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Fast-rotating nearby solar-type stars[★],[★★]

II. Li abundances, $v \sin i$ and X-ray luminosities relationships

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Abstract. We present an analysis of our high-resolution spectroscopic and high-precision $UBV(RI)_c$ photometric observations of a sample of 110 nearby late-F and G-type stars selected for their large rotational velocity. The relationships between Li abundance, X–ray luminosity, and $v \sin i$ are investigated. We find that, as expected, the stars in our sample show statistically higher Li abundance and activity level than field star samples with similar characteristics, but slower rotation. Surprisingly, however, we also find four rapidly-rotating single main-sequence stars with very low Li abundance. For both single and binary stars we find a large spread of Li abundance for stars with rotation lower than about 18 km s^{-1}. The well-established correlation between X–ray luminosity and rotation rate is clearly observed. All single unevolved solar type stars with $v \sin i$ larger than 18 km s^{-1} are strong X–ray emitters and have high Li abundance. Finally, we find also five evolved stars with very low Li abundance that are still rather fast rotators. The results from our sample confirm the presence of young very active stars close to the Sun, in agreement with recent findings from EUV and X–ray surveys, although our sample does not show such extreme characteristics as those selected from EUV and X–ray surveys at the current flux limits.

Key words. stars: abundances – stars: activity – stars: fundamental parameters – stars: variables: general – X-rays: stars

1. Introduction

One of the main topics in stellar astrophysics is to explain how the non-classical phenomena observed on the Sun and solar-type stars depend on the main stellar parameters, particularly the magnetic and dilution processes responsible for stellar activity. In practice, such studies focus on the connection between rotation, magnetic activity diagnostics and light element (in particular Li) abundances, and on the dependence of any such connections on metallicity, mass and age. In low-mass main sequence (MS) stars, *internal* structure is determined primarily by stellar mass rather than age. In contrast, *surface* activity as manifested in X–rays, at least for late-type dwarfs, seems to scale directly with rotation and by consequence with age, but is only slightly dependent on mass (Pallavicini et al. 1981; Schmitt et al. 1985; Hempelmann et al. 1995; Stauffer et al. 1997). This fact would seem to result from the significant decrease in rotation, due to the magnetic torque from a magnetically-coupled stellar wind.

Hence, we believe that it would be extremely interesting to study a sample of stars selected directly on the basis of high rotational velocity rather than from such parameters as high (X–ray) activity or young age. We would expect such a sample to be composed, essentially without exception, by stars with high coronal activity, including both young single (or binary) stars as well as short-period older binaries. The former should then have a very high Li abundance (i.e. higher than the Hyades), the latter a large spread of Li abundance. In any case, the average Li abundance should be higher than that expected in field stars of the same spectral type, selected only on the

basis of their distance from the Sun. We stress that in such a sample we would not expect to find neither low-activity stars nor single stars with low Li abundance.

There are several reasons to expect that our sample will show higher Li abundances than randomly selected star samples with similar spectral type. For single stars the reason is that, although a strict one-to-one correlation does not hold, it has been shown that young stars tend to have higher Li abundances than old stars (see the discussion in Pasquini et al. 1997). Hence, because our sample is selected on the basis of fast rotation (i.e. a rotational velocity similar to or higher than the value observed for stars of comparable spectral type in the Hyades), the single stars are expected to be rather young, typically younger than 1 Gyr. Therefore, they are expected to show Li abundance levels similar to or higher than those observed in the Hyades. For binary stars the reason is that the rapid rotators which are not young are likely to be members of tidally locked systems. Although for some of them we expect to find low Li abundances, it has been recognized that the Li content in such systems is, at least on a statistical basis, larger than in randomly selected stars (Randich et al. 1993, 1994; Fernandez-Figueroa et al. 1993; Barrado y Navascues et al. 1998).

However, we note that it is not clear which is the physical cause for this difference; several theories predict that rotation itself (or the rotational history of the star) may influence the Li depletion through either meridional circulation or rotationally induced mixing (Charbonnel et al. 2000; Pinsonneault et al. 2000). Evidence for some dependence of Li abundance on rotation has been observed among K-type stars in young clusters (Soderblom et al. 1994; Garcia-Lopez et al. 1994) and even among slow rotators in the αPer cluster (Randich et al. 1998). We also need to consider that the clusters in which this rotational dependence of Li has been observed are all rather young, and stars in such clusters may have rotations up to several tens of km s^{-1}. Finally, it is not clear if such dependence of Li on rotation is an artifact due to the use of inappropriate atmospheric models or if phenomena like stellar activity play an important role in this context (cf. Pasquini 2000; Randich 2001; Cutispoto 2002).

A sample of nearby fast-rotating solar-type stars was selected and studied by Cutispoto et al. (2002), hereafter referred to as Paper I. Accurate spectral classifications, effective temperatures (T_{eff}), rotational velocities ($v \sin i$), Li abundances (A_{Li}), radial velocities (RV), and X–ray luminosities (L_X) were determined. In this paper we discuss the $\log T_{\mathrm{eff}}$ vs. A_{Li} diagrams, compare the A_{Li} of the stars of our sample with those of the Pleiades and Hyades clusters and with a sample of stars not selected on the basis of $v \sin i$; we also discuss the relationships between $v \sin i$, A_{Li} and L_X and the global properties of our sample.

2. Sample definition and observations

In order to identify young solar-type stars in the solar neighborhood we started from the CORAVEL survey of 3200 F to G-type stars brighter than $V \simeq 8.6$ (Nordström et al. 1999). We defined the sample by selecting all stars with significant rotational velocity as measured from the width of the CORAVEL

cross-correlation profile. Specifically, a lower limit of 8 km s^{-1} was chosen for the σ of the Gaussian fit to the profile (see Sect. 2.1 in Paper I for further details). This choice ensures that all the selected stars are likely to fulfil one of the signatures for youth, significant rotational velocity.

Among the stars thus selected, 129 can be observed in the southern hemisphere, and we observed them spectroscopically with the 1.4-m ESO CAT telescope, and photometrically with the 50-cm ESO telescope, in various observing runs. For each star we derived an accurate spectral classification and determined RV, $v \sin i$, A_{Li} and L_X (see Paper I for details). All data used in the analysis and figures presented in this paper are taken from Table 1 of Paper I.

Out of the 129 stars observed, we found that 19 are not true solar-type stars (see Sect. 3.2 in Paper I), and they are not further studied in this paper. The remaining 110 stars here presented comprise 42 single stars, 33 visual binaries (VB), and 35 spectroscopic binaries (SB). Among the VB components, 35 are *not* SBs (see Table 1 in Paper I).

