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Lithium abundances of 21 solar-type stars near the Sun

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ABSTRACT

We present high-resolution spectroscopic observations for a sample of 21 young, solar-type stars near the Sun recently discovered in the X-ray wavelength range during the ROSAT all-sky survey. Based on these observations, we derive the lithium (Li) abundances of these 21 sample stars. Using the lithium abundances and the X-ray luminosity, we investigated the relationship between the Li abundances and the X-ray activity. We found a clear correlation between the lithium abundances and the X-ray luminosity: as the X-ray luminosity became stronger, the lithium abundance decreases in our sample stars. Our sample results provide further evidence that a correlation appears to exist between Li abundances, X-ray activity and age for a large number of solar-type stars. The results also confirm the presence of very active young stars close to the Sun, in agreement with recent findings from UV and X-ray surveys.

1. Introduction

Solar-type stars are low-mass, late spectral-type stars. They are similar to the Sun in mass and evolutionary state. Physically, they have a broadly similar structure and present a convective envelope; however, they do not have completely dominant convection, similar to M dwarfs. Young, solar-type stars (weak-line T Tauri star (WTTS), low-mass Zero-Age-Main- Sequence (ZAMS) and young Main-Sequence (MS) stars) display various forms of activity caused by dynamic processes.

Lithium has long been recognized as a powerful tool for investigating the internal mixing of low-mass stars. Because lithium isotopes in low-mass stars are destroyed by proton capture at low temperatures, they allow us to directly probe the depths of outer-mixed envelopes. Observations of field stars and open clusters clearly show that the destruction rate of Li depends on the mass, age, and chemical composition of a star (Duncan, 1981; Spite and Spite, 1982; Duncan and Jones, 1983; Cayrel et al., 1984; Boesgaard and Tripicco, 1986; Hobbs and Pilachowski, 1986; Rebolo et al., 1988). In particular, different authors have proposed empirical expressions for Li abundance as a function of star age (Rebolo, 1989; Boesgaard, 1991).

Increasing evidence indicates that a dispersion in Li abundances exists among stars with similar ages, metallicities, and masses (Soderblom et al., 1993a; Boesgaard et al., 1998). Such a dispersion suggests that some other stellar property is important in determining the amount of Li depletion in stars. Observational data clearly indicate that rotation plays a key role in determining the amount of Li depletion in a star (Barrado y Navascués and Stauffer, 1996; Jones et al., 1997). In addition, there is some clear evidence of a correlation between rotation rates and Li abundances in the Pleiades and Hyades, with the fastest rotators having the highest Li abundance (Tschäpe and Rüdiger, 2001; Rebolo and Beckman, 1988). In particular, the X-ray surface flux is a good measure of stellar activity because it shows a clear dependence on stellar rotational velocity (Preibisch, 1997). The enhanced X-ray emission displayed by rapid rotators (T Tauri stars and RS CVn systems), compared with main-sequence stars, can be accounted for by their higher rotational velocities (Bouvier and Bertout, 1985a). Therefore, a correlation can be expected between lithium abundances and star activity.

To study the relationship between lithium and X-ray activity in normal solar-type stars and determine the effectiveness of lithium and kinematics as activity indicators, we performed a survey of lithium over a sample of nearby dwarfs. Our aim is to investigate the relationship of lithium abundances to X-ray activity using log L_x. The observations and data reduction are presented in Section 2. The analysis of the lithium abundance is provided in Section 3, and the results and discussion are presented in Section 4.

2. Observations and data reduction

Spectroscopic observations were carried out for ten nights from October 6 to 8, 2009, January 26 to 28, 2010, and February 18 to 21, 2011 with the Coude Echelle Spectrograph and a 1024 × 1024 Tek CCD attached to the 2.16 m telescope at the Xinglong station of the National Astronomical Observatories, Chinese Academy of Science

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(NAOC). The red arm of the spectrograph with a 31.6 groove/mm grating was used in combination with a prism as the cross-disperser, which provided good separation between the echelle orders (Zhao and Li, 2001). With a 0.5 mm slit (1.1 arcsec), the resolving power was on the order of 37,000. The exposure time was chosen to obtain a signal-to-noise ratio over 100. The spectral coverage is 580–880 nm. This relatively high resolution was judged to be important in view of the relatively weak lithium lines in some stars.

