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ASTRONOMY AND ASTROPHYSICS

A Lithium-Survey for Pre-Main Sequence Stars in the Upper Scorpius OB Association⋆ ⋆⋆

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Abstract. We present the results of an intermediate resolution spectroscopic survey for pre-main sequence (PMS) stars in the Upper Scorpius OB association. In a 160 square-degree area we were able to identify 39 new PMS stars by follow up observations of X-ray selected stars with the multi object spectrograph FLAIR at the UK Schmidt Telescope.

We also investigated the completeness of our X-ray selected sample by observing more than 100 stars that were *not* detected as X-ray sources, but have proper motions indicating membership to Upper Sco. While the new X-ray selected PMS stars with known proper motions have kinematics consistent with membership, none of the X-ray quiet proper motions candidates is a PMS star. We conclude that our X-ray selected sample of PMS stars seems to be rather complete. For stars in the magnitude interval $11.5 \lesssim B \lesssim 13.5$ we derive a conservative lower limit of 75% completeness.

Key words: Associations: Scorpius Centaurus; Stars: pre-main sequence, coronae, kinematics; X-rays: stars

1. Introduction

Most stars in the Galaxy are supposed to form in OB associations (Miller & Scalo 1978). The knowledge of the stellar content of OB associations is a key towards an understanding of the star formation process and the origin of the initial mass function. One important point is the comparison of the low-mass populations in OB associations and T associations. This can yield information on whether star formation is bimodal (c.f. Walter & Boyd 1991) and to what extent the environment influences the star formation process.

While the low-mass stellar population in T associations (like in Taurus) is rather well-known, not much is known about the low-mass stellar contents of OB associations. This is due to our extremely poor knowledge of membership for all but the brightest O and early B stars. The low-mass population remains largely unexplored, because most of the low-mass pre-main sequence (PMS) stars cannot be easily distinguished from normal field stars. Only the classical T Tauri stars can be rather easily found by their strong Hα emission, e.g. by objective prism surveys. However, the PMS population is dominated by the weak-line T Tauri stars (cf. Krautter 1996), which lack such an easily detectable signature and thus are very hard to find among the many thousands of foreground and background field stars in the huge area on the sky (several hundred square-degrees) covered by nearby OB associations.

Interestingly, most PMS stars are strong X-ray emitters, probably due to their rapid rotation (cf. Montmerle 1996). Since their X-ray luminosities are about 2 − 3 orders of magnitude above those of main sequence stars of similar spectral type, X-ray observations have proven to be extremely efficient in discovering the PMS stars among the older field stars (e.g. Walter et al. 1988; Neuhäuser 1997; Wichmann et al. 1997).

The Scorpius Centaurus association is the OB association nearest to the Sun. It contains several hundred B stars which cluster in the three subgroups Upper Scorpius, Upper Centaurus Lupus, and Lower Centaurus Crux (cf. Blaauw 1964). With an age of about 5 Myrs, Upper Sco is the youngest subgroup. De Geus et al. (1989) list 98 B and early A stars as probable association members and claim completeness to spectral type B9.

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⋆ Based on observations obtained at the UK Schmidt Telescope of the Anglo-Australian Observatory

⋆⋆ Tables A1 and A2 are only available in electronic form at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via http://cdsweb.u-strasbg.fr/Abstract.html

The Scorpius Centaurus association was very well investigated by the astrometry satellite Hipparcos. Astrometric data from Hipparcos are now available for 1215 stars in Upper Sco. De Bruijne et al. (1997) present first results of kinematic membership determinations making full use of the proper motions and parallaxes measured by Hipparcos. For $\sim 70\%$ of the probable members from the list of de Geus et al. (1989) membership is confirmed by the Hipparcos data. Furthermore, de Bruijne et al. (1997) could identify 115 new members, and their analysis of the trigonometric parallax distribution gives a mean distance of 145 ± 2 pc for Upper Sco.