In the following analysis we treated the 35 single components of VBs, whether primaries or secondaries, as single stars, because their rotation rate is not influenced by the presence of the companion. Moreover, we were able to obtain separate spectral classifications for 61 of the components of SBs (see Table 1 and Appendix 2 in Paper I for details). In summary, therefore, data for 138 objects, including 77 single stars ($42 + 35$ as explained above) and 61 close binary components are available for the analysis performed in this paper.

Figure 1a shows the $B - V$ vs. M_V colour-magnitude diagram (CMD) for these 138 stars. In this figure we also plot the MS region and the giant sequences determined from Hipparcos data (Houk et al. 1997). Our sample contains a total of 99 MS stars (59 single and 40 close binaries) and 39 non-main sequence stars (18 single and 21 close binaries). It also contains a higher percentage of close binary stars compared to what is expected from a sample of randomly selected field stars. This is expected, not only because the binaries are on average brighter than single stars, but also because our selection criterion (i.e. high rotation rate, see Sect. 4.1 in Paper I) favours the inclusion of tidally synchronised binary stars. In this context, our working sample is one of the most complete samples of solar-type stars studied yet. In Fig. 1b we highlight the CMD diagram for the stars we believe to be very young (see Sect. 3.1).

3. Results

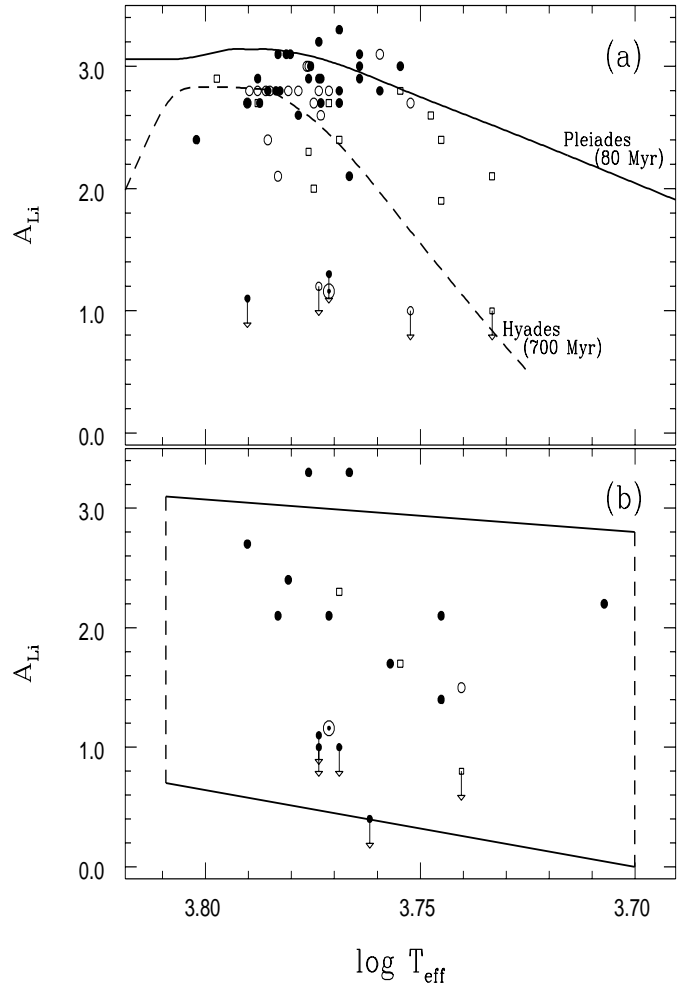### 3.1. The A_{Li} vs. log T_{eff} diagram: single stars

Figure 2a shows the A_{Li} vs. $\log T_{\mathrm{eff}}$ distribution for MS single stars and MS single components of VBs (a total of 59 stars). The solid and dashed curves are the fiducial A_{Li} vs. $\log T_{\mathrm{eff}}$ curves for the Pleiades (top envelope) and the Hyades clusters, respectively (adapted from Deliyannis 2000). Figure 2b shows the same distribution, but for the stars above the MS (a total of 18 stars). The area inside the quadrangle is the region populated by subgiants, giants and supergiants (adapted from Mallik 1999). The Sun's position is shown in both panels.
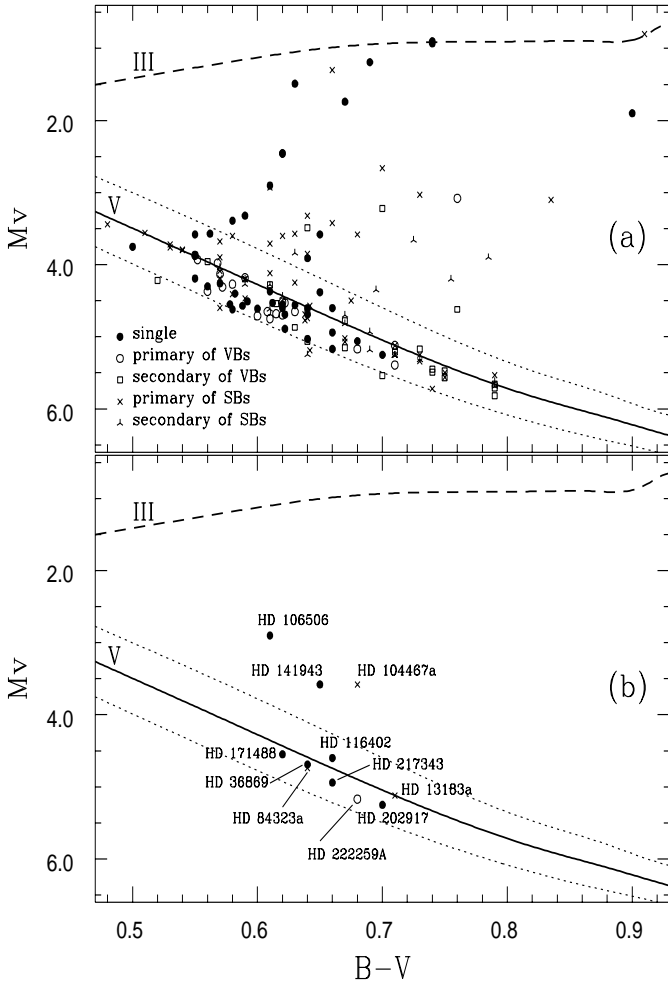
Fig. 1. The $B - V$ vs. M_V diagram for the stars in our sample. Single stars and primary and secondary componentes of VBs and of SBs are indentified by different symbols. The continuous line and the long-dashed line outline the main sequence and giant regions, respectively, from Hipparcos data (Houk et al. 1997); the short-dashed lines indicate the limits of the dispersion of main sequence stars from Hipparcos data. Panel **a)** shows the complete sample; panel **b)** shows the stars we believe to be very young.