First, all observational data were reduced using the Image Reduction and Analysis Facility (IRAF) software package in the standard fashion, including image trimming, bias subtraction, flat-field division, spectrum extraction, and cosmic ray removal. Then, the wavelength calibration was obtained by taking the spectra of a Th-Ar lamp. Finally, all spectra were normalized using a cubic spline fit to the observed continuum. Fig. 1 shows the spectra of four sample stars in the range of the Li I λ 6707.8 Å line.

For the determination of Li I λ 670.8 nm equivalent widths (EW (Li)), all spectral lines of the relevant order were averaged to find regions in the continuum unaffected by metal lines. These regions were used to fit the continuum with a straight line. The EW of the Li I λ 670.8 nm line was determined by fitting a Gaussian curve. The nominal resolving power, $\lambda/\Delta\lambda$, was 10^5, which was sufficient to resolve the Li I feature from a nearby Fe I line at 6707.44 Å in all regions. Because we observed bright stars and the seeing conditions were generally good, the S/N ratio of our observations was high, between 100 and 300.

Following Palla et al. (2005), the relationship between the true and measured EWs is $\mathrm{EW_{true}} = \mathrm{EW_{meas}}\ (1 - r)$, where r is the ratio of the excess to the photospheric continuum. To estimate r, we 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. We compared them with those measured in the spectra of stars of similar temperature in IC 2391 and IC 2602, which were old enough (30–50 Myr, Randich et al., 2001) to ensure that their spectra are not affected by veiling. Therefore, we did not attempt any veiling correction in our young, solar-type stars.

In Fig. 2, we compare our measurement of the Li equivalent widths with those obtained by other authors for the same stars (Christian and Mathioudakis, 2002; Wichmann et al., 2000; Gregorio-Hetem and Hetem, 2002; Takeda and Kawanomoto, 2005; Montes et al., 2001). The agreement between the values was good; however, for small equivalent widths, we noted some differences between the samples of other authors and our results. We found an agreement better than 15% for 8 stars when compared with the literature data, and we estimated an average error bar of 5% in the EW values at 1σ, resulting mainly from uncertainties in the continuum placement.

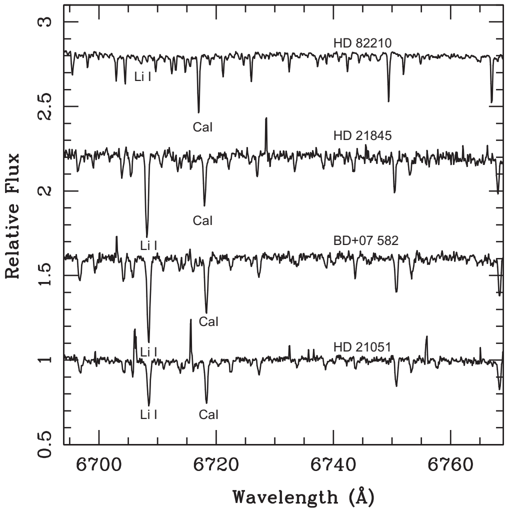

Fig. 1. Examples of a portion of spectra of stars in the range of Li I λ 6707.8 Å lines.

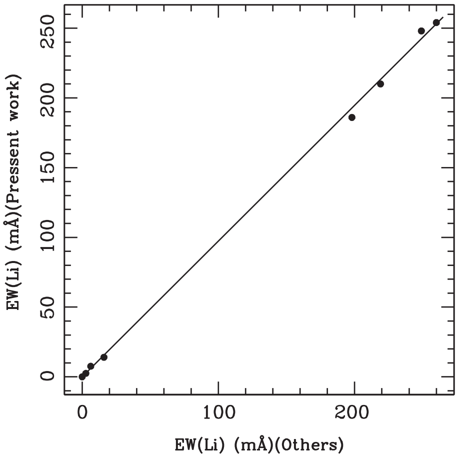

Fig. 2. Comparison of our measurement of the Li equivalent width obtained with a Gaussian fit and those measurements obtained by other authors for the same stars (Christian and Mathioudakis, 2002; Wichmann et al., 2000; Gregorio-Hetem and Hetem, 2002; Takeda and Kawanomoto, 2005; Montes et al., 2001).