Immediately to the east of Upper Sco lie the Ophiuchus dark clouds. The center of this cloud complex, the ρ Oph cloud core, contains many PMS stars, X-ray sources, embedded infrared sources, and displays several signposts of very recent star forming activity (cf. Wilking 1991, Casanova 1995). In contrast to its spatial proximity to the Ophiuchus dark clouds, Upper Sco is essentially free of dense interstellar matter and there is no evidence for ongoing star formation in Upper Sco. This is probably due to the strong stellar winds of the numerous B stars, which have dispersed the original molecular cloud. Furthermore, a supernova explosion presumably has swept out the molecular gas a few million years ago. This is the reason for the generally quite low extinction of the young stars in Upper Sco ($A_V \lesssim 1$ mag; c.f. de Geus et al. 1989, Walter et al. 1994).

In contrast to the well studied population of high mass stars in Upper Sco, virtually nothing was known about the population of the low-mass PMS stars, until recently. Only 6 PMS stars in Upper Sco are listed in the catalog of Herbig & Bell (1988). The first systematic search for PMS stars in Upper Sco was performed by Walter et al. (1994, W94 hereafter), who observed the optical counterparts of X-ray sources detected in 7 individual EINSTEIN fields and could detect 28 PMS stars. A quite surprising result of this study was that the PMS stars seem to have isochronal ages of 1 – 2 Myrs with a very small dispersion. This is significantly younger than the well established age of the B stars (~ 5 Myrs) and was interpreted as an indication that the formation of these PMS stars was triggered.

Since this result was based on the assumption of a common distance of 160 pc for all PMS stars, it should be treated with some caution, because the new Hipparcos data imply a slightly smaller distance of 145 pc and probably there is a spread in the individual distances of the PMS stars. We can gain some information about the spread in distances for the early type members from the histogram of parallaxes presented in Fig. 2 of de Bruijne et al. (1997). The central 90% range of the distribution of parallaxes extends from 4 mas to 9 mas. We must take into account that this distribution of parallaxes is broadened by measurement errors. The typical measurement errors are $\sim 15\%$ for parallaxes near 9 mas and $\sim 30\%$ for parallaxes near 4 mas. If we correct the range of parallaxes by this amount, we find that the data are consistent with the assumption that the distances of the individual stars vary between ~ 130 pc and ~ 190 pc.

Recently, Martin (1998) disputed the results of W94 and argued that there is a large age spread among the PMS stars. Using the 6708 Å lithium line data from W94, he classified 8 of the 28 PMS stars, i.e. a fraction of about 30%, as "post T Tauri stars" with ages of $10 - 20$ Myrs, what would imply that these stars are at distances of only $80 - 120$ pc. However, we note that these stars are radial velocity members of Upper Sco (W94), and, as we will show below, the population of late type PMS stars seems to be spatially coincident with the early type members. Thus there is no expectation that the late type members should have a much broader distribution of distances than the $\sim 130 - 190$ pc range we have estimated for the early type members above. So the scenario of Martin (1998) does not fully convince us.

In any way, it must be kept in mind that the EINSTEIN observations covered only about 7 square-degrees, a tiny fraction of the whole association (cf. Fig. 1), and the sample of 28 PMS stars is clearly far from being complete. Further conclusions about the star formation history of the association require a much larger sample of PMS stars and thus the observation of many more stars in Upper Sco. A first step in this direction was a study by Kunkel (1998, K98 hereafter), who investigated more than 200 ROSAT All Sky Survey X-ray sources in a ~ 60 square-degree area in Upper Sco. He claimed the detection of 93 new PMS stars. 35 of these stars are located in the area investigated in our study and satisfy our classification criteria for PMS stars (see Section 4.1).

The main intention for the study presented in this paper was to provide a more complete and homogeneously selected sample of PMS stars in a large area around the previously known PMS stars. This requires optical spectroscopy of several hundred targets in an area of several hundred square-degrees. Therefore we have used the wide-field multiobject spectrograph FLAIR at the UK Schmidt telescope, which is ideally suited for this project.