Fig. 2. A_{Li} vs. $\log T_{eff}$ for single stars and single VB components. Symbols as in Fig. 1. Panel **a)** stars on the main sequence; the solid and dashed curves are the fiducial A_{Li} vs. $\log T_{eff}$ curves for the Pleiades (top envelope) and the Hyades clusters, respectively (adapted from Deliyannis 2000). Panel **b)** stars above the main sequence; the area inside the quadrangle is the region populated by subgiants, giants and supergiants (adapted from Mallik 1999). The Sun's position is shown in both panels.

Most of our MS single stars are above the Hyades track. We know that stars with low A_{Li} exist among old, inactive, slow-rotating field stars (Pasquini et al. 1994). Intermediate-age stars have comparable, albeit slightly lower A_{Li}, than the Hyades, as confirmed by the observations of Li in intermediate-age open clusters (Randich et al. 2000), which, however, do not show objects with low A_{Li} in the colour range we consider. In contrast, a large scatter in A_{Li} is clearly present in the solar-age open cluster M 67 (Pasquini et al. 1997). In summary, while A_{Li} is not a good age tracer for stars older than about 1 Gyr, it has been shown that stars with A_{Li} comparable to or above that of the Hyades can be confidently classified as being as young as the Hyades or even younger.

Accordingly, it is immediately clear that many single stars in our sample are indeed quite young, with ages lower than 1 Gyr. In particular, we find that among the single MS stars studied, 6 ($\simeq 10\%$) have an A_{Li} higher than that of the Pleiades,

38 ($\simeq 64\%$) have an A_{Li} between that of the Pleiades and Hyades, and 10 ($\simeq 17\%$) have an A_{Li} lower than that of the Hyades, while for only 5 stars ($\simeq 9\%$) we were just able to measure an upper limit for A_{Li}. This result can be compared with the observations by Pasquini et al. (1994) of a sample of field stars of similar spectral type, but not selected on the basis of high $v \sin i$. Of the 42 MS single stars they studied, none has an A_{Li} higher than that of the Pleiades, 10 ($\simeq 24\%$) have an A_{Li} in between that of the Pleiades and Hyades, and 20 ($\simeq 48\%$) have an A_{Li} below that of the Hyades, while for 12 stars ($\simeq 28\%$) only an upper limit for A_{Li} could be measured.

The six stars we find above the Pleiades top envelope are likely *bona-fide* ZAMS stars (see also Fig. 1b, where we plot all stars which we consider to be very young). This is reflected by both their fast rotation and high A_{Li}. Listed in order of decreasing T_{eff} these stars are: HD 171488 ($A_{Li} = 3.1$,

$v \sin i = 45$ km s^{-1}), HD 36869 ($A_{\mathrm{Li}} = 3.3$, $v \sin i = 30$ km s^{-1}), HD 116402 ($A_{\mathrm{Li}} = 3.1$, $v \sin i = 35$ km s^{-1}), HD 217343 ($A_{\mathrm{Li}} = 3.0$, $v \sin i = 12$ km s^{-1}), HD 222259 A ($A_{\mathrm{Li}} = 3.1$, $v \sin i = 17$ km s^{-1}) and HD 202917 ($A_{\mathrm{Li}} = 3.0$, $v \sin i = 14$ km s^{-1}).

It is quite surprising that our sample includes also four apparently single MS stars with significant rotation and an A_{Li} much lower than that of the Hyades, and comparable to or lower than that of the Sun. Their low A_{Li} is not easily understood, and they deserve a separate discussion. Listed in order of decreasing T_{eff} these four stars are: HD 199672 ($v \sin i = 11$ km s^{-1}), HD 108361 A ($v \sin i \leq 9$ km s^{-1}), HD 184525 ($v \sin i = 9$ km s^{-1}) and HD 207377 A ($v \sin i \leq 11$ km s^{-1}). The last two are particularly intriguing because they are both chromospherically active (showing Ca II K emission line), and HD 184525 is also a bright X–ray source. Hence, their very low A_{Li} is quite puzzling. HD 108361 A has no emission in the Ca II K line, while for HD 199672 we do not have a spectrum of the Ca II H&K region.

These four stars are very interesting. They could be objects which suffered peculiar angular momentum histories, and they may represent the elusive population of young Li-poor stars predicted by rotational mixing induced models (e.g. Pinsonneault et al. 2000; Delyiannis et al. 2000). Considering that we do not expect to have any selection bias in our sample, apart from rotation, and making the assumption that all our single stars are due to a recent star formation burst, we can conclude that these young Li-poor stars represent much less than $\simeq 10\%$ of the entire population. These objects would have to be born as extremely fast rotators (if rotational mixing was the mechanism responsible for Li depletion), considering that, even after a strong spin-down, they still maintain rotational velocities of the order of 10 km s^{-1}.

To conclude, it is not obvious how to explain the low A_{Li} found in these four single rapidly rotating MS stars. They clearly deserve further investigation, in particular HD 184525. As it can be seen from Fig. 2a, there is a fifth star (HD 127352 B, $\log T_{\mathrm{eff}} = 3.725$, $B - V = 0.79$) with a very low A_{Li}; but for such cool stars most of the Li is already depleted at the age of the Hyades, therefore the upper limit we found is not unsual even for a fast rotator.

Figure 2b shows the A_{Li} vs. $\log T_{\mathrm{eff}}$ distribution for the single stars above the MS. A large dispersion is present, but in this case the low A_{Li} which occurs for five stars, in order of decreasing T_{eff}, HD 20837 B ($v \sin i = 8$ km s^{-1}), HD 68676 ($v \sin i = 12$ km s^{-1}), HD 84353 ($v \sin i = 15$ km s^{-1}), HD 101117 ($v \sin i = 10$ km s^{-1}) and HD 153926 ($v \sin i = 11$ km s^{-1}) is not surprising. If we compare our results with those of Mallik (1999), we see that in the restricted T_{eff} range of our sample the two distributions are quite similar. Many surveys of evolved stars have shown a rather sharp decrease in A_{Li} in the subgiant phase just after the objects leave the MS (Randich et al. 2000; Lèbre et al. 1999). It is interesting to note that the drastic drop in A_{Li} after the MS has been associated with effects related to the stellar rotational history. In other words, it happens because the stars are slowed down from an initial high rotation (Talon & Charbonnel 1998). However, the five stars mentioned above are still pretty fast rotators despite their low A_{Li}.