3. Lithium abundances of young solar-type stars

3.1. Effective temperatures and surface gravity

The effective temperature of our 21 sample stars was determined from the line-depth ratios of V I λ 6251.83 and Fe I λ 6252.527, using the calibrations of Gray and Johanson (1991). The line depths were measured with a ruler on a plot of the profiles (Xing, 2010). We also determined the effective temperature for 21 program stars from the (B–V) color index, using the calibrations of Casagrande et al. (2006). The effective temperature of program stars derived from different methods is listed in Table 1.

From the relations $g \propto M/R^2$ and $L \propto R^2\, T_{\mathrm{eff}}^4$, where M is the stellar mass, R is the radius, and T_{eff} is the effective temperature, we obtain:

$$\log g = \log g_{\odot} + \log(M/M_{\odot}) + 4\log\left(T_{\mathrm{eff}}/T_{\mathrm{eff},\odot}\right) - \log(L/L_{\odot}),$$

where $g_{\odot}$ is the solar surface gravity, and M, T_{eff}, and L are the stellar mass, photometric effective temperature, and luminosity, respectively, in the respective solar units.

Here the luminosity is given by:

$$L/L_{\odot} = 0.0813 \times r^2 \times 10^{-0.4\times m},$$

where r is the distance to star and m is the apparent magnitude of the star. The distance was derived from the trigonometric parallax searched from VizieR. The mass of a star was estimated from its position in the $\log(L/L_{\odot}) - \log T_{\mathrm{eff}}$ diagram using the PMS evolutionary models of Palla and Stahler (1999).

Following the uncertainty analysis of Chen et al. (2000), we can estimate the mean uncertainty of log g. The largest uncertainty of the gravity comes from the parallax. A typical relative error of 5% corresponds to an error of 0.04 dex in log g. The estimated errors of 70 K of effective temperature and 0.05 mag of apparent magnitude each leads to an uncertainty of 0.02 dex in log g, while error of 0.05 $M_{\odot}$ in mass leads to an error of 0.03 dex in gravity. In total, the estimated error of gravity is less than 0.20 dex.

Table 1

Photometric results and other parameters of our sample stars. Reference to table 1: C: The effective temperature was determined from B–V color; R: The effective temperature was determined from the line-depth ratios of V I λ 6251.83 and Fe I λ 6252.527.

#	Stars	SpT.	V	B–V	T^C_{eff} (K)	T^R_{eff} (K)	EW (Li) (mÅ)	log N (Li)	log L_x (erg/s)
1	RX J0156.4 + 1224	G	10.35	0.598	5956	5961	284	3.14	28.46
2	HD 21845	K2	8.250	0.800	5068	5076	210	2.88	30.08
3	HD 232862	G8II	9.46	0.878	5008	5012	191	2.51	30.46
4	BD + 07 582	K0	9.8	0.747	5498	5508	295	3.26	29.48
5	HD 26913	G8V	6.92	0.680	5640	5648	58	2.28	30.67
6	HD 283716	K0IV	10.34	0.769	5403	5422	39	1.89	31.48
7	HD 31281	G0	9.19	0.672	5647	5639	0	1.01	31.73
8	HD 287927	G5	10.6	0.709	5498	5507	254	3.24	29.16
9	HD 59058	G5V	7.73	0.738	5374	5379	60.2	2.11	29.41
10	HD 82443	K0V	7.01	0.779	5324	5332	186	2.81	29.48
11	HD 82210	G5III	4.565	0.781	5249	5244	30	1.59	30.33
12	HD 90373	G0	8.69	0.614	5824	5831	26.6	2.03	29.75
13	HD 90709	G5	7.06	0.789	5287	5283	25.3	1.53	30.71
14	HD 101501	G8V	5.32	0.723	5453	5447	25	0.86	28.22
15	HD 108891	G5	8.83	0.695	5587	5592	37.5	2.04	31.04
16	HD 111395	G5V	6.31	0.703	5508	5513	7.6	1.36	28.41
17	HD 129920	G2V	8.24	0.659	5608	5614	57.7	2.31	29.21
18	HD 141004	G0V	4.43	0.604	5868	5862	14	1.96	27.67
19	HD 141272	G8V	7.42	0.801	5279	5288	17.8	0.89	29.50
20	BD + 48 3686	K1V	8.9	0.847	5092	5084	248	2.48	29.74
21	BD + 66 1664	G8	8.74	0.708	5489	5482	25	1.51	32.94

