

Lithium, X-ray activity and rotation in an X-ray selected sample of solar-type stars^{*}

F. Favata¹, M. Barbera², G. Micela², and S. Sciortino²

¹ Astrophysics Division - ESA/ESTEC, Postbus 299, NL-2200 AG Noordwijk, The Netherlands
 e-mail: fabio.favata@astro.estec.esa.nl

² Istituto e Osservatorio Astronomico di Palermo, Piazza del Parlamento 1, I-90134 Palermo, Italy

Received 11 March 1994 / Accepted 8 August 1994

Abstract. We present an analysis of the connection between X-ray activity level, photospheric abundance of lithium and surface rotation in late type active main sequence stars (G and K), using the ratio between optical and X-ray luminosity f_X/f_v as a uniform activity indicator. We perform this analysis for a sample of X-ray selected sources from Einstein-based surveys compared to stars from the Pleiades open cluster and to a sample of active binary stars. We show that these parameters show different degrees of statistical correlation in the three samples. In particular, the Pleiades sample shows a significant correlation between all three quantities, while in the X-ray selected sample lithium and rotation are significantly correlated with each other but neither is correlated with the activity level. No correlation is evident for the three quantities studied in the active binary sample. We show how the behavior of the X-ray selected sample can be used to discriminate among different hypotheses about the nature of the so-called “yellow star excess” observed in X-ray flux-limited surveys, showing that this is composed by a population of young, near ZAMS stars with characteristics similar to the Pleiades.

Key words: stars: abundances – stars: activity – Galaxy: stellar content – X-rays: stars – binaries: close – stars: late-type

1. Introduction

The study of X-ray selected samples from *Einstein* observations has shown that the stellar population detected is not easily explained in terms of what we have learned from the detailed study of volume limited samples and of nearby open clusters. In particular present X-ray surveys show more late-type stellar

sources than expected on the basis of the X-ray luminosity distribution of normal nearby stars and of current models for the spatial distribution of stars in the Galaxy. This was already noted by Favata et al. (1988) using the small statistics of the original *Einstein* Medium Sensitivity Survey together with a fairly simple Galaxy model. Although representative of the X-ray stellar sky, an X-ray selected sample is not free from selection effects, being heavily biased toward X-ray luminous sources. In particular, due to the time evolution of X-ray luminosity (which, in late-type stars is observed to decrease with age, see Micela et al. 1990), such a sample is expected to contain a much larger fraction of young stars than it would be the case in a volume limited sample of stars, and, at a given age, to oversample the high luminosity tail of the X-ray luminosity function with respect to its body.

The original analysis of Favata et al. (1988) did not include age evolution. Sciortino et al. (1994, hereafter SFM) have performed a more sophisticated analysis, based on the larger sample of the Extended *Einstein* Medium Sensitivity Survey (EMSS, Gioia et al. 1990), using the XCOUNT numerical model (Favata et al. 1992). This analysis used the improved knowledge on the X-ray luminosity functions and a more sophisticated Galaxy model, keeping into account the age evolution of X-ray luminosity in late-type stars. Even by allowing for age evolution, SFM concluded that a significant excess of yellow stars is still present in the EMSS. The excess must therefore be due to the detection in the X-ray surveys, of a new class of stellar X-ray sources, which is not conspicuous in the immediate solar neighborhood. Favata et al. (1988) originally proposed that the “yellow” stars excess could be due to either a population of active binaries, looking like normal stars in their low resolution spectra, or to a population of young active stars, similar, for example, to π^1 UMa. SFM point out that neither normal giants nor active binaries can be the major contributors to this excess. About one normal giant is predicted to be present in the EMSS, and one is present in our sample, 1E0413.7-6235. As for active binaries, about 20 are detected in the complete EMSS, and a number between 20 and 30 is shown by SFM to be expected, by assum-

Send offprint requests to: F. Favata

^{*} Based on observations collected at the ESO La Silla and DAO Victoria observatories

ing currently accepted values for the spatial density. SFM also show that if the number of unknown binaries still present in the EMSS would be considerable, their spatial density would have to be much higher than currently accepted values, with strong impacts, for example, on their possible contribution to the soft X-ray background. In particular their contribution to the galactic ridge (Ottman & Schmitt 1992) would become higher than the ridge itself.

A similar yellow excess emerges if the $\log(N)$ - $\log(S)$ based on the EUV luminosity function of nearby coronal sources detected in the ROSAT WFC all-sky survey is compared with the $\log(N)$ - $\log(S)$ derived from the flux limited WFC Bright Source Catalog (Hodgkin & Pye 1994) providing additional evidence for the excess not being model dependent. Hodgkin & Pye (1994) suggest that this excess population is actually of the same nature (very young, active sources) as the excess population detected in *Einstein* surveys. Jeffries & Jewell (1993) also reach a similar conclusion, starting from a study of the kinematics of nearby ROSAT EUV sources, making the additional hypothesis that at least a fraction of them are actually part of the Pleiades moving group. This conclusion is further supported by the recent detection of high Li I equivalent widths in a ROSAT EUV selected stellar sample (Jeffries et al. 1993).

In an effort to understand the nature of this population, Favata et al. (1993) have performed a survey of photospheric lithium abundances in a sample of EMSS late-type stars. They show that the EMSS contains a large fraction of lithium-rich objects, very different from what would be expected in a randomly selected sample of field late-type stars (Herbig 1965). Based on observations of a smaller sample of EMSS stars than the one used in this paper, they concluded that lithium abundance alone favors the hypothesis that the excess EMSS population is composed of young stars of age around ZAMS. A similar conclusion has recently been reached by Tagliaferri et al. (1994) for a sample of stars detected in EXOSAT observations. Given the current status of knowledge about the behavior of photospheric lithium abundance with age, lithium alone is not a sufficient diagnostic to pinpoint the nature of the excess yellow population. Lithium is one of the classical age indicators for late type main sequence stars, based on the conventional wisdom that lithium is destroyed at the basis of the convective envelope, and that therefore the lithium abundance in these stars should decrease steadily with age, with a law which varies with stellar mass. The advent, in recent years, of digital detectors and better spectrographs has allowed the photospheric lithium abundance to be studied in fainter and more uniform and complete samples of late-type stars than ever before. These studies have shown that the classical picture of lithium abundance being only a function of stellar mass and age was too simplistic. In fact, each new detailed study of lithium abundance in the last few years seems to open up new questions.

The aim of this paper is to investigate the relation of Li I 6708 Å equivalent width with X-ray activity as measured by f_X/f_v in *Einstein* surveys (in the 0.16–3.5 keV band), and with projected rotational velocities. As a comparison, we extend the study to other, well differentiated and more homogeneous sam-

ples of solar-type stars, in particular a sample from the Pleiades and a sample composed of active binaries. In the course of the study it became evident that the location occupied in the $W(\text{Li})$, f_X/f_v and $v \sin(i)$ “space” by a group of stars can be used to characterize (at least statistically) a stellar population, and therefore to discriminate between apparently similar populations of yellow stars. We have therefore used the information in turn to analyze the population content of our X-ray selected sample. To this end, we have enlarged the sample of Favata et al. (1993) by observing the Li I 6707.8 Å line in an additional sample of late-type stars from the EMSS and in a sample of stars from the *Einstein* Slew Survey (ESS, Elvis et al. 1992). The *Einstein* Slew Survey is characterized, with respect to the EMSS, by a larger sky coverage and by a shallower limiting sensitivity, given the much shorter effective exposure time (usually hundreds of seconds versus the thousands of seconds typical of EMSS fields). Any flux limited survey will preferentially select the more active sources; we expect this effect to be more pronounced in the ESS.

In addition, we have used all of our samples to investigate some open questions about the behavior of lithium abundance in late type stars: is the photospheric lithium abundance a good proxy for stellar activity? Does stellar activity actually enhance the (apparent) photospheric lithium abundance? Is the lithium abundance correlated with stellar rotation? Does this correlation, if present, extend across a large range of stellar ages and spectral types? To this end, the approach of studying an X-ray selected sample of stars is, in a sense, complementary to the one of studying open clusters, given the larger range of stellar ages represented in such a sample, and given that the age distribution in such a sample should be continuous.

In the course of the present work the equivalent width of the Li I 6708 Å line $W(\text{Li})$, rather than the “computed” lithium abundance has been uniformly used as indicator of the lithium abundance. This should enable a better comparison of heterogeneous data sets, as it eliminates the influence of uncertainties in T_{eff} and differences in the analysis methods (different curves of growth and usage of the curve of growth approach versus fitting of model spectra) used to compute abundances by different authors. The choice of f_X/f_v as our activity indicator derives from the lack of reliable distances in the X-ray selected sample, and therefore of reliable luminosities L_X .

2. The observed and the comparison samples

2.1. The X-ray selected sample

Our complete X-ray selected sample includes stars from both the *Einstein* Extended Medium Sensitivity Survey and the *Einstein* Slew Survey. They have been selected from the complete stellar EMSS and ESS samples on the basis of being of spectral type F or later, and of being brighter than m_V about 12 (our observational limit). Most of the observations of the EMSS sample analyzed here (66 objects) have been described by Favata et al. (1993) (hereafter FBMS), who describe in more detail the sample and the data analysis procedures that were followed. A

further 7 EMSS sources which satisfied these same selection criteria have been observed more recently for this program, and they are listed in Table 2 in the Appendix.