Single evolved stars with enhanced rotation are rare and pose, until now, a difficult challenge for astrophysics. A dredge-up of angular momentum from a rapidly rotating deep interior to the stellar surface is hypothesized by different authors (e.g., Simon & Drake 1989), but other hypotheses like the accretion of brown dwarfs or planets by giant stars can lead to significant spin-up of the stellar surface (Siess & Livio 1999). Both scenarios are still open for observational test. For the five fast rotators discussed above these two scenarios may be hypothesized to explain their enhanced rotation. Nevertheless, because these stars show low A_{Li}, an additional hypothesis seems necessary: if dredge-up of angular momentum did occur, one should not expect lithium production in the stellar interior; on the other hand, if accretion of brown dwarfs or planets is the origin of the observed high rotation, these objects have had no significant A_{Li}. A crucial test for such a hypothesis would be, in the present case, an observation of CNO ratios combined with beryllium measurements.

Finally, Fig. 2b shows two stars, HD 106506 ($v \sin i = 125$ km s^{-1}) and HD 141943 ($v \sin i = 38$ km s^{-1}), with $A_{\mathrm{Li}} = 3.3$. Such a high value of A_{Li} has never been found among evolved stars in the spectral range we are considering. As they also show extremely fast rotation, we consider these objects to be PMS stars. Their position in the $B - V$ vs. M_V CMD is shown in Fig. 1b.

3.2. The A_{Li} vs. $\log T_{\mathrm{eff}}$ diagram: close binaries

Figure 3 shows the A_{Li} vs. $\log T_{\mathrm{eff}}$ distribution for the close binaries (i.e. for components of SBs, including SBs that are members of VBs). Panels a and b show the distribution of close binary components on (40 objects) and above (21 objects) the MS, respectively.

As expected, the close binaries contain a higher proportion of stars with low A_{Li} than the single fast-rotating stars. In fact, high rotation can be sustained by tidal interaction also in old systems, which would otherwise have had enough time to destroy their Li. Thus, if one selects stars based on their high rotation rate, one may expect to select both young and old objects in the case of binaries. Moreover, we know that binarity can affect both A_{Li} and its links with rotation and activity (e.g. Randich et al. 1993, 1994; Fernandez-Figueroa et al. 1993; Barrado y Navascues et al. 1998), and that tidal effects are expected to influence A_{Li} in close binaries, which should retain more Li than single stars of the same age (Zahn 1994). For all these reasons it is not surprising that among the MS single components of SBs in our sample, 3 ($\simeq 8\%$) have an A_{Li} higher than that of the Pleiades, 16 ($\simeq 40\%$) have an A_{Li} between the Pleiades and Hyades, and 5 ($\simeq 12\%$) have an A_{Li} below that of the Hyades, while for 16 stars ($\simeq 40\%$) only an upper limit to A_{Li} could be determined.

The distribution of A_{Li} in binaries is different from that in single stars: more Li-poor objects are found in the binaries. The three stars above the Pleiades upper envelope are the binary components HD 202908 Ab ($A_{\mathrm{Li}} = 3.2$, $v \sin i = 10$ km s^{-1}), HD 84323 a ($A_{\mathrm{Li}} = 3.1$, $v \sin i = 32$ km s^{-1}) and HD 13183 a ($A_{\mathrm{Li}} = 3.1$, $v \sin i = 22$ km s^{-1}). While HD 84323 a and
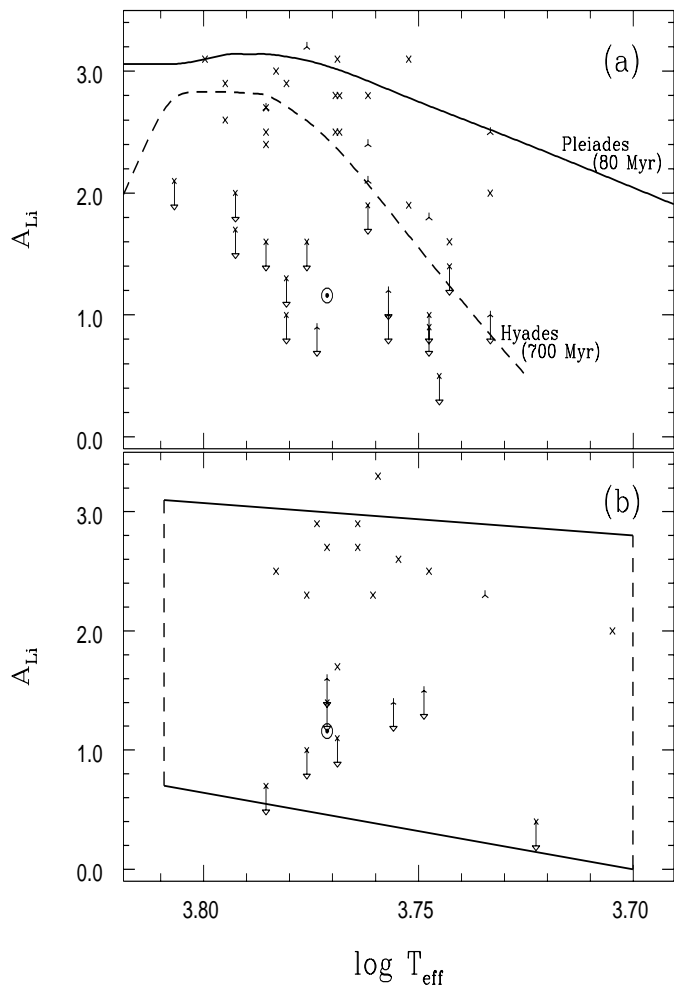
Fig. 3. A_{Li} vs. $\log T_{eff}$ for the close binaries. Symbols as in Fig. 1. Panel **a)** MS stars; the solid and dashed curves are the fiducial A_{Li} vs. $\log T_{eff}$ curves for the Pleiades (top envelope) and Hyades, respectively (adapted from Deliyannis 2000). Panel **b)** stars above the MS; the area inside the quadrangle is the region populated by subgiants, giants and supergiants (adapted from Mallik 1999). The Sun's position is shown in both panels.

HD 13183 a are likely to be ZAMS binaries (see their position in Fig. 1b), the classification of HD 202908 is more difficult. In fact, HD 202908 Ab is part of a multiple system and is itself a VB whose primary component is an SB2 system (see Table 1 and Appendix 2 in Paper I). The A_{Li} values we computed for HD 202908 are 3.0 ($v\sin i$ = 10 km s^{-1}), 3.2 ($v\sin i$ = 10 km s^{-1}) and 2.4 ($v\sin i$ = 9 km s^{-1}) for the Aa, Ab and B component, respectively. This system deserves further investigation and its evolutionary status is not clear at this time. Finally, between the non-MS binaries (Fig. 3b) there is one, HD 104467, with A_{Li} = 3.3 and $v\sin i$ = 23 km s^{-1}, which we believe to be a PMS binary star (see also Fig. 1b).