3.2. Calculation of lithium abundance

Lithium abundances (on a scale where log N (H) = 12.00) were obtained from comparison of the measured Li I λ 670.8 nm equivalent widths with the curve of growth calculations in non-LTE (NLTE) conditions (Pavlenko and Magazzú, 1996, used the newest models (Kurucz, 1993) with solar metallicity and gravities and effective temperatures in the range log g = 3.0–4.5 and $T_{\rm eff}$ = 3500–6000 K). They were computed assuming a microturbulence velocity of 2 km s^{-1}. In Fig. 3, we show a set of the NLTE curves of growth employed in this work. This computational method was described by Pavlenko and Magazzú (1996, and references therein). All the relevant references of cross sections, damping constants, and oscillator strengths were similar to those in Pavlenko and Magazzú (1996).

The lithium abundances of 21 observed sample stars are reported in Table 1. The main source of error in the derived log N (Li) values is the uncertainty regarding the effective temperature. Following the uncertainty analysis of Martín et al. (1994), we can estimate the mean uncertainty of log N (Li). From Fig. 3, we can see that the uncertainty of ±250 K in $T_{\rm eff}$ or 0.5 dex in log g, translates into error bars in log N (Li) of approximately 0.4 dex and 0.1 dex, respectively. The effects of microturbulence on the derived Li abundance are probably negligible. Basri et al. (1991) showed that, for 5200 K and an equivalent width of EW (Li) = 0.40 Å, changing the microturbulence from 1.8 to 3.5 km s^{-1} only affects the derived abundances by −0.1 dex (King, 1993). The uncertainty in log N (Li) is due to negligible error in the value of log g, based on consistent calculations. However, to be conservative, we adopted an uncertainty of σ(log g) = ±0.1 dex in the relative Li abundances. The uncertainty in the equivalent widths is ±10%, introducing an uncertainty $\leqslant \pm 0.1$ dex to the abundances. An uncertainty of ±70 K in $T_{\rm eff}$ results in an uncertainty of $\leqslant$±0.15 dex in the abundances. Adding these values in quadrature gives a final uncertainty for the relative abundances of $\leqslant$±0.2 dex for all but one star (HD 31281).

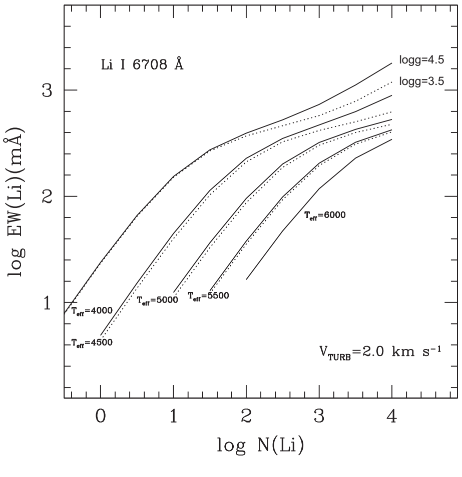

Fig. 3. Li I λ 6707.8 curves of growth for temperatures between 3500 K and 6000 K from Pavlenko and Magazzú (1996).The solid lines are for log g = 4.5; the dashed lines are for log g = 3.5.

3.3. Calculation of X-ray luminosity

X-ray activity measures, L_X, were calculated for each star using the ROSAT All-Sky Bright Source Catalogue data. The X-ray flux, f_X, is:

$$f_X = \mathrm{ECF} \cdot \text{ count rate } (\mathrm{erg\,cm^{-2}\,s^{-1}}),$$

where ECF is the energy conversion factor given as:

$$\mathrm{ECF} = (5.30 \cdot 8.31) \times 10^{-12} \; (\mathrm{erg\,cm^{-2}\,cts^{-1}})$$

according to Schmitt et al. (1995).

$$L_X = 4\pi d^2 f_X$$

where d is the distance to the star. The distance was derived from the trigonometric parallax. The trigonometric parallax of the star was taken from VizieR.