In the framework of a program aimed at identifying the optical counterparts of the *Einstein* Slew Survey, we have selected a number of X-ray sources whose most likely counterpart is a late type star. The identification process is described in detail by Schachter et al. (1994). Here we only include in the X-ray selected sample the ESS stars of which we have obtained a spectrum in the Li I 6708 Å region and which satisfy the same selection criteria as the EMSS sources. The *Einstein* Slew Survey sample contains 25 objects, which are also listed in Table 2 in the Appendix.

For the complete sample of 73 EMSS plus 25 ESS sources rotational velocities ($v \sin(i)$) have been determined, as described later; for the more recently observed sample of 7 EMSS plus 25 EMSS stars also Li I 6707.8 Å equivalent widths ($W(\text{Li})$) have been obtained.

Both the EMSS and the ESS samples contain stellar sources which are not of interest in the framework of our study of the “yellow excess” sources. In particular some normal giants are present in the X-ray selected sample, together with some identified active binaries (such as RS CVn type binaries). Both active binaries and giants stars have been removed from the “normal” sample, which should therefore only consist of main sequence normal coronal sources.

For the purposes of the present work, we define an active binary as an object in which its binary nature influences, on the basis of current knowledge, either the lithium abundance or the activity level, typically through tidal locking of the rotational and orbital period. To be classified as an active binary, an object in our X-ray selected sample must satisfy the following criteria: it must be a binary containing an object which is evolved for its activity level, i.e. normally spectral class IV or III, and it must have a short enough period as to be tidally locked (i.e. of the order of 10 days or less). This implies that active binaries should have a $v \sin(i)$ higher than normal for its age and spectral class. Also, given the lack of evidence of evolved objects with very high lithium abundances (with the exception of AGB stars), we exclude from the active binary group any object with $N(\text{Li}) \geq 2.0$. Notice that our criteria differ, from example, from the ones used in Fleming et al. (1989), which uses the following four criteria: 1) radial velocity variations, 2) rapid rotation, 3) spectral type between F and early K and 4) unusually strong CaII H and K emission. We feel that this set of criteria, which omits the evolutionary status of an object, would easily include, for example, solar-type binaries in the Pleiades, in which both the fast rotation and activity level are due to young age rather than to the binary nature. In particular, Pleiades solar-type binaries show the same activity level as Pleiades single stars (Micela et al. 1990) and no difference in their lithium abundance (Soderblom et al. 1993, hereafter SJBS), and should therefore be considered “normal” for the purposes of this work. This difference in criteria actually results in only two systems being considered active binaries by Fleming et al. (1989) which not satisfy our criteria.

We have verified that their inclusion or exclusion in our normal sample does not change the results (see Table 1).

A considerable number of the sources which we included in the normal sample are known to be binaries, although with no evidence of being classifiable as active binaries according to the above criteria. The objects which have been included in the study of the $W(\text{Li}) - f_X/f_v$ correlation as normal main sequence (or pre-main sequence) coronal sources are marked in Tables 3 and 4 with an “ms”. The active binaries present in the sample were separately analyzed, and are marked in Tables 3 and 4 with an “a”. Finally the systems which do not satisfy our criteria for an active binary but are considered as such by Fleming et al. (1989) are marked with “abc” in the tables.

In principle, our X-ray selected sample has been cleaned as described before, and should only contain “normal” stellar coronal sources. However, given the nature of the X-ray selected sample and of the optical counterpart identification process, it is not unlikely that the sample could be contaminated, specially among the optically fainter objects, with a small number of other types of X-ray active stellar systems. In particular, it is conceivable that a small number of unrecognized active binaries could still be still present. Many (38 out of 73) of the objects coming from the EMSS have been searched for radial velocity variations (indicative of stellar multiplicity) by Fleming (1988). Of these, 18 show radial velocity variations, indicating a binary fraction of about 50%, typical for solar-type main sequence objects (Duquennoy & Major 1991).

Not many unrecognized active binaries should remain among these objects, given that they are classified as luminosity class V. Some of the object coming from the EMSS were however not in the Fleming (1988) sample, and for these objects the amount of optical information available is usually limited, being in most cases restricted to the classification of Stocke et al. (1991), based on low resolution spectrograms and UBV photometry. Our own observations of these stars consist usually of a single high resolution spectrogram, and it is therefore possible that a few unrecognized SB1 active binaries could be present among these objects. On the other hand, as discussed above, only a handful of undetected active binaries can be present in the EMSS.

2.2. The Pleiades sample

Our Pleiades sample is formed by the intersection between the sample of Pleiades stars on which SJBS report the lithium abundance and the value of $v \sin(i)$ and the sample of Pleiades stars for which Micela et al. (1990) report the value of X-ray flux (either detection or upper limit) based on *Einstein* IPC X-ray observations. The SJBS sample contains all known Pleiades dwarfs with unreddened colors $0.40 \leq B - V \leq 1.40$, while the Micela et al. (1990) sample contains all known Pleiades members falling in Einstein IPC fields (283 stars). Our Pleiades sample, resulting from the intersection of the two above subsamples, contains 102 stars, and it should be representative of the whole Pleiades population. Additionally, it covers well the spectral type range of our X-ray selected sample.

2.3. The RS CVn sample

The sample of active binaries has been selected from the Dempsey et al. (1993) survey of active binaries observed in the ROSAT All Sky Survey (RASS), which reports soft X-ray count rates for the 136 RS CVn systems listed in Strassmeier et al. (1988). From the Dempsey et al. (1993) sample we have selected the 25 objects which were also observed in the lithium 6708 Å region by Pallavicini et al. (1992), who give $B - V$, T_{eff} , Li I 6708 Å equivalent width and $v \sin(i)$ values. The f_x/f_v values were computed using mean optical magnitudes from Strassmeier et al. (1988) and RASS count rates, using a conversion factor of 6.0×10^{-12} (erg s⁻¹ cm⁻²)/(count s⁻¹), as given by Dempsey et al. (1993). This procedure has allowed the selection of a sample of (mostly optically selected) RS CVn type active binaries with the same observational quantities as our X-ray selected sample, i.e. soft X-ray flux, $W(\text{Li})$ and $v \sin(i)$.

Note that one object (HD 155555) has been removed from the RASS sample as it does not satisfy the definition of active binary used here, as discussed in Section 2.1. This object is classified as an RS CVn-type binary in Strassmeier et al. (1988), as it shows many of the properties of an active binary: short orbital period (1.7 d), spectral types G and K, signs of stellar activity. This system has been studied in detail by Pasquini et al. (1991), who show that the system has a photospheric lithium abundance $N(\text{Li}) \geq 3.5$, strongly pointing toward its being a pre-main sequence object, in which the high level of stellar activity is the consequence of its youth rather than of the mechanisms acting in evolved active binaries. One object apparently similar to HD 155555 is also present in our X-ray selected sample, 1E 0315.7-1955, an SB1 system with a fairly high $v \sin(i)$ value of 33 km/s, and a surface lithium abundance $N(\text{Li}) \geq 3.5$. It was classified by Stocke et al. (1991) as an RS CVn candidate, but on the basis of the very high lithium abundance it is likely to be an object in the same league as HD 155555, i.e. a pre-main sequence binary. As it again does not satisfy our definition of active binary, we have maintained it as a normal object in the sample. The case of HD 155555 points out the difficulty of considering active binaries as an homogeneous sample: the Strassmeier et al. (1988) catalog, widely used as a starting point in selecting RS CVn samples, contains binary systems of widely different periods, spectral types, luminosity class and evolutionary status. Therefore the resulting samples are most likely rather heterogeneous, and any global property inferred from the sample should be treated with caution.

3. Observations and data reduction

For a description of the observations of the previously published sample of 66 EMSS stars the interested reader is referred to FBMS. Here we will describe the observations of the 25 *Einstein* Slew Survey plus the additional 7 Extended Medium Sensitivity Survey stars. The observations presented here were obtained at the European Southern Observatory (ESO) in La Silla on December 1992, using the 1.44m CAT telescope and the Coude Echelle Spectrograph (CES) with the short camera

and the RCA (ESO #9) CCD, at about 2.6 Å/mm dispersion, corresponding to a resolving power of approx. 50 000 as measured on Th-Ar lamp exposures. All the spectra discussed here were taken in a region centered on the Li I 6708 Å line, and covered about 45 Å. Standard data reduction (bias subtraction, flat fielding, spectrum extraction and wavelength calibration) was performed using the IRAF software package, as described in detail in FBMS. The equivalent width of the Li I 6707.81 Å line was extracted from the spectra, using the procedure described in FBMS, which keeps into account the effect of the nearby Fe I 6707.44 Å line. The equivalent widths were converted into lithium abundances by interpolating the curves of growth of Pallavicini et al. (1987) to obtain the lithium abundances shown in Table 1 (although only equivalent widths have been used in the rest of the analysis). The effective temperatures were determined from the $B - V$ index, when available, or from the spectral type, using a spline fit to the color-temperature and spectral type-temperature relationships of Zombeck (1990). In the case of binaries, if the color or spectral type of the two components, separate T_{eff} values were derived, otherwise the integrated color or spectral type was used, assuming that the two components are similar.

