. 1997, Mem. Soc. Astr. It., 68, 807
Duncan, D. 1981, ApJ, 248, 651
Duncan, D. K., & Jones, B. F. 1983, ApJ, 271, 663
Favata, F., Micela, G., & Sciortino, S. 1997, A&A, 323, 809
Flower, F. 1996, ApJ, 469, 355
Fuhrmann, K. 2008, MNRAS, 384, 173

Gaidos, E. J., Henry, G. W., & Henry, S. M. 2000, AJ, 120, 1006
Gaidos, E. J., & Gonzalez, G. 2002, New A, 7, 211
Galazutdinov, G. A. 1992, Preprint SAO RAS, 92
Girardi, L., Bressan, A., Bertelli, G., & Chiosi, C. 2000, A&A, 141, 371
Guedel, M. 2004, A&ARv, 12, 71
Guinan, E. F., & Engle, S. G. 2009, The Ages of Stars, Proc. International Astronomical Union, IAU Symp., 258, 395
Hall, J. C., Lockwood, G. W., & Skiff, B. A. 2007, AJ, 133, 862
Henry, T. J., Soderblom, D. R., Donahue, R. A., & Baliunas, S. L. 1996, AJ, 111, 439
Herbig, G. H. 1965, ApJ, 141, 588
Huensch, M., Schmitt, J. H. M. M., Sterzik, M. F., & Voges, W. 1999, A&ASS, 135, 319
Iben, I. Jr. 1965, ApJ, 141, 993
Israelian, G., Santos, N. C., Mayor, M., & Rebolo, R. 2004, A&A, 414, 601
Jenkins, J. S., Murgas, F., Rojo, P., et al. 2011, A&A, 531, A8
Jones, B. F., Fischer, D., Shetrone, M., & Soderblom, D. R. 1997, AJ, 114, 352
Katsova, M. M., & Livshits, M. A 2006, Astron. Rep., 50, 579
Katsova, M. M., & Livshits, M. A. 2011, Astron. Rep., 55, 1123
Katz, D., Soubiran, C., Cayrel, R., et al. 1998, A&A, 338, 151
King, J. R., Schuler, S. C., Hobbs, L. M., & Pinsonneault, M. H. 2010, ApJ, 710, 1610
Kovtyukh, V. V., Soubiran, C., & Belik, S. I. 2004, A&A, 427, 923
Kurucz, R. L. 1993, CD ROM, 13
Lambert, D. L., Heath, J. E., & Edvardsson, B. 1991, MNRAS, 253, 610
Lovis, C., Dumusque, X., Santos, N. C., et al. 2011, A&A, submitted [arXiv:1107.5325]
Lubin, D., Tytler, D., & Kirkman, D. 2010, ApJ, 716, 766
Luck, R. E., & Heiter, U. 2006, AJ, 131, 3069
Livshits, M. A. 1997, Sol. Phys., 173, 377
Maldonado, J., Martínez-Arnáiz, R. M., Eiroa, C., Montes, D., & Montesinos, B. 2010, A&A, 521, 12
Mamajek, E. E., & Hillenbrand, L. A. 2008, ApJ, 687, 1264
Martin, E. L., Basri, G., Pavlenko, Ya., & Lyubchik, Yu. 2002, ApJ, 579, 437
Martínez-Arnáiz, R., Lóopez-Santiago, J., Crespo-Chacóon, I., & Montes, D. 2011, MNRAS, 414, 2629
Masana, E., Jordi, C., & Ribas, I. 2006, A&A, 450, 735
Michaud, G., Richer, J., & VandenBerg, D. A. 2004, ApJ, 606, 452
Mishenina, T. V., & Tsymbal, V. V. 1997, Pis'ma v Astron. Zhurn., 23, 693
Mishenina, T. V., Soubiran, C., Kovtyukh, V. V., & Korotin, S. A. 2004, A&A, 418, 551
Mishenina, T. V., Soubiran, C., Bienayme, O., et al. 2008, A&A, 489, 923
Montes, D., & Ramsey, L. W. 1998 A&A, 340, L5
Moultaka, J., Ilovaisky, S. A., Prugniel, P., & Soubiran, C. 2004, PASP, 116, 693
Nordström, B., Mayor, M., Andersen, J., et al. 2004, A&A, 418, 989
Pallavicini, R., Cerruti-Sola, M., & Duncan, D. K. 1987, A&A, 174, 116
Pallavicini, R., Randich, S., & Giampapa, M. S. 1992, A&A, 253, 185
Pallavicini, R., Cutispoto, G., Randich, S., & Gratton, R. 1993, A&A, 267, 145
Poppenhaeger, K., Robrade, J., & Schmitt, J. H. M. M. 2010, A&A, 515, A98
Poppenhaeger, K., Robrade, J., & Schmitt, J. H. M. M. 2011, A&A, 529, A1
Queloz, D., Allain, S., Mermilliod, J.-C., Bouvier, J., & Mayor, M. 1998, A&A, 335, 183
Randich, S. 2010, Proc. IAU Symp., 268, 275
Randich, S., Gratton, R., & Pallavicini, R. 1993, A&A, 273, 194
Randich, S., Primas, F., Pasquini, L., Sestito, P., & Pallavicini, R. 2007, A&A, 469, 163
Schmitt, J. H. M. M., & Liefke, C. 2004, A&A, 417, 651
Skumanich, A. 1972, ApJ, 171, 565
Soderblom, D. R., Jones, B. F., Balachandran, S., & Stauffer, J. R. 1993a, AJ, 106, 1059
Soderblom, D. R., Stauffer, J. R., Hudon, J. D., & Jones, B. F. 1993b, ApJS, 85, 315
Soderblom, D. R., Stauffer, J. R., MacGregor, K. B., & Jones, B. F. 1993c, ApJ, 409, 624
Takeda, Y., & Kawanomoto, S. 2005, PASJ, 57, 45
Takeda, Y., Kawanomoto, S., Honda, S., Ando, H., & Sakurai, T. 2007, A&A, 468, 663
Takeda, Y., Honda, S., Kavanomoto, S., et al. 2010, A&A, 515, A93
Tatischeff, V., & Thibaud, J.-P. 2007, A&A, 469, 265
Thorburn, J. A., Hobbs, L. M., Deliyannis, C. P., & Pinsonnealt, M. H. 1993, ApJ, 415, 150
Tokovinin, A. A. 1992, A&A, 256, 121
Tsymbal, V. V. 1996, ASP Conf. Ser., 108, 198
Valenti, J. A., & Fischer, D. A. 2005, ApJS, 159, 141
Vaughan, A. H., & Preston, G. W. 1980, PASP, 92, 385
Voges, W., Aschenbach, B., Boller, T., et al. 1999, A&A, 349, 389
Wright, J. T., Marcy, G. W., Butler, R. P., & Vogt, S. S. 2004, ApJS, 152, 261