3.3. A_{Li} vs. $v\sin i$

The behavior of A_{Li} as a function of the projected rotational velocity $v\sin i$ is presented in Figs. 4a, b for both single and binary stars. The first interesting feature that stands out is the large spread in the values of A_{Li} for stars with rotation lower than about 18 km s^{-1}: their A_{Li} show a spread of about 3 orders of magnitude, ranging from 0.4 dex to 3.0 dex for both single and binary stars. However, for single stars the spread decreases with increasing rotation, and the very fast rotators have all high A_{Li}. In particular, all single MS stars rotating faster than about 15 km s^{-1} have $A_{Li} > 2.3$, and all single evolved stars rotating faster than about 18 km s^{-1} have $A_{Li} > 2.0$. No single MS star with $A_{Li} < 1.9$ is observed for $v\sin i > 14$ km s^{-1}.

These results seem to indicate that another stellar parameter plays a significant role in the connection between rotation and A_{Li}. This parameter seems to be important only for single solar-type stars with $v\sin i$ smaller that about 18 km s^{-1}, while for higher rotation rates A_{Li} is always very high. These results are also found for evolved solar-type stars (de Medeiros et al. 2000; do Nascimento et al. 2000). We note that HD 106506 ($v\sin i \simeq 125$ km s^{-1}, $A_{Li} = 3.3$) is not included in Fig. 4a not to compress the dynamic range of the figure too much. For both MS and evolved binary stars, as shown in Fig. 4b, the decrease of the spread in the A_{Li} distribution at high rotation rates is less marked than for single stars. Again this can be explained by the effect of tidally locked rotation: very old binaries can be strongly depleted in lithium while still maintaining a high rotation rate.

Pasquini et al. (1994) found a clear tendency for chromospherically active solar-type stars to have high A_{Li} and vice versa, despite the large scattering observed in the diagram of A_{Li} vs. Ca II surface flux. Similar results are found in samples of X–ray or EUV selected active stars (Favata et al. 1993, 1995; Tagliaferri et al. 1994, 2000; Jeffries 1995). The dependence of A_{Li} on stellar activity is consistent with the predictions of standard evolutionary models, according to which A_{Li} in MS stars should depend on stellar temperature, metallicity and age. Here, stellar activity is considered a good indicator of age for solar–type stars (e.g. Soderblom et al. 1991; Pizzolato et al. 2000). What is not clear is the physical cause of the large spread of the A_{Li} values for single stars with $v\sin i < 18$ km s^{-1}.

Of course, one should expect that for some of these stars the low rotation rate reflects the $\sin i$ effect, i.e. stars seen pole-on. If the stars with $v\sin i < 18$ km s^{-1} and high A_{Li} are all seen pole–on, this could reduce the observed spread somewhat. But it is difficult to believe that *all* the Li-rich slow-rotating stars analysed in this work should have such a preferred orientation of their axes.

One possible explanation is that the observed spread was produced during early MS lifetime. We recall that our sample is not homogeneous in age, and that substantial depletion occurs in G-type stars between the ZAMS and the Hyades age (Pasquini 2000). The observations of young open clusters show that cool ($T_{eff} < 5300$ K) MS stars present a clear spread of A_{Li} (Soderblom et al. 1994; Garcia Lopez et al. 1994; Randich et al. 1998) and that the fast rotators (i.e. stars rotating faster that ~15 km s^{-1}) are all close to the upper envelope of the A_{Li} distribution, while among the slower rotators a large spread is observed. Such a spread among the slower rotators has been discussed in the framework of the time needed to dissipate circumstellar disks during the PMS phase and its consequences on the stellar momentum evolution and the associated mixing in
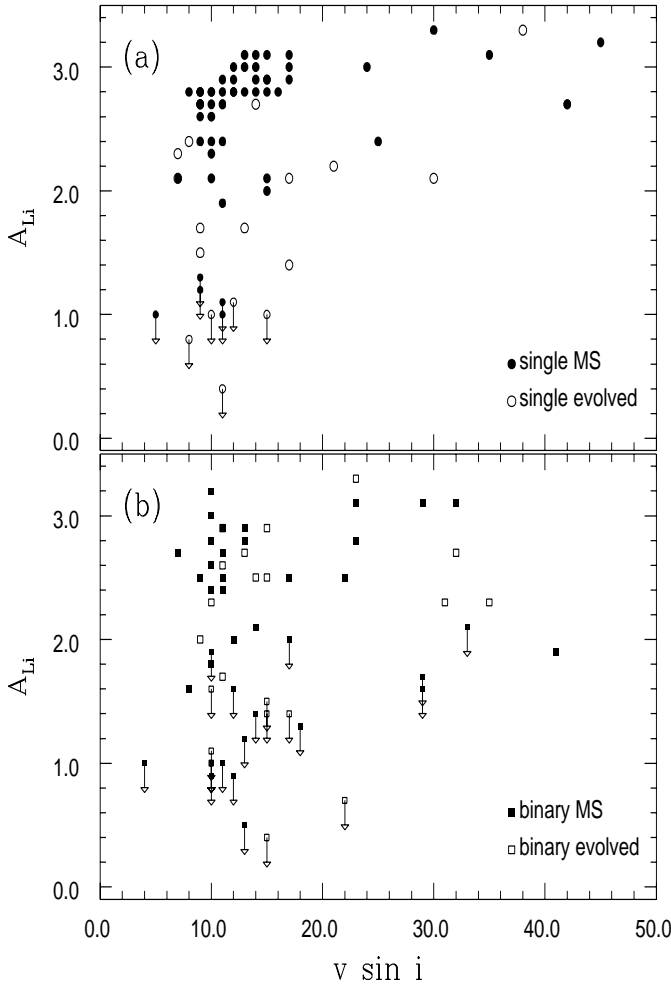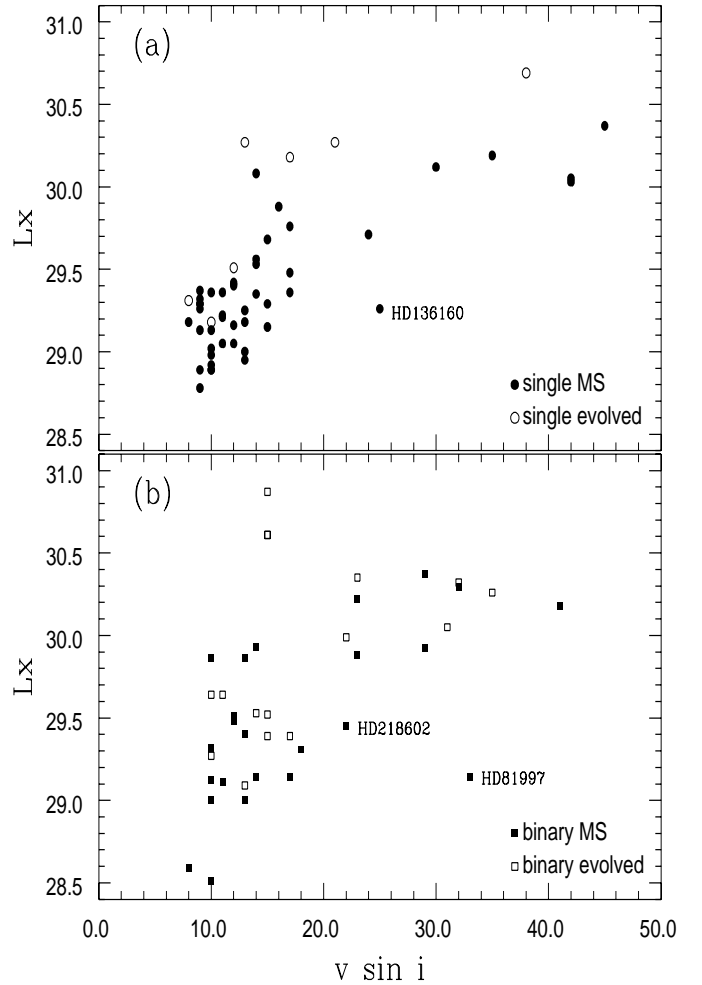
Fig. 4. A_{Li} vs. $v \sin i$ for single **a)** and binary stars **b)**. Note that while all single stars with $v \sin i > 18$ km s^{-1} have $A_{Li} \geq 2.0$, there are binaries with $v \sin i \sim 30$ km s^{-1} for which only an upper limit to A_{Li} was obtained. In our sample of fast rotators, single stars have, on average, higher A_{Li} values than binary stars.