3.1. Determination of the rotational velocity ($v \sin(i)$)

We have re-analyzed the complete data set, that is the 66 spectra for which lithium abundances have already been published by FBMS, plus the 25 ESS and 7 EMSS new stars, to determine the projected rotational velocity $v \sin(i)$. To this end we have performed a cross-correlation between the object spectra and a solar spectrum of the same spectral region exposed on the dusk sky using the IRAF *fxcor* software task. A gaussian fit was performed on the cross-correlation peak, and the FWHM of the fitted peak was determined. As discussed for example by Soderblom et al. (1989), the fitted FWHM of the cross-correlation peak is a measure of the rotational velocity of the program object. We have calibrated the technique by observing a sub-sample of the rotational velocity standard stars of Soderblom et al. (1989). The relationship between the FWHM of the cross-correlation peak and the projected rotational velocity for the standard stars is shown in Fig. 1. The linear relationship shown in Fig. 1 has then been used to determine the rotational velocity for the program stars. The effective upper limit for detectability of rotation when using the cross-correlation technique is determined, among other things, by the spectral resolution of the instrument, and is therefore not uniform in our sample, as some of the stars from FBMS have been observed with the Dominion Astrophysical Observatory (DAO) 1.22m telescope and Coude Spectrograph, in a configuration yielding an effective resolving power of about 30 000. We estimate the effective limit for detection of rotational velocity to be about 8 km/s for the ESO observations and about 14 km/s for the DAO observations. The objects used for calibrating the rotational velocity versus cross-correlation peak width are of spectral types F and G. The usage of a solar template calibrated against F and G stars can introduce systematic errors when measuring the rotation rate in later

type stars, due for example to the different macro-turbulence values. We have verified, by using a slowly rotating later type (K0V) spectrum as template, that the eventual systematic errors are smaller than our quoted uncertainties on $v \sin(i)$, that is, ± 3 km/s. In the case of SB2 multiple systems two cross-correlation peaks (in one case three) are clearly evident in the correlograms, and the $v \sin(i)$ value has been determined separately for each component. As also discussed by Soderblom et al. (1989) the cross-correlation method becomes less accurate for large values of $v \sin(i)$ (greater than about 50 km/s), where the cross-correlation peak becomes significantly non-gaussian, and where the rotational broadening of a single line begins to cover a significant fraction of the limited spectral region (about 45 \AA) observed. Therefore the higher values of $v \sin(i)$ reported here should be treated with caution.

We show in Table 2 the Li I 6707.8 \AA equivalent width for the X-ray selected sample, including the ESS sources, and in Tables 3 and 4 the $v \sin(i)$ value determined in the present work. The f_X/f_V index was determined using optical magnitudes (taken from Stocke et al. 1991 for EMSS sources and from standard catalogs for ESS sources) and X-ray count rates (from Stocke et al. 1991 for EMSS sources and from Elvis et al. 1992 for ESS sources), converted into X-ray flux using a $2.0 \times 10^{-12} \text{ (erg s}^{-1} \text{ cm}^{-2})/(\text{count s}^{-1})$ conversion factor, appropriate for coronal sources observed with the *Einstein* IPC.

4. Relationships between lithium, activity and rotational velocity

4.1. The Pleiades sample

SJBS show, in their Fig. 2b, that there is a very clear tendency for Pleiades stars with higher values (for their color) of observed Li I 6708 \AA equivalent width to also have a high value of $v \sin(i)$. An analogous effect is evident from their Fig. 2c where the R_{8542} activity index (an index of chromospheric activity, determined from the strength of the emission core of the Ca II 8542 \AA line) replaces $v \sin(i)$. We have plotted the f_X/f_V values obtained from the X-ray flux data of Micela et al. (1990) in a manner similar to SJBS's Fig. 2, using SJBS's values of $W(\text{Li})$. This plot is shown in our Fig. 2. It is apparent that there is tendency for the stars with high $W(\text{Li})$ values to also be X-ray bright. To test whether this is a real effect we have computed a local robust regression to the $W(\text{Li})$ values of SJBS as a function of $B - V$ (using the algorithm of Cleveland 1979, suitably modified to take into account the presence of upper limits, as discussed by Micela et al. 1988), and have subdivided the sample in high lithium and low lithium objects, based on their lying above or below the robust fit in the $N(\text{Li})$ vs. $B - V$ plane, as shown in Fig. 2.

The X-ray data contain a large number of upper limits (46 stars out of 102); it is therefore appropriate to use maximum-likelihood distributions, computed using a technique that keeps into account both detections and upper limits (Avni et al. 1980; Schmitt et al. 1985; Feigelson & Nelson 1985). The distribution functions in f_X/f_V were computed, separately for the high

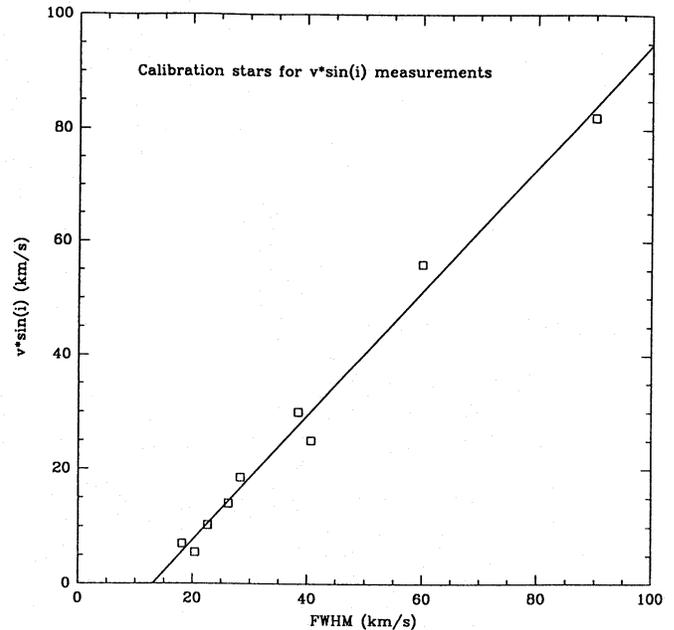


Fig. 1. Rotational velocity for the calibration stars plotted against the width (FWHM) of the cross-correlation peak with a solar spectrum. The line is a linear fit to the data, which has been used to compute the $v \sin(i)$ for the program stars

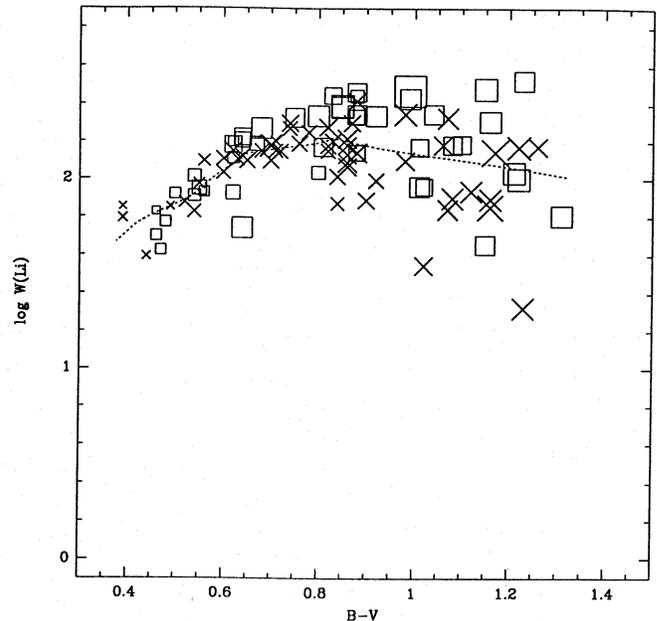


Fig. 2. Scatter plot of the Li I 6707.8 \AA equivalent width versus $B - V$ for our Pleiades sample, using the data of SJBS. Symbol size is proportional to the $\log(f_X/f_V)$ ratio, computed using the X-ray luminosity data of Micela et al. (1990) (squares represent X-ray detections, while crosses represent X-ray upper limits). The robust fit we have used to separate the high and low lithium samples is also plotted

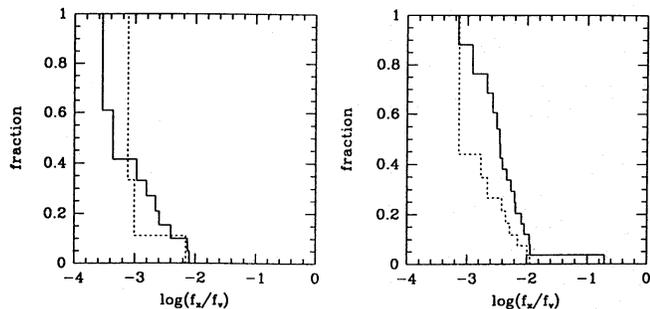


Fig. 3. Distributions in $\log(f_X/f_v)$ for the two Pleiades sub-samples, the high lithium and the low lithium one. The left panel shows the distribution for Pleiades G stars, the right panel shows the distributions for Pleiades K stars. In both cases the continuous line is the distribution of the high lithium sub-sample, while the dotted line is the distribution of the low lithium sub-sample

lithium and the low lithium sub-samples. This has been done separately for G ($5200 \leq T_{\text{eff}} \leq 5900\text{K}$) and K ($5200 \leq T_{\text{eff}} \leq 4150\text{K}$) stars. The f_X/f_v distribution functions are shown in Fig. 3.

The two Pleiades K sub-samples, although with a superposition of activity levels, have strongly different f_X/f_v distributions, while the f_X/f_v distributions for the two G stars sub-samples appear very similar. A Wilcoxon test was applied to the low and high lithium distributions, separately for G and K stars, and the results (Table 1) show that we can reject the null hypothesis that the f_X/f_v distribution for the high and low lithium Pleiades sub-samples are drawn from the same parent distribution to a probability level of better than 97.3% for the K sample, while the probability level is only 25.9% for the G sample, indicating that the two samples are basically indistinguishable on the basis of these data.