The very efficient observing mode possible with FLAIR even allowed us to address another important question: *How complete is the X-ray selected sample of PMS stars?* Since nearly all known PMS stars in Upper Sco have been found by follow-up observations of X-ray sources, this question is of fundamental importance for any conclusions. The significance of this question has recently been demonstrated in a study of PMS stars in the Orion nebula region. Wolk (1996) found PMS stars not only among X-ray selected stars but also among *non*-X-ray selected stars with similar positions in the color-magnitude-diagram. This means that a rather large fraction of the PMS stars in this region have much lower X-ray luminosities than typical for the X-ray detected PMS stars of similar bolometric luminosity. This surprising result implies the existence of a

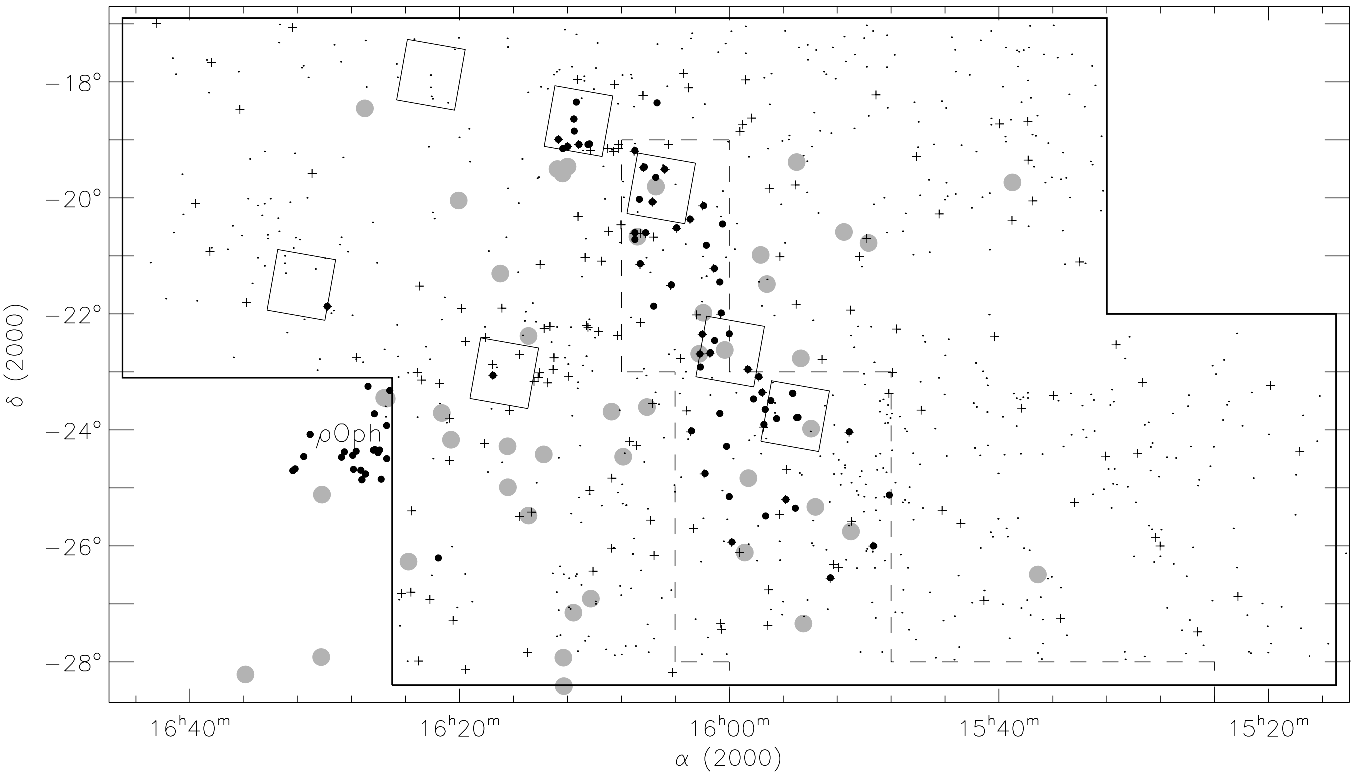

Fig. 1. Map of the Upper Scorpius region. The previously known PMS stars (from Herbig & Bell 1988, Walter et al. 1994 and Kunkel 1998) are shown as small solid dots. The big squares show the EINSTEIN fields investigated by Walter et al. (1994). The dashed line marks the region studied by Kunkel (1998), which extends further to the south. The big grey dots mark the B star members from the list of de Geus et al. (1989). The area investigated in our study is marked by the solid line. The positions of X-ray selected PMS candidates are marked by crosses, those of the X-ray quiet proper motion candidates by points.

population of "X-ray quiet" PMS stars and shows that the X-ray selected sample of PMS stars in Orion is probably considerably incomplete.