Fig. 5. L_X vs. $v \sin i$ for the single **a)** and binary **b)** stars in our sample detected in the RASS. As expected, L_X correlates with $v \sin i$, although with a large scatter, and all fast rotators are also very active in X–rays (with the exception of a few stars that are not detected, see text).

the early MS phase (Randich et al. 1998). However, the observations of young open clusters show no evidence for scattering among the hottest G-type stars, and these are the objects forming the bulk of our sample (in fact only a few of our stars are as cool as 5300 K). Finally, we recall that Jones et al. (1999) have speculated that extra mixing on the MS could be driven by spin-down and angular momentum loss. If this is indeed true, the observed scattering in the A_{Li} versus $v \sin i$ diagram could be due to different initial rotation rates.

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3.4. L_X vs. $v \sin i$

Solar type stars with moderate to high rotation rates are expected also to be active X–ray sources. Thus we searched the ROSAT all sky survey catalog (RASS, Vöges et al. 1999) and, in case of detection, derived the ROSAT PSPC X–ray luminosity in the 0.2–2.5 keV energy band (see Sect. 3.6 in Paper I).

We found that 81 out of the 110 solar-type stars we studied were detected in the RASS (note that in the X–ray data we cannot separate the contribution of the components of VBs or SBs; see Paper I). In particular, of the 25 stars in our sample with $v \sin i > 18$ km s^{-1}, only three (10%) are *not* detected: HD 73204, HD 92648 and HD 141710: two binary systems with F6V and F7/8V primary stars, respectively, and a single G1/2 III star (see Paper I). In contrast, of the 85 stars in our sample with $v \sin i < 18$ km s^{-1}, only 59 ($\simeq$69%) are detected.

In Figs. 5a, b we plot L_X as a function of $v \sin i$. We note that among the single stars with $v \sin i > 18$ km s^{-1} (Fig. 5a), all the 10 stars detected, except one, have L_X close to or larger than 5×10^{29} erg s^{-1}, a very large value for single stars. The exception is HD 136160 ($v \sin i = 25$ km s^{-1}; $L_X = 1.8 \times 10^{29}$ erg s^{-1}), which, among single stars, has the earliest (F6V) spectral type in our sample and moderately slow rotation for that spectral type. The well-established correlation between L_X and rotation rate (Pallavicini et al. 1981; Schmitt et al. 1985; Hempelmann et al. 1995; Stauffer et al. 1997) is clearly observed. There also seems to be a sort of saturation limit, which would appear even more clearly if we had included HD 106506, which has
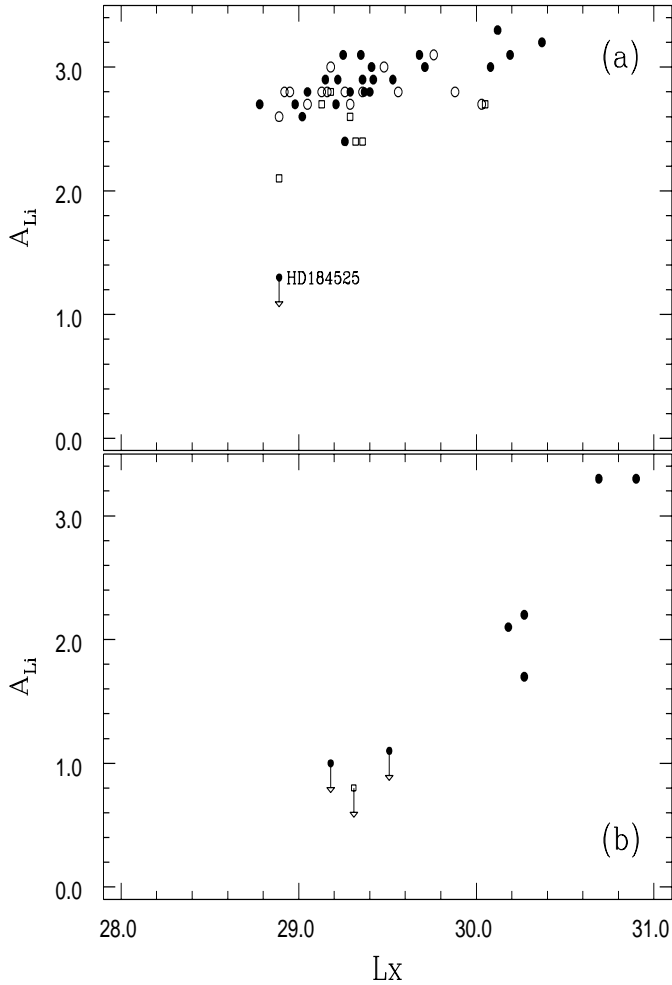
Fig. 6. L_X vs. A_{Li} for single stars. Symbols are as in Fig. 1. Panel **a)** stars on the main sequence; Panel **b)** stars above the main sequence. L_X is clearly correlated with A_{Li}. The correlation is particularly prominent for non-MS stars (panel **b)**), although the latter sample is rather small and the correlation is dominated by the two PMS candidates.
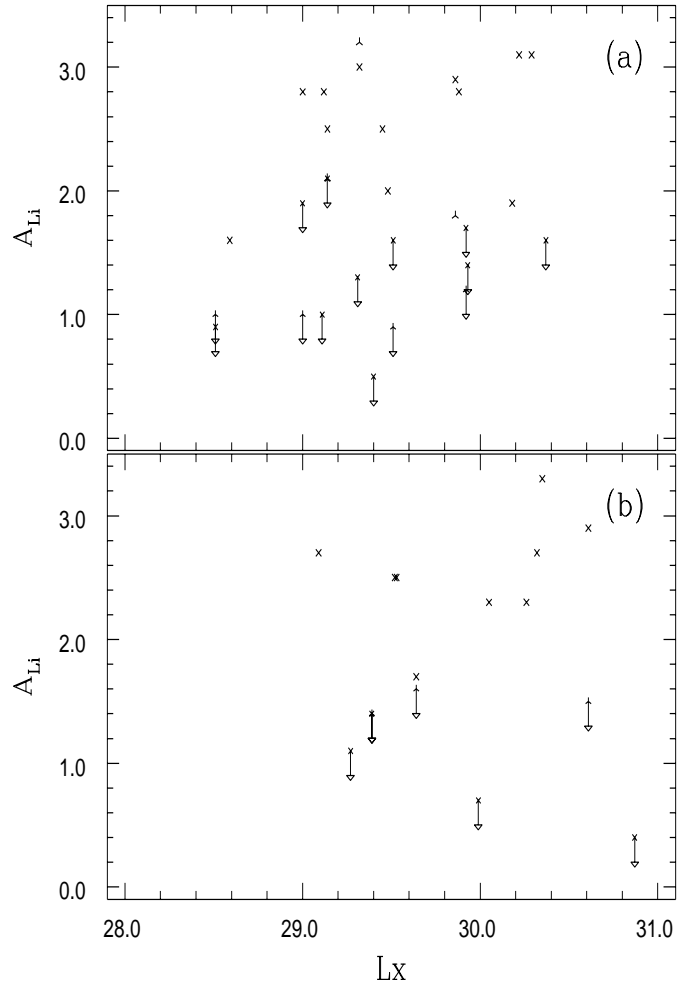
Fig. 7. L_X vs. A_{Li} for the binary sample. Symbols as in Fig. 1. Panel **a)** MS stars; Panel **b)** stars above the main sequence. No correlation is apparent.