A similar analysis of the Pleiades data has then been performed by using $v \sin(i)$ instead of $W(\text{Li})$ as a discriminant. Figure 4 shows a scatter plot of $v \sin(i)$ versus $B - V$, still using the data of SJBS. Again, a robust fit is plotted, which is used to separate high and low $v \sin(i)$ sub-samples. Similarly to what was done for the high and low Li sub-samples, maximum likelihood distribution functions were computed for the two sub-samples (Fig. 5). Distribution functions in both f_X/f_v and $W(\text{Li})$ were separately subject to a Wilcoxon test. Rotational velocity appears to discriminate efficiently in K stars between low and high lithium stars (at the 99.0% probability level), doing only very marginally so in G stars (67.1% probability level). Finally, rotational velocity appears to discriminate between low and high X-ray activity very efficiently in both G and K stars (at the 97.7 and 99.9% level, respectively). Already Micela et al. (1990), using a smaller (and presumably less homogeneous) set of Pleiades $v \sin(i)$ measurements, had shown that in the Pleiades, notwithstanding the fact that the usual L_X vs. $v \sin(i)$ relationship ($L_X \propto v \sin(i)^2$, Pallavicini et al. 1981) does not appear to hold, stars with higher values of $v \sin(i)$ tend to also have high L_X values (cf. Fig. 7 of Micela et al. 1990). It should be noted that the apparent lack of dependence of $W(\text{Li})$

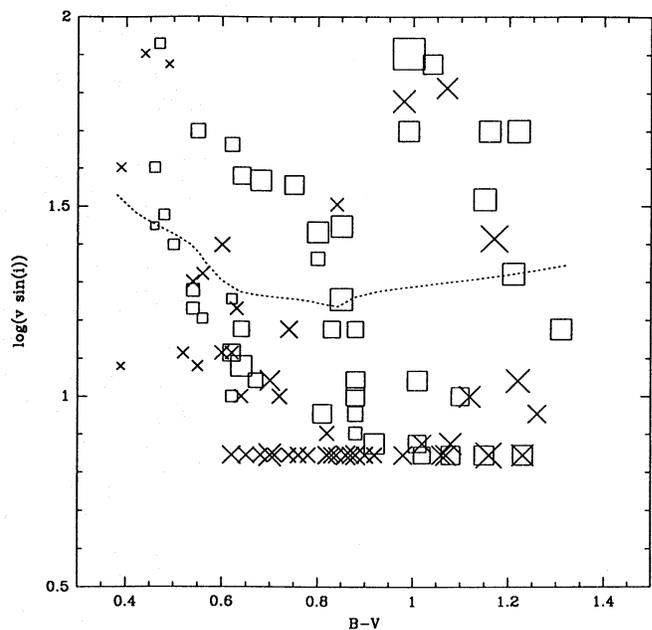


Fig. 4. Scatter plot of $v \sin(i)$ versus $B - V$ for our Pleiades sample, using the data of SJBS. Symbol size is proportional to $\log(f_X/f_v)$ ratio, computed using the X-ray luminosity data of Micela et al. (1990) (squares represent X-ray detections, while crosses represent X-ray upper limits). The robust fit we have used to separate the high and low $v \sin(i)$ samples is also plotted

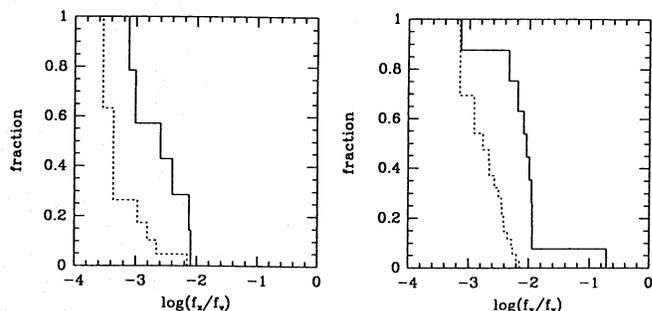


Fig. 5. Distributions in $\log(f_X/f_v)$ for the two Pleiades sub-samples, the high $v \sin(i)$ and the low $v \sin(i)$ one. The left panel shows the f_X/f_v distributions for Pleiades G stars, the right panel the same distributions for Pleiades K stars. In both cases the continuous line is the distribution of the high $v \sin(i)$ sub-sample, while the dotted line is the distribution of the low $v \sin(i)$ sub-sample

on rotation in Pleiades G stars may be due to the restricted spread in $W(\text{Li})$ present, in which measurement errors may hide the correlation. This would not contradict the presence of such a dependence in X-ray selected G stars, which show a much greater range of $W(\text{Li})$.

As discussed in detail by SJBS, the Pleiades sample is essentially coeval, and the spread observed in both $W(\text{Li})$ and $v \sin(i)$ at a given mass cannot be explained by any reasonable initial age spread. Therefore the spread in both $W(\text{Li})$ and $v \sin(i)$ must be intrinsic, being the consequence either of a difference in the initial conditions or of a different evolutionary

Table 1. Results of the Wilcoxon test, on the null hypothesis that the distributions in both f_X/f_V and $W(\text{Li})$ for the high and low lithium Pleiades and X-ray selected sub-samples, and the high and low $v \sin(i)$ sub-samples respectively are not drawn from the same parent population. The two set of values reported in the table for the X-ray selected sub-samples are for the “nominal” main sequence sample and for the sample from which known active binary candidates (ABC) have been excluded, as indicated in Tables 3 and 4. None of the samples includes established active binaries.

Discriminated by	$W(\text{Li})$	$v \sin(i)$	
Distributions tested	f_X/f_V	f_X/f_V	$W(\text{Li})$
Pleiades G sample	0.259	0.977	0.671
Pleiades K sample	0.973	0.999	0.990
X-ray sel. G sample	0.048	0.541	0.986
X-ray sel. K sample	0.842	0.612	0.983
X-ray sel. G sample (w/o ABC)	0.048	0.514	0.984
X-ray sel. K sample (w/o ABC)	0.842	0.612	0.983

history. The high level of significance in our tests shows that present-day rotational velocity is an important parameter in determining, directly or indirectly, the surface lithium abundance. Current models of the evolution of rotating solar-type stars are not easily reconcilable with observations, as discussed in more detail later.

4.2. The normal stars from the X-ray selected sample

A plot of $W(\text{Li})$ versus $(B - V)$ for the apparently normal stars from the X-ray selected sample is shown in Fig. 6, while Fig. 7 shows a $v \sin(i)$ versus $B - V$ scatter plot. In these figures square symbols indicate stars from the EMSS, while hexagonal symbols indicate stars from the ESS. While the EMSS sample occupies essentially the whole $(B - V)$ – $W(\text{Li})$ plane below the line roughly determined by the primeval Li abundance, the Slew Survey sample is strongly concentrated toward the high values of $W(\text{Li})$, in a region similar to the one covered by the Pleiades. This difference between the two sub-samples will be discussed in detail in Sect. 5.

To study whether, similarly to the behavior of the Pleiades sample, a connection between $W(\text{Li})$ and activity is present the X-ray selected sample has been sub-divided in two sub-samples: $5200 \leq T_{\text{eff}} \leq 5900$ (equivalent to $0.60 \leq B - V \leq 0.80$, corresponding to main sequence G stars) and $4150 \leq T_{\text{eff}} \leq 5200$ (equivalent to $0.80 \leq B - V \leq 1.30$ approximately corresponding to main sequence K stars).

The procedure used has been the same as the one used for the Pleiades sample: first the sample has been sub-divided into two sub-samples, high $W(\text{Li})$ and low $W(\text{Li})$ then a Wilcoxon test has been applied to compare the f_X/f_V distribution functions of the two sub-samples. The same procedure has been repeated for the f_X/f_V and $W(\text{Li})$ distributions segregated on the basis

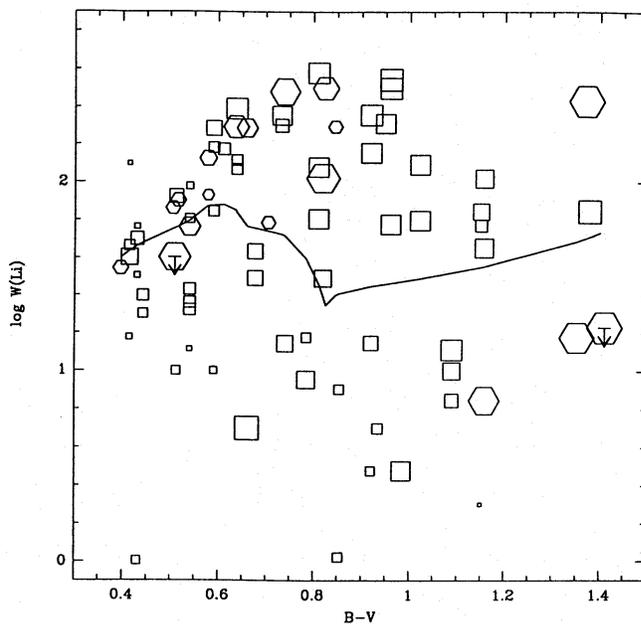


Fig. 6. Scatter plot of the lithium 6707.8 Å equivalent width versus $B - V$ for our X-ray selected sample. Square symbols indicate stars from the EMSS, while hexagonal symbols indicate stars from the ESS. Symbol size is proportional to the f_X/f_V ratio. $W(\text{Li})$ upper limit are indicated. The robust fit we have used to separate the high and low lithium samples is also plotted. The plotted $B - V$ value is computed from the spectral type for the stars which have no $B - V$ measurements available