4. Discussion and results

For the sake of consistency, we show in Fig. 4 a comparison of log N (Li) from this work with other works (Christian and Mathioudakis, 2002; Lébre et al., 1999, 2009; do Nascimento et al., 2003; Takeda and Kawanomoto, 2005; Montes et al., 2001). As expected, only minor differences with respect to other original lithium

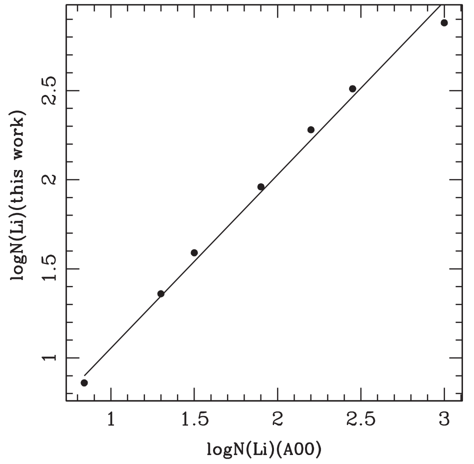

Fig. 4. A comparison of log *N* (Li) of the sample stars of Christian and Mathioudakis (2002), Lébre et al. (1999, 2009), do Nascimento et al. (2003), Takeda and Kawanomoto (2005) and Montes et al. (2001) with those of this work.

abundances are found. We are confident that our lithium abundances are reliable.

Fig. 5 indicates that most of our sample stars are above the Hyades track. Clearly, many stars in our sample are quite young. We find that, among the stars in our sample, seven have a log *N* (Li) higher than that of the Pleiades (younger than a ZAMS, Pleiades star, should be a pre-main sequence (PMS) star), eight have a log *N* (Li) between that of the Pleiades and Hyades (younger than Hyades star, should be ZAMS), and six have a log *N* (Li) lower than that of the Hyades (should be a young, solar-type star).The figure also indicates that for these young, solar-type stars, no dependency of log *N* (Li) on $T_{\rm eff}$ is discernible.

Soderblom et al. (1993a) studied lithium abundance in conjunction with rotational velocity and chromospheric activity in the Pleiades and found that (for $0.8 < B - V < 1.2$) stars with a high equivalent width of the Li I 6708 Å line tend to have a high value of projected rotational velocity. Additionally, in the α Per cluster, faster rotators appear to have a stronger lithium abundance (Balachandran et al., 1988; Stauffer et al., 1993). These results are the same for nearby field solar-type stars (de Medeiros et al., 2000; do Nascimento et al., 2000; Cutispoto et al., 2003). Observations and data analysis show that the rapid rotation of young, solar-type stars exhibits higher X-ray luminosity (Bouvier et al., 1985b; Xing et al., 2007a). The mean levels of both lithium abundance and X-ray luminosity are known to decrease with decreasing projected rotational velocity (although perhaps with a large dispersion) in solar-type MS stars. Therefore, some level of correlation between lithium abundances and X-ray luminosity was expected in the nearby field young, solar-type stars.

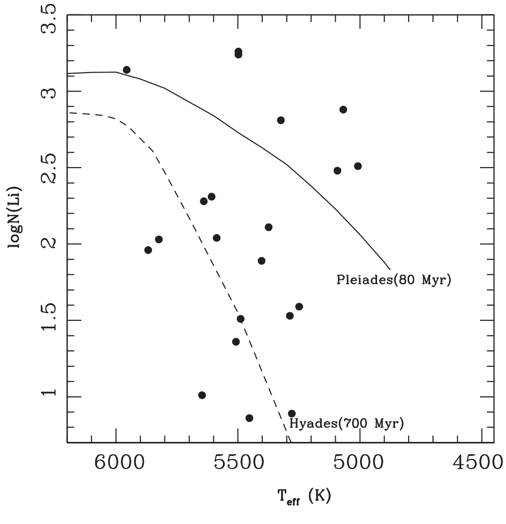

Fig. 5. Lithium abundances versus effective temperature for the stars in the present survey. The solid and dashed curves are the fiducial log *N* (Li) vs. T*eff* curves for the Pleiades (top envelope) and Hyades, respectively (adapted from Deliyannis, 2000).