$v \sin i \simeq 125 \text{ km s}^{-1}$ and $L_X = 8 \times 10^{30} \text{ erg s}^{-1}$ (we have omitted this star in order to obtain a reasonable dynamic range of the figures and preserve clarity). As expected, in particular at saturation level, single evolved stars have larger L_X compared to single MS stars for similar values of $v \sin i$.

Among the binary stars (Fig. 5b) with $v \sin i > 18 \text{ km s}^{-1}$ all the 13 stars detected, except two, have an L_X near or larger than $8 \times 10^{29} \text{ erg s}^{-1}$. The exceptions are HD 218602, an SB1 (F9V + ?) system with $L_X = 3 \times 10^{29} \text{ erg s}^{-1}$ and HD 81997, an F5V + K5V binary system with $L_X = 1.4 \times 10^{29} \text{ erg s}^{-1}$. The L_X vs. $v \sin i$ correlation is clearly observed also for binary stars. The L_X distributions for MS and evolved binaries are similar, although the largest L_X are observed for evolved binaries. The spread seen for $v \sin i < 18 \text{ km s}^{-1}$ could be partially due, for both single and binary stars, to the presence of a solar-like activity cycle, which in case of the Sun causes L_X to vary by more than a dex (Peres et al. 2000).

3.5. L_X vs. A_{Li}

The behavior of A_{Li} as a function of L_X is displayed in Figs. 6a, b. Despite the lower number of stars in our sample which have both A_{Li} and L_X measured, one observes that for single stars (Fig. 6a) there is a clear tendency for a correlation between A_{Li} and L_X. The only star in Fig. 6a with a very low A_{Li} is HD 184525, which we have already found to be a peculiar object (see Sect. 3.1). Such a correlation between A_{Li} and coronal activity in solar-type stars is also reported by other authors (Tagliaferri et al. 1994; Favata et al. 1995; Jeffries 1995).

It is clear from Figs. 7a,b that no correlation between A_{Li} and L_X exists for binary stars. This is an interesting, but not surprising result, because old binaries, which have suffered strong Li depletion, can still sustain high activity levels through high, tidally induced rotation rates. In contrast, the single fast-to-moderately rotating nearby solar-type stars show a definitive tendency for a correlation between A_{Li} and rotation, as well as between A_{Li} and L_X. We conclude that all single unevolved solar type stars with $v \sin i > 18 \text{ km s}^{-1}$ are strong X–ray emitters and have high A_{Li}. Most likely, they are all very young objects, either ZAMS or PMS.
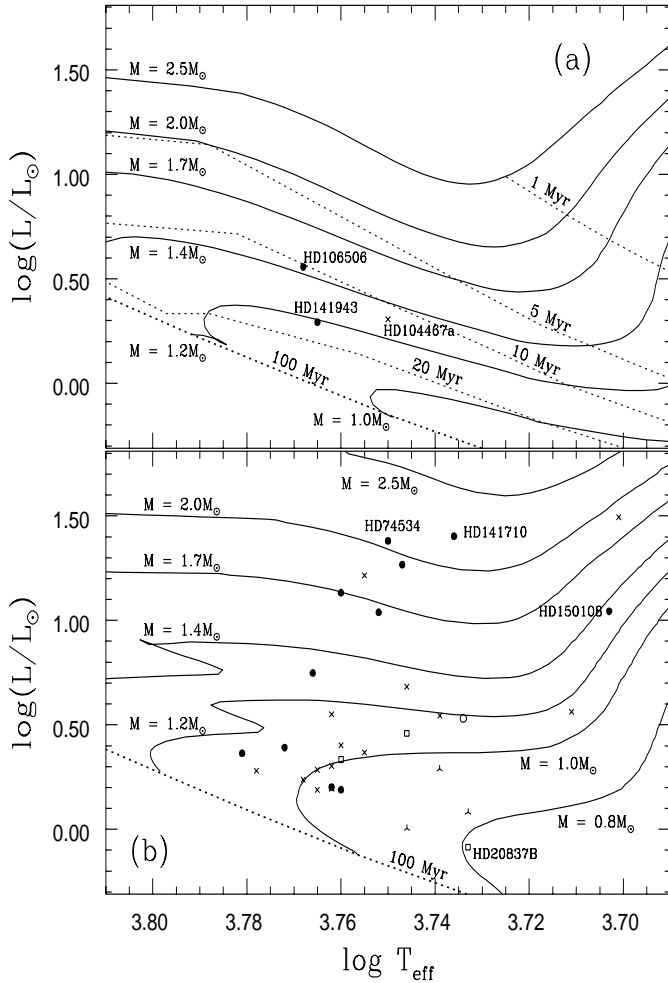
Fig. 8. log $(L/L_\odot)$ vs. log $T_{\rm eff}$ diagram for the PMS and evolved stars of our sample. Symbols are as in Fig. 1. Panel **a)** shows the stars believed to be PMS objects as well as evolutionary tracks (continuous lines) and isochrones (dotted lines) for PMS stars (adapted from D'Antona & Mazzitelli 1997). Panel **b)** shows the stars found to lie above the upper limit of the Hipparcos MS (see Fig. 1) as well as evolutionary tracks (continuous lines) and the 100 Myr isochrone (dotted line) for evolved stars (adapted from Ventura et al. 1998).