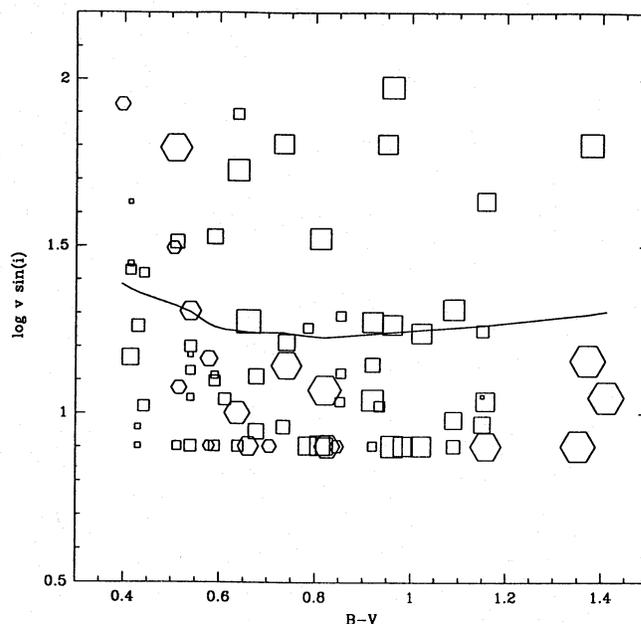


Fig. 7. Scatter plot of $v \sin(i)$ versus $B - V$ for our X-ray selected sample. Symbol size is proportional to the f_X/f_V ratio. The robust fit we have used to separate the high and low $v \sin(i)$ samples is also plotted. The plotted $B - V$ value is computed from the spectral type for these stars which have no $B - V$ measurements available

of high and low $v \sin(i)$. The results of the Wilcoxon test are shown in Table 1.

The results show that, while the lithium has a marginal, if any, connection with the activity level (probability level is only 84.2%) for X-ray selected K stars, rotational velocity acts as a strong discriminator of surface lithium abundance, at a level comparable to the Pleiades sample, for both G and K stars. Similarly to what happens in Pleiades K stars, fast rotating X-ray selected G and K main sequence stars have significantly more lithium than slowly rotating ones. To check whether the definition of active binary that we have used influences the results, we have repeated the test by excluding the objects which do not satisfy our definition of active binary but which are classified as such by Fleming (1989). As is can be seen from Table 1, this effectively makes no difference in the confidence levels.

The connection between $W(\text{Li})$ and activity observed in the X-ray selected sample appears to be at most weak (if not downright absent), and rotation appears not to influence the activity level of our objects, in agreement with what has been found by Fleming et al. (1989) (See their Fig. 5a), who justify this lack of correlation on the basis of saturation of the activity level. On the other hand rotational velocity appears to discriminate strongly among systems with a high and a low lithium abundance, to a probability level of about 98%, both in G and in K main sequence stars. As shown in Table 1, the exclusion of the active binary candidates from our sample does not modify this result. This correlation is similar to the one seen in Pleiades K stars, with faster rotators on the average being lithium-rich with respect to slow rotators.

The mean level of each of the three quantities ($W(\text{Li})$, $v \sin(i)$, f_X/f_v) is known to decrease with age (although perhaps with a large dispersion) in solar-type stars, and therefore some level of correlation was expected in a sample, like the X-ray selected sample, in which a fairly wide age range is considered. It is therefore somewhat surprising that while activity is not being influenced by neither rotation nor lithium (perhaps an indication of saturation of the activity level), lithium and rotation appear to be linked with each other. The lithium rotation connection could either be an intrinsic characteristic of solar-type stars, in which case the observed correlation would be analogous to the one observed in the Pleiades, or it could simply be a reflection of the average declining levels of both lithium and rotation with age. Given that, as it will be shown later, there are strong indications that the X-ray selected sample is strongly biased toward young stars, the hypothesis of an intrinsic correlation is favored. The current sample size does not allow to test this hypothesis by further trying to subdivide the sample in young and old sub-samples, because one quickly runs into small number statistics. Further light on the problem will be shed by the study of larger, volume limited samples of solar-type stars (Favata et al. 1994).

5. The composition of the X-ray selected sample

By comparing the behavior of $W(\text{Li})$, f_X/f_v and $v \sin(i)$ in the various samples studied here we can derive constraints on the nature of the X-ray selected “normal” population and on

the excess of solar-type sources present in the EMSS. We have sub-divided the sample of normal stars from the EMSS into three “age” groups based on the value of $W(\text{Li})$. The first group (“Pleiades-like” stars) includes all the stars which, in the $W(\text{Li})$ – $B - V$ diagram fall in the region defined by the envelope of the Pleiades sample. The second (“Hyades-like” stars) group includes all the stars with $W(\text{Li})$ values too low to fall into the Pleiades region but higher or equal to the line defined by the Hyades $W(\text{Li})$ measurements of Thorburn et al. (1993). The third group (“old disk-like” stars) includes all the stars with $W(\text{Li})$ lower than the previous groups. To evaluate to which one of these three ranges of $W(\text{Li})$ do the excess sources belong we have computed the expected number of sources in each age range using the XCOUNT numerical Galaxy model (Favata et al. 1992). The contribution to the total population of the three age groups corresponding to Pleiades-like, Hyades-like and old disk-like, has been computed separately, as described in detail by SFM. Note that this could not be done for the ESS sample, because the detailed distribution of limiting sensitivity for the ESS is not known (Elvis et al. 1992), and therefore ESS sources have been removed from the X-ray selected used in the following discussion.

We have compared, separately for G and K spectral types and for each of the three age ranges described above, the frequency histograms for $\log(f_X/f_v)$ predicted by the model with the observed ones, as shown in Fig. 8. The observed and predicted histograms shown in Fig. 8 are not normalized to the same absolute value, as the predicted values are based on the sky coverage of the complete EMSS sample, while our EMSS sub-sample includes only about half of the EMSS stars. Given that our EMSS sub-sample is reasonably unbiased down to about spectral type K5 (Favata et al. 1993), starting to be severely incomplete for later types, we have only considered types G0 to G9 and K0 to K5 in this comparison.

All the predicted $\log(f_X/f_v)$ frequency histograms appear to match well in terms of range of $\log(f_X/f_v)$ values with the observed histograms. At the same time, while the older sub-samples are under-represented in the presently considered EMSS sub-sample with respect to the predicted values (as it is to be expected given that it is a sub-sample), the younger sub-samples, in particular the Pleiades-like one, are strongly over-represented, showing that the most, if not all of the excess sources are Pleiades-like with regard to their $W(\text{Li})$.

We have also compared the distributions in $W(\text{Li})$ and f_X/f_v for the G and K Pleiades-like X-ray selected sub-samples (which are by construction very similar to the distributions for Pleiades G and K stars) to the corresponding distributions for RS CVn stars. In all cases the distributions show very little if any overlap, with the RS CVn stars showing lower $W(\text{Li})$ and f_X/f_v , confirming the different nature, by this criterion, of the Pleiades-like X-ray selected population with respect to the RS CVn population.

Finally we have compared the distributions in $v \sin(i)$ for the same groups as above. Rotational velocity distributions for Pleiades, X-ray selected Pleiades-like and RS CVn groups cover more or less the same range, although the X-ray selected

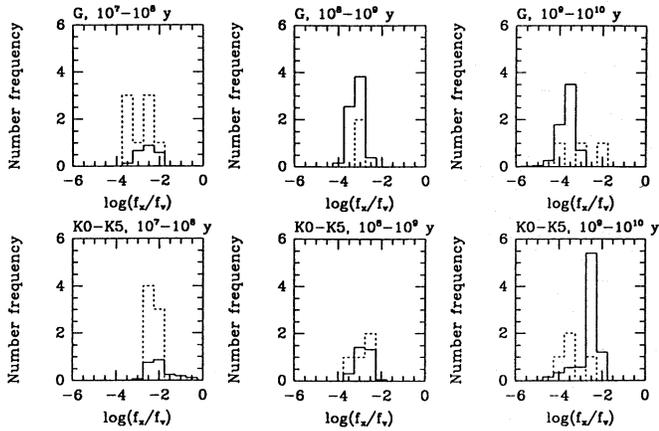


Fig. 8. Continuous line, source counts predicted by XCOUNT in each age range; dashed, sources in each age range in the EMSS sub-sample for which $W(\text{Li})$ data have been obtained

Pleiades-like population has a higher fraction of fast rotators with respect to the Pleiades, as it is to be expected from the bias present in an X-ray selected population with respect to an optically selected one. A similar difference is present between the optically selected and the X-ray selected active binary samples, with the latter showing a higher fraction of fast rotators. Rotational velocity is therefore not, in this context, a good criterion for discriminating different X-ray selected populations.

Fig. 9 shows a scatter plot in the $W(\text{Li})-f_x/f_v$ plane of the Pleiades-like sources from the X-ray selected sample in the K0-K5 range, together with the sources from the Pleiades and the optically selected RS CVn sample in the same spectral type range. Pleiades stars and active binaries occupy clearly separated regions in this plot, showing that young active stars and active binaries can be well separated, as a group, on the basis of their location in a lithium-activity diagram. The Pleiades-like X-ray selected sources (indicated with a cross), which have “Pleiades-like” $W(\text{Li})$ by construction, cover the same region as the Pleiades, and are effectively separated, as a group, from the active binaries. EMSS stars with $W(\text{Li})$ lower than the Pleiades are not shown in this plot, as their number matches well with the numbers expected on the basis of their being normal stars.