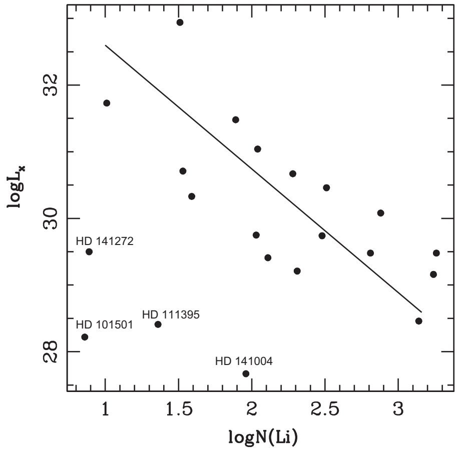

Fig. 6. Lithium abundances as a function of the X-ray luminosity (log Lx) for the sample of young, solar-type stars.

Fig. 6 presents the relationship between X-ray luminosity (log L_X) and lithium abundances for the sample of 21 stars (7 PMS, 8 ZAMS and 6 young MS) selected from the ROSAT survey. Except for two variable stars of the type BY Dra (a multi-star system in the constellation Draco, HD 141272 and HD 111395) and the multiplicity of two solar-type stars (HD 101501 and HD 141004), Fig. 6 shows a clear correlation between X-ray activity and Li abundance: as the X-ray luminosity, L_X becomes stronger, the lithium abundance decreases.

Pasquini et al. (1994) found a clear tendency for nearby, chromospherically active, solar-type stars to be characterized by high log *N* (Li) despite the large scattering observed in the diagram of log *N* (Li) vs. Ca II surface flux. Similar results are found in X-ray samples or EUV selected active stars (Favata et al., 1993; Tagliaferri et al., 1994, 2000; Jeffries, 1995). A similar connection is observed between the Li I equivalent width and a stellar activity indicator, the chromospheric flux indicator based on the Ca II 8542 Å line (Montes et al., 2001). Stellar activity is considered a good indicator of age for solar-type stars (e.g., Soderblom et al., 1991; Pizzolato et al., 2000).

The main features of the rotation evolution of low mass, late-type stars are that they exhibit strong PMS spin up (in the phase from moderate rotation in the T Tauri to ultrafast rotation at ZAMS) and an increase in rotational period (spin down) with increasing age for main sequence stars (e.g., Bouvier, 1994; Soderblom et al., 1993b; Collier Cameron et al., 1995; Keppens et al., 1995). Therefore, the EW (Li) decreases with decreasing $P_{\rm rot}$ when a star develops in the PMS phase, whereas EW (Li) decreases with increasing $P_{\rm rot}$ (decreasing rotational velocity) when stars develop in the MS phase (Xing et al., 2007b). However, the rapid rotation of young, solar-type stars shows higher X-ray luminosity (Bouvier et al., 1985b; Xing et al., 2007a). It is easy to understand that when solar-type stars develop in the PMS phase, their lithium abundance decreases as the X-ray luminosity (L_X) becomes stronger. In contrast, in the MS phase, faster rotators appear to have a strong X-ray flux (L_X) and high lithium abundance. The results of the present study are in good agreement with the results of Pasquini (1994), Favata et al. (1993,1995), Tagliaferri (1994,2000) and Jeffries (1995).

Lithium and activity show a possible correlation in the 21 young, solar-type stars in our sample. These results are in good agreement with the rotation evolution model (e.g., Bouvier, 1994; Soderblom et al., 1993b; Collier Cameron et al., 1995; Keppens et al., 1995), and Li could serve as a "clock" of stars that develops in the PMS phase (Drake et al., 2003). The correlation in the present sample appears to be simply an age effect, with lithium decaying and activity increasing with age for PMS solar-type stars. Our results, which show agreement with recent findings from X-ray surveys, confirm the presence of very active young stars close to the Sun.

5. Conclusions

In summary, we present high-resolution spectroscopic observations for a sample of 21 young, solar-type stars recently discovered in the X-ray wavelength range during an ROSAT all-sky survey. Based on our observations, we derived the lithium abundances of the stars by comparing the measured Li I λ 6707.8 nm equivalent widths with the curve of growth calculations in non-LTE (NLTE) conditions (Pavlenko and Magazzú, 1996). We found a clear correlation between lithium abundances and X-ray luminosity; as the X-ray luminosity became stronger, the lithium abundance decreased in our sample stars. The results of our sample provide further evidence that a correlation appears to exist between Li abundances, X-ray activity and age for a large number of solar-type stars. The results also confirm the presence of very active young stars close to the Sun, in agreement with recent findings coming from UV and X-ray surveys.

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