3.6. Masses and evolutionary status

We have roughly estimated masses and ages for the PMS and evolved stars in our sample. For the PMS stars we used the evolutionary tracks and isochrones of D'Antona & Mazzitelli (1997), for the evolved stars we used those by Ventura et al. (1998). In both cases, we corrected for the different temperature scales and/or other systematic errors by forcing the 100 Myr isochrone to fit the Hipparcos MS. The resulting shift in log $(L/L_\odot)$ of the models, adopting the Hipparcos M_V and bolometric corrections, was about -0.2 dex.

Figure 8a shows the stars we believe to be PMS objects, and Fig. 8b the stars we found to lie beyond the upper limit of the Hipparcos MS (see Fig. 1). The PMS stars have ages in the 10–18 Myr interval and masses in the 1.4−1.2 $M_\odot$ interval. HD 106506, which is the fastest rotator in our sample, is also found to be the youngest and the most massive star among the PMS objects. Among the evolved stars HD 141710 and HD 74534, with masses of about 2.2 $M_\odot$ and 2 $M_\odot$,

respectively, are the most massive stars in our sample. Their estimated ages are <0.9 Gyr and <2 Gyr, respectively. Among the most evolved single stars we find HD 150108 which has $M \simeq 1.35\ M_\odot$ and an age $\simeq 4$ Gyr. With an age >10 Gyr, HD 20837 B ($M \simeq 0.8\ M_\odot$) is the oldest in our sample of evolved stars.

We have tried to detect any correlation between the stellar mass and the residuals of the individual stars from the correlations discussed above. None was found, showing that the observed surface activity is much more strongly controlled by the rotation and magnetic field in the stellar envelope than by the interior structure, which is primarily dependent on the mass of the star.

4. Conclusion

In this paper, we have discussed the results of high-resolution spectroscopy and high-precision photometry of a sample of 110 nearby solar-type stars (42 single stars, 33 VBs, and 35 SBs), selected for their fast rotation from a CORAVEL radial-velocity survey of late-F to G-type stars brighter than $V \simeq 8.6$. Counting single stars, single components of VBs (which are treated as single stars), plus SB components with inferred spectral classifications, we discussed results for a total of 138 objects (77 single stars and 61 close binary components). Of these, 99 are MS stars (59 single and 40 components of close binaries) and the remaining 39 are evolved stars (18 single and 21 components of close binaries).

The single stars of our sample show statistically higher $A_{\rm Li}$ and activity level than unbiased samples of nearby field stars with similar spectral types. In particular, among the MS single stars of our sample we find that about 10% of them have an $A_{\rm Li}$ higher than that of the Pleiades, while about 64% have $A_{\rm Li}$ between that of the Pleiades and Hyades. Quite surprisingly, we also find four rapidly-rotating single MS stars with very low $A_{\rm Li}$. These four stars could represent examples of stars which suffered peculiar angular momentum histories, but it is not clear how to explain the observed characteristics. These stars deserve further investigation.

The distribution of $A_{\rm Li}$ for single evolved stars is characterized by a large spread, as already observed by other authors for evolved field stars. We find five evolved stars with very low $A_{\rm Li}$ that are still rather fast rotators. Their low $A_{\rm Li}$ cannot be explained by effects related to the stellar rotational history, and these stars also deserve further detailed investigation. We finally identify two new single PMS stars.

The MS binaries of our sample show a larger fraction of stars with low $A_{\rm Li}$. Only 8% of the binaries have $A_{\rm Li}$ higher than that of the Pleiades, while about 40% have $A_{\rm Li}$ between that of the Pleiades and Hyades. This is not surprising, as high stellar rotation can be maintained by tidal interaction also in old binaries which have had enough time to destroy their Li. Thus, in the case of binaries our selection criteria allow both young and old systems to be selected. We also find one new PMS binary star.

The behaviour of $A_{\rm Li}$ as a function of $v \sin i$ for single stars is characterized by a large scattering in $A_{\rm Li}$ for rotations lower than about 18 km s^{-1}. The scattering decreases with

increasing rotation, and the single very fast rotators are all stars with high A_{Li}. These results seem to indicate that another stellar parameter plays a relevant role for the rotation-A_{Li} connection in single solar-type stars with $v \sin i < 18$ km s^{-1}. Although the physical cause of the large scattering is not clear, it could reflect different initial rotation rates. For both MS and evolved binaries the spread of A_{Li} remains large also at high rotation rates. This is because even very old close binaries can maintain a high $v \sin i$ through tidal synchronization.

We have also searched the ROSAT All Sky Survey catalog and derived the PSRC X–ray luminosity for the stars detected. We find that 81 of the 110 possible stars were detected in the RASS (for X–ray data we cannot separate the contribution of VBs and SBs components). Of the 25 stars in our sample with $v \sin i > 18$ km s^{-1} only three are not detected. Out of the 85 stars with $v \sin i < 18$ km s^{-1}, 59 are detected. The well-established correlation between L_X and $v \sin i$ is thus clearly observed, in particular for single stars. There also seems to be a kind of saturation limit.

Our results, in agreement with recent findings from EUV and X–ray surveys, confirm the presence of young very active stars close to the Sun, although our sample has less extreme characteristics than the samples so far selected in the EUV and X–ray bands at the current flux limits (essentially the ROSAT all-sky survey limits).

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