Figure 6 shows that there are basically no low lithium ESS solar-type sources in our sample. The ESS stellar population appears to be essentially identical to the “excess” population of the EMSS, indicating that the bias toward brighter X-ray fluxes of the ESS survey tends to eliminate all the older, normal sources from the sample, essentially selecting the young population, presumably Pleiades-like in age, within the solar neighborhood. In fact, as discussed earlier, the stronger bias toward high activity levels present in the ESS with respect to the EMSS select a population with more extreme characteristics than the EMSS one.

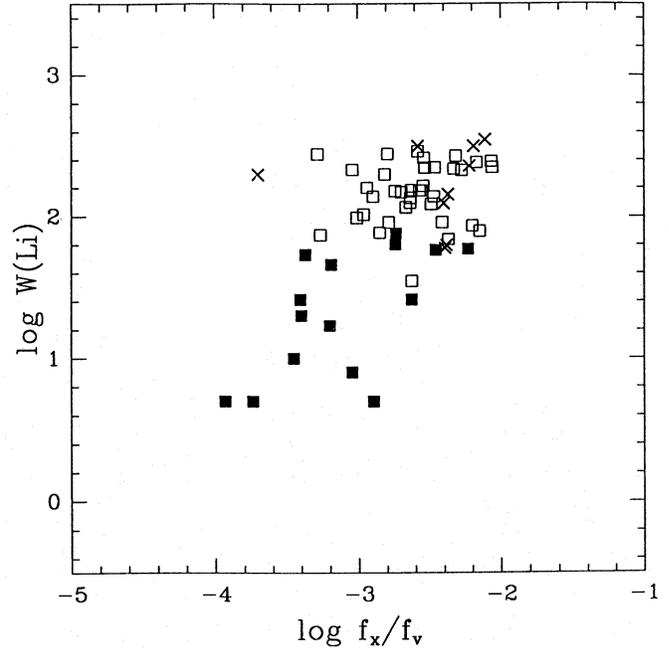


Fig. 9. Scatter plot of the lithium 6707.8 Å equivalent width versus f_x/f_v for K0-K5 Pleiades (open square), optically selected RS CVn (filled squares) and “excess” X-ray selected sources (crosses)

6. Discussion

Soderblom et al. (1993) have studied in detail lithium abundance in conjunction with rotational velocity and chromospheric activity in the Pleiades open cluster. Their main result is that later type stars in the Pleiades ($B - V > 0.8$) exhibit a spread in the equivalent width of the photospheric lithium line considered intrinsic to the cluster and not explainable on the basis of a possible initial age spread. They also show 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 $v \sin(i)$. A similar connection is observed between the same Li I equivalent width $W(\text{Li})$ and a stellar activity indicator, the chromospheric flux indicator based on the Ca II 8542 Å line. Although SJBS do not present a formal analysis of these relationships, they are quite evident in their Fig. 2.

The relationship between $v \sin(i)$ and $W(\text{Li})$ in the Pleiades G and K stars appears to be different, in that rotation seems to have a marginal, if any, effect on the observed surface lithium abundance in G stars (see Table 1). On the other hand, in both groups, the statistical connection between $v \sin(i)$ and f_x/f_v is strong, and behaves as expected on the basis of the well known rotation-activity connection. We therefore consider it likely that the observed statistical connection between $W(\text{Li})$ and f_x/f_v in Pleiades K stars is simply a reflection of the rotation-activity connection on one side, and of the $W(\text{Li})$ -rotation connection on the other side. Also in the α Per cluster faster rotators appear to have a stronger lithium abundance (Balachandran et al. 1988; Stauffer et al. 1993)

Observations of the older Hyades open cluster show that, by the time late type stars are about 8×10^8 years old, the spread in lithium abundances has become very small, or even disappeared completely, the relationship between $W(\text{Li})$ and $B - V$ becoming quite tight, at least for stellar masses corresponding to spectral type G or earlier. Thorburn et al. (1993) find that a small spread (no more than 0.2 dex in $W(\text{Li})$) is present in Hyades G stars at the 8σ confidence level, although they also claim that a small error in the assumed temperature scale might reduce the confidence level to 2σ . It is in any case clear that the dispersion of $N(\text{Li})$ at a given stellar mass in Hyades, if present, is much smaller than in the Pleiades (where it reaches about 1 dex in equivalent width in G stars and is even greater in K stars). Soderblom (1994) shows that also K-type Hyades show little if any spread in $W(\text{Li})$. The evolution of lithium abundance with age appears to mimic the behavior of rotational velocity: at the Pleiades age there appears to be a large spread in $v \sin(i)$, with a limited number of ultra fast rotators present (Soderblom et al. 1993); by the time the age of the Hyades is reached, rotational velocities converge toward a single valued function of $B - V$.

The results for the active binary sample are suggestive of a possible (low) level of correlation between $W(\text{Li})$ and f_X/f_v , with no evidence for correlation between $W(\text{Li})$ and $v \sin(i)$. Unfortunately, the optically selected RS CVn sample is quite small, and breaking it up in different sub-samples to perform a detailed statistical analysis quickly leads to small number statistics. In fact, as only six objects fall in each of the high and low $W(\text{Li})$ bins for K type stars, any number based on such a small sample would have to be treated with caution. Therefore quantitative studies of possible connections between surface lithium, activity and rotation in active binaries will have to wait for larger and more homogeneous samples.

The sample of X-ray selected active binaries appears to behave, from the point of view of both $W(\text{Li})$ and $v \sin(i)$ distributions, very similarly to the sample of optically selected RS CVn-type stars, showing no evidence of differences between the optically and X-ray selected active binaries populations, with the possible exception of the very fast rotators at $B - V \leq 0.8$ which are present in the X-ray selected sample. Active binaries as a class show strongly enhanced $W(\text{Li})$ values (up to 2 dex) with respect to non-active evolved objects of a similar evolutionary status (Randich et al. 1993). In the RS CVn sample studied here the connection between $W(\text{Li})$ and activity, if at all present, is at best weak, with no evidence for any influence of rotation on $W(\text{Li})$. Such a behavior would appear to be hardly compatible with proposed $W(\text{Li})$ enhancement mechanisms which imply a direct strong connection with the activity level, as for example lithium production in stellar flares, and $W(\text{Li})$ enhancement in starspots, and are also not compatible with mechanisms requiring a link with the present-day rotation rate.

High surface lithium equivalent width is a common feature in young, near ZAMS, low mass stars, but the value of $W(\text{Li})$ for an individual object is strongly influenced by its rotation rate. This behavior, together with the fact that, in the X-ray selected sample, $W(\text{Li})$ is influenced by rotation and not by activity, points toward a connection between $W(\text{Li})$ and $v \sin(i)$,

rather than a direct connection between lithium and activity. This observational result is more in agreement with a picture in which the range of $W(\text{Li})$ values observed is an effect of the changes in the internal stellar structure and circulation patterns rather than a surface effect of stellar activity. Unfortunately, current models of the evolution of rotating solar-type stars actually predict a correlation between initial angular momentum and lithium depletion which appears to go in the opposite direction of what's actually observed: high initial angular momentum is supposed to lead to a *faster* surface lithium depletion, leading to a lower abundance, (Pinsonneault et al. 1989, 1990). Nevertheless, the actual rotational history for non-tidally locked stars, and therefore the relationship between initial angular momentum and present-day surface rotational velocity, is still unclear.

The behavior of $W(\text{Li})$ and f_X/f_v in the X-ray selected sample gives strong clues to the actual nature of the “excess” yellow star population. The Pleiades (which we consider here as a prototypical ZAMS solar-type population) occupy in the $W(\text{Li})$ -color plane a different region than the active binary samples. Their position is also different in the f_X/f_v - $W(\text{Li})$ plane, and, as discussed above, they behave differently in terms of the lithium-activity connection. As it was shown in Fig. 8, the excess yellow sources occupy the same region as the Pleiades in the $W(\text{Li})$ -color plane. The same group of stars occupies, in the f_X/f_v - $W(\text{Li})$ plane, a region which overlaps with the one covered by the Pleiades but different from the one covered by the optically selected active binaries.

The above features appear to discriminate strongly the nature of the yellow excess population present in the EMSS, as being composed by a population of young, Pleiades-like objects, and ruling out the hypothesis of its being composed by active binaries. As already discussed in Section 1, an excess of yellow stars, a feature originally detected in the *Einstein* Medium Sensitivity Survey by Favata et al. (1988), appears now to be present also in other stellar samples selected on the basis of their activity, as for example in the ROSAT WFC sky survey. For the ROSAT WFC sample Jeffries & Jewell (1993) reach a similar conclusion about the nature of the excess population using a different sample and a different argument based on its kinematics. These conclusions can be most likely extended to the ROSAT All-Sky Survey of soft X-ray sources, which has a sensitivity comparable to the EMSS in a similar energy band (0.1–2.4 keV) and contains many thousands sources. It is easy to predict that a large fraction (of the order of one third) of the detected stellar population will be composed of very young stars. More in general, in any ROSAT frame of sensitivity at least comparable to the EMSS, a similar fraction of the stellar sources can be expected to be young stellar sources.

Acknowledgements. M.B., G.M. and S.S. acknowledge financial support from ASI (Italian Space Agency), and MURST (Ministero della Università e della Ricerca Scientifica e Tecnologica). We have extensively used the Simbad database to prepare the observations presented here, and the IRAF software system for the data reduction. We would like to thank the staff of ESO and DAO observatories for their dedicated support throughout the observation program. We thank T. Maccacaro

Table 2. Optical information and lithium abundances for the newly observed Extended Medium Sensitivity Survey and *Einstein* Slew Survey stars. The spectral types and apparent magnitudes are taken from the literature. The T_{eff} values are derived from published $B - V$ values, when available, or from published spectral types. $N(\text{Li})$ is expressed in the usual scale where $N(\text{H}) = 12$.

EMSS/Slew name	Other name	m_V	Sp.	T_{eff} (K)	$W(\text{Li})$ (mÅ)	$N(\text{Li})$
1E0324.1-2012	-	10.6	G4V	5670	228	3.93
1E0632.2-5351	-	11.5	K3V	4660	≤ 3	≤ -0.40
1E0820.2+0201	SAO116694	8.8	G6V	5850	149	3.30
1E0948.2+0822	SAO117942	7.7	K2V	4780	≤ 3	≤ -0.23
1E0956.8-2225	SAO178272	9.2	K2V	4780	143	2.00
1E1022.6+1121	-	10.5	G6V	5520	≤ 40	≤ 1.85
1E1049.4-0849	-	11.2	G7V	5400	≤ 7	≤ 0.78
1ES0143-253	SAO167275	5.7	F2IV	6688	35	2.89
1ES0226-615	SAO248569	8.8	F7V	6310	≤ 40	≤ 2.60
1ES0237-531A	HD16699	7.0	F8IV/V	6200	58	2.81
1ES0237-531B	HD16699	7.0	G5V	5610	193	3.57
1ES0238+057A	BD+05378	10.6	M	4058	15	-0.46
1ES0238-009A	SAO130055	5.7	F7IV	6320	73	3.00
1ES0250-129A	HD17925	6.0	K1V	5049	197	2.88
1ES0305-284	CD-281030	10.2	K7V	3945	17	-0.57
1ES0327-242A	SAO168581	9.4	K4V	4457	≤ 10	≤ 1.74
1ES0357-400A	HD25300	9.9	K0	5240	105	2.26
1ES0412+060A	HD26923	6.3	G0V	5968	85	2.78
1ES0412+060B	HD26913	6.9	G8V	5540	61	2.14
1ES0444-704	-	11.0	M0V	3920	≤ 10	≤ -0.65
1ES0447+068	SAO112106	3.2	F6V	6472	15	2.27
1ES0457+017A	GJ182	10.1	M1Ve	4015	270	1.77
1ES0504-575A	GJ189	4.7	F7V	6287	80	3.00
1ES0510-119C	SAO150223B	10.0	G8Ve	5490	303	4.10
1ES0528-654	SAO249286	6.8	K1IV	5200	315	3.10
1ES0538+037A	SAO113040	7.1	G5	4500	80	1.06
1ES0635-698A	HD47875	9.2	G3V	5720	196	3.70
1ES0637-614	HD48189	6.2	G1.5V	5968	133	3.30
1ES1002-559Aa	SAO237656	8.0	K1-2III	4500	57	0.86
1ES1002-559Ab	SAO237656	8.0	K1-2III	4500	38	0.62
1ES1044-491	SAO222321	2.7	G5III	4862	≤ 2	≤ -0.30
1ES1212+078A	SAO119284	8.4	K0	5240	≤ 5	≤ 0.57
1ES1252-060	GJ9424	10.4	K8V	4398	7	-0.33
1ES2257-340	SAO214237	8.6	G5Vp	5610	≤ 32	≤ 1.80

for a helpful discussion of recent RASS results, and S. Serio and F. Damiani for the several helpful comments on drafts of this paper. We also thank an anonymous referee for the several helpful comments.

Appendix A: optical data for the EMSS and ESS samples

The tables present the optical data for the EMSS and ESS objects used in this study. Typical uncertainties are 2.5 km/s for $v \sin(i)$ values, 10 mÅ for $W(\text{Li})$ values, and about 150 K for T_{eff} values. The resulting uncertainty on $N(\text{Li})$ depends on whether the objects is on the linear or on the saturated part of the curve of growth, with a typical value of about 0.15 dex.

Appendix B: notes on individual objects

- **1E0009.9+1407:** reported to be an RS CVn type system by Stocke et al. (1991), this system actually appears to be an active Pop II binary, as reported by Pasquini & Lindgren (1994). Although it is not an RS CVn in the classical definition, it satisfies our definition of active binary, in that the rotational velocity and therefore the activity level are strongly increased by the tidal locking with respect to normal Pop II objects.
- **1E0011.6+0840:** a short-period binary from Fleming (1989), which considers it a BY Dra candidate, who also report a K0Ve spectral type, with a maximum radial velocity difference of about 50 km/s, indicative of a close binary; the $v \sin(i)$ of about 22 km/s is also compatible with rotational locking. FBMS find a lithium abundance ($N(\text{Li})=1.75$) on

Table 3. Rotational velocity computed for the stars from FBMS. In the “sample” column stars included in the “normal” sample are indicated with an “ms”, stars included in the X-ray selected active binary sample are marked with an “a”. An asterisk indicates a note in Appendix B.

EMSS name	$v \sin(i)$ (km/s)	sample	comments	EMSS name	$v \sin(i)$ (km/s)	sample	comments
1E0002.8+1602	11	ms		1E0515.4-0710	11	ms	
1E0003.3-4201	13	ms		1E0519.3-4544	64	ms	
1E0009.9+1407	25	a	Pop II binary, *	1E0535.7-2839	43	ms	
1E0011.6+0840	28	a	*	1E0538.5-0949	79	ms	
1E0031.9-0646	27	ms		1E0617.0-5847	18	ms	
1E0132.5+2101	34	ms		1E0648.1-5042	95	ms	
1E0134.4+2027a	≤ 14	ms		1E1100.2+6155	≤ 14	ms	
1E0134.4+2027b	≤ 14	ms		1E1109.8+3606	≤ 14	ms	
1E0138.0-5627	11	ms		1E1254.8+0142	28	ms	
1E0206.2-1019	19	ms		1E1256.2+3833	19	ms	
1E0234.2-0321	11	ms	*	1E1256.2+3833	19	ms	
1E0234.7-0210	≤ 8	ms		1E1309.7+3221	≤ 14	ms	
1E0236.4-0148a	≤ 8	ms	SB3, $v \sin(i)$ uncertain	1E1330.5-0811	≤ 8	ms	
1E0236.4-0148b	16	ms	SB3, $v \sin(i)$ uncertain	1E1436.8-2628	10	ms	
1E0236.4-0148c	≤ 8	ms	SB3, $v \sin(i)$ uncertain	1E1441.7+5208	≤ 14	ms	
1E0239.9+0704	18	ms		1E1520.7-0625	44	a	RS CVn, *
1E0244.8-0024	≤ 8	a	*	1E1521.1+3027	≤ 14	ms	
1E0257.3+0733	11	ms	*	1E1552.0-2338	53	ms	
1E0300.1-1528a	20	ms		1E1558.4-2232	≤ 8	ms	
1E0300.1-1528b	13	ms		1E1634.7+2638	≤ 14	ms	
1E0303.8+1717	≤ 8	ms		1E1704.3+5432	26	ms	
1E0307.5+1424	9	ms		1E1737.2+6847a	≤ 14	ms	
1E0308.3+1413	≤ 8	ms		1E1737.2+6847b	≤ 14	ms	
1E0315.7-1955	33	ms	*	1E1751.0+7045	21	a	FK Com cand.
1E0318.5-1926	17	ms		1E1753.5+1830	≤ 8	ms	
1E0326.6-2008	15	ms		1E1810.3+6940	≤ 14	ms	
1E0327.2-2416	14	ms		1E1906.8-6339	9	ms	
1E0333.1+0607	33	ms		1E1907.0-6405	21	ms	
1E0337.6-0202	18	ms		1E2148.2+1420	≤ 8	a	RS CVn cand.
1E0348.2-1404a	≤ 8	ms		1E2254.2+0219	43	ms	
1E0348.2-1404b	≤ 8	ms		1E2302.4-4427	16	ms	
1E0413.7-6235	≤ 8	a	Giant	1E2315.1-3640a	12	ms	SB2, $v \sin(i)$ uncertain
1E0438.5+0213	48	ms	*	1E2315.1-3640b	12	ms	SB2, $v \sin(i)$ uncertain
1E0443.8-1006	11	ms		1E2332.4+0119	13	ms	
1E0448.4+1058	13	ms		1E2335.2+0305	11	ms	
1E0452.2+0225a	≤ 8	ms		1E2349.8-0112	64	ms	
1E0452.2+0225b	≤ 8	ms					
1E0457.5+0312	37	a	RS CVn, *				
1E0505.0-0527	22	a	RS CVn, *				

the upper range of the values found in active binaries, and definitely below the values found in very young EMSS stars. We therefore include it in the “extended” active binary sample.

- **1E0234.2-0321**: a high proper motion object, but not metal poor, from Sandage & Kowal (1986) who consider it a thick-disk object. Fleming (1989) reports it to be a binary, but as the evidence for its being a very old object is not compelling, we include it in the main sequence sample. A “thick-disk binary”?
- **1E0244.8-0024**: an RS CVn candidate of Fleming (1989), which has been studied in detail by Tagliaferri et al. (1994),

who classify it as G6V+K6V or K2IV+F7V, on the basis of photometric data. Through their revised photometry they also derive a higher distance than Fleming (1989), which increases the X-ray luminosity of the system by at least 0.5 dex. Its lithium abundance (FBMS, Tagliaferri et al. 1994) is within the normal range observed in active binaries, and we therefore include it in the active binary sample.

- **1E0257.3+0733**: this star is classified as G6III in Stocke et al. (1991) and subsequent EMSS papers. This classification is clearly in error given that this star has a measured parallax of about 30 pc, which, together with its m_V of 8.3, clearly makes it a dwarf.

Table 4. Rotational velocity computed for the newly observed EMSS and ESS stars. In the “sample” column stars included in the “normal” sample are indicated with an “ms”, stars included in the X-ray selected active binary sample are marked with an “a” and the two active binaries candidates are indicated with “abc”. An asterisk indicates a note in Appendix B

EMSS/ESS name	$v \sin(i)$ (km/s)	sample	comments	EMSS/ESS name	$v \sin(i)$ (km/s)	sample	comments
1E0324.1-2012	13	ms		1ES0412+060A	≤ 8	ms	uncertain ID
1E0632.2-5351	≤ 8	ms		1ES0412+060B	≤ 8	ms	uncertain ID
1E0820.2+0201	11	ms		1ES0444-704	11	ms	
1E0948.2+0822	≤ 8	ms		1ES0447+068	16	ms	
1E0956.8-2225	19	ms		1ES0457+017A	14	ms	
1E1022.6+1121	73	a, abc	RS CVn cand., *	1ES0504-575A	12	ms	
1E1049.4-0849	95	a, abc	RS CVn cand., *	1ES0510-119C	14	ms	
1ES0143-253	84	ms		1ES0528-654	≤ 80	ms	*
1ES0226-615	62	ms		1ES0538+037A	12	a	RS CVn, *
1ES0237-531A	20	ms	uncertain ID	1ES0635-698A	10	ms	
1ES0237-531B	≤ 8	ms	uncertain ID	1ES0637-614	15	ms	
1ES0238+057A	≤ 8	ms		1ES1002-559Aa	16	a	*
1ES0238-009A	31	ms		1ES1002-559Ab	10	a	*
1ES0250-129A	≤ 8	ms		1ES1044-491	≤ 8	a	Giant
1ES0305-284	30	ms		1ES1212+078A	≤ 8	ms	
1ES0327-242A	≤ 8	ms		1ES1252-060	≤ 8	ms	
1ES0357-400A	12	ms		1ES2257-340	72	a	BY Dra cand., *

- **1E0315.7-1955**: an RS CVn candidate of Fleming (1988). The lack of an evolved component and the very high lithium abundance point toward its being a PMS binary system.
- **1E0438.5+0213**: a W UMa candidate of Stocke et al. (1991), and a binary from Fleming (1988). As discussed in FBMS, the spectral classification of this object and its reported color are strongly discordant, and it is not therefore included in our analysis.
- **1E0457.5+0312**: an RS CVn from Randich et al. (1993), who classify it as K2III.
- **1E0505.0-0527 & 1E1520.7-0625**: both are RS CVn from Fleming (1988), the presence of an evolved component and the high rotational velocity indicative of locking puts them in the active binary group.
- **1E1022.6+1121 & 1E1049.4-0849**: both are fast binaries from Fleming (1988). The lack of an evolved component, and the fact that both the rotational velocity and the f_X/f_V level are compatible with stars of the Pleiades age would weigh against their being considered active binaries. On the other hand its lack of detectable lithium makes it unlikely that it they are very young stars. Certainly dubious cases; we have decided to exclude them from the main sequence sample, both objects will need to be studied further.
- **1ES0528-654**: AB Dor, a well known PMS binary. Has a dMe companion, likely to be responsible for part of the X-ray flux.
- **1ES0538+037A**: an RS CVn from Randich et al. (1993), who classify it as K2III.
- **1ES1002-559**: an SB2 giant, relatively fast rotator for its luminosity class. CaII H&K emission cores are clearly visi-

ble in low resolution spectrograms, most likely to be an RS CVn binary.

- **1ES2257-340**: a well known binary, with a peculiar spectrum and a strong detected microwave flux. Classified as a BY Dra system, with a period of 1.63 d, the hypothesis of tidal locking appears reasonable. Given the lack of detectable lithium, we include it in the active binary sample.

References

- Avni, Y., Soltan, A., Tananbaum, H., Zamorani, G. 1980, ApJ 238, 800
Balachandran, S., Lambert, D.L and Stauffer, J.R. 1988, ApJ 333, 267
Brown, J.A., Sneden, C., Lambert, D.L., Dutchover, E.Jr. 1989, ApJS 71, 293
Cayrel de Strobel, G., Cayrel, R. 1989, A&A
Cayrel, R., Cayrel de Strobel, G., Campbell, B., Dappen, W. 1984, ApJ 283, 205
Cleveland, W. 1979, JASA 74, 829
Dempsey, R.C, Linksy, J.L., Fleming, T.A., Schmitt, J.H.M.M. 1993, ApJS 86, 559
Duquenooy, A., Mayor, M. 1991, A&A 248, 485
Elvis, M., Plummer, D., Schachter, J., Fabbiano, G. 1992, ApJS 80, 257
Favata, F., Micela, G., Sciortino, S. 1994, in preparation.
Favata, F., Barbera, M., Micela, G., Sciortino, S. 1993, A&A 277, 428 (FBMS)
Favata, F., Micela, G., Sciortino, S., Vaiana, G.S. 1992, A&A 256, 86
Favata, F., Rosner, R., Sciortino, S., Vaiana, G.S. 1988, ApJ 324, 1010
Feigelson, E.D., Nelson, P.I. 1985, ApJ 257, 695
Fekel, F.C., Balachandran, S. 1993, ApJ 403, 708
Fleming, T.A. 1988, Ph.D. Thesis, Univ. of Arizona
Fleming, T.A., Gioia, I.M., Maccacaro, T. 1989, ApJ 340, 1011
Fleming, T.A., Gioia, I.M., Maccacaro, T. 1989, AJ 98, 2, 692
Gioia, I.M., Maccacaro, T., Schild, R.E. et al. 1990, ApJS, 72, 567

- Herbig, G., ApJ, 141, 588
- Hodgkin, S.T., Pye, J.P. 1994, MNRAS, in press
- Jeffries, R.D., James, D., Bromage, G.E. 1993, in *The 8th Cambridge Workshop on Cool Stars, Stellar Systems and the Sun*, in press
- Jeffries, R.D., Jewell, S. 1993, MNRAS, 264, 106
- Micela, G., Sciortino, S., Favata, F. 1993, ApJ 412, 618
- Micela, G., Sciortino, S., Vaiana, G.S. et al. 1990, ApJ 348, 557
- Micela, G., Sciortino, S., Vaiana, G.S. et al. 1988, ApJ 325, 798
- Ottman, R & Schmitt, J.H.M.M. 1992, A&A 256, 421
- Pallavicini, R., Randich, S., Giampapa, M.S. 1992, A&A 253, 185
- Pallavicini, R., Cerruti-Sola, M., Duncan, D.K. 1987, A&A 174, 116
- Pallavicini, R., Golub, L., Rosner, R. et al. 1981, ApJ 248, 279
- Pasquini, L., Cutispoto, G., Gratton, R. et al. 1991, A&A 248, 72
- Pasquini, L., Lindgren, H. 1994, A&A 283, 179
- Pinsonneault, M.H., Kawaler, S.D., Demarque, P. 1990, ApJS 74, 501
- Pinsonneault, M.H., Kawaler, S.D., Sofia, S. 1989, ApJ 338, 424
- Randich, S., Gratton, R., Pallavicini, R. 1993, A&A 273, 194
- Sandage, A., Kowal, C. 1986, AJ 91, 1140
- Schachter, J., Remillard, R., Saar, S., Favata, F., Sciortino, S., Barbera, M. 1994, in preparation
- Schmitt, J.H.M.M., Golub, L., Harnden, F., Maxson C., Rosner, R., Vaiana, G. 1985, ApJ 290, 307
- Sciortino, S., Favata, F., Micela, M. 1993, A&A, in press (SFM)
- Soderblom, D.R. 1994, Bull. AAS 25, 4, 1319
- Soderblom, D.R., Jones, B.F., Balachandran, S. et al. 1993, AJ, 106, 1059 (SJBS)
- Soderblom, D.R., Oey, M.S., Johnson, D.R.H., Stone, R.P.S. 1990, AJ 99, 2, 595
- Soderblom, D.R., Pendleton, J., Pallavicini, R. 1989, AJ 97, 2,
- Stauffer, J.R., Prosser, C.F., Giampapa, M.S. et al. 1993, AJ 106, 1, 229
- Stoeck, J.T., Morris, S.L., Gioia, I.M. et al. 1991, ApJS, 76, 813, 218
- Strassmeier, K.G., Hall, D.S., Zeilik, M., Nelson, E., Eker, Z., Fekel, F.C. 1988, A&AS 72, 291
- Tagliaferri, G., Cutispoto, G., Pallavicini et al. 1994, A&A 285, 272
- Thorburn, J.A., Hobbs, L.M., Deliyannis, C.P. and Pinsonneault, M.H. 1993, ApJ, 415, 150
- Zombeck, M.V., in *Handbook of Space Astronomy & Astrophysics, 2nd ed.*, Cambridge Univ. Press, Cambridge 1990, p. 68