We have investigated this question for Upper Sco with a slightly different approach. In addition to the X-ray selected candidates, we also studied a large sample of stars which were *not* detected as X-ray sources, but which we regarded as possible members of the Upper Scorpius association because of their proper motions being similar to the ones of the known early-type members.

The region we have studied has a total area of about 160 square-degrees and is defined by a 3×2 mosaic of 6 individual UK Schmidt Telescope survey fields (see Fig. 1). Our area contains all the EINSTEIN fields analyzed in W94 and partially overlaps with the region studied by K98. Before our study, 69 PMS stars were known in our area: Six from Herbig & Bell (1988), 28 from W94, and 35 from K98. Since all the PMS candidates we have observed are listed in the Guide Star Catalog (GSC; Lasker et al. 1990), we use GSC numbers to identify the stars. Throughout this paper we use the B magnitudes as given in the GSC.

2. Selection of PMS candidates

2.1. X-ray selected candidates

The ROSAT X-ray satellite (see Trümper 1983) performed an All Sky Survey (RASS) in the 0.1 – 2.4 keV soft X-ray band. The mean limiting flux of the survey was about $2 \times 10^{-13}\,\mathrm{erg/(sec\,cm^2)}$ and more than 60 000 X-ray sources were detected. The data of this survey provide a spatially complete, flux-limited sample of X-ray sources and have led to the detection of hundreds of new PMS stars in star forming regions all over the sky (for a review see Krautter 1996 or Neuhäuser 1997).

In Upper Sco the typical RASS exposure time was about 400 sec, the minimum detectable source count rate was about 0.02 counts/sec. For a distance of 145 pc and a typical extinction of $A_V \approx 0.5$ mag this corresponds to X-ray luminosities of about 10^{30} erg/sec if we assume thermal plasma emission with $kT = 1$ keV as typical for PMS stars (cf. Montmerle 1996). In our field in Upper Sco, 606 X-ray sources were detected in the RASS data. Of course, not all of these X-ray sources are PMS stars: active field stars, RS CVn binaries, galaxies and quasars build up a large fraction of the RASS sources. In order to keep the observational effort in the search for PMS stars within reasonable limits, a selection method for finding promising PMS candidates in the RASS data was introduced by Sterzik et al. (1995). This method compares several properties of each RASS source to those of a "training-set", consisting from known PMS stars and non-PMS stars. These properties are the hardness ratios, the magnitude of the closest optical counterpart in the GSC within $40''$ around the X-ray source position, and the X-ray to optical flux ratio. For each RASS source a discrimination probability P is computed. High values of P indicate that the source properties are similar to those within the sample of known PMS stars in the training-set. All details of this method are described in Sterzik et al. (1995). We used $P \geq 0.5$ as a cutoff value for the X-ray selected PMS candidates. This resulted in a total of 180 PMS candidates in our field. For observational reasons (see section 3), we excluded all stars brighter than $B \approx 11$ and all stars fainter than $B \approx 14.5$ from this sample, reducing the sample to 130 objects. 31 of these RASS candidates are known PMS stars from the studies of W94 and K98. This left us with 99 unidentified RASS candidates.

We are fully aware that our RASS selected sample is flux-limited and not complete. Many known PMS stars in other star forming regions have X-ray luminosities considerably below 10^{30} erg/sec; a rough estimate shows that only about 30% of the PMS stars exceed this limit (cf. Neuhäuser et al. 1995; Preibisch et al. 1996; Preibisch 1997). Some regions in Upper Sco have also been observed in deep ROSAT pointed observations with exposure times up to 30 000 sec and many additional X-ray sources can be found in these deep data. We did not attempt to systematically include these faint X-ray sources into our sample of X-ray selected PMS candidates. The first reason is that these pointed observations cover only a small fraction of our area and with very inhomogeneous sensitivity. The second reason is of technical nature: We could take spectra of rather bright stars ($B \lesssim 14$) only, and most of the faint X-ray sources have fainter counterparts. However, we have included the rather bright optical counterparts of 9 X-ray sources detected in 7 individual pointed observations in order to get some insight in the completeness of the RASS selected sample of PMS stars.

Finally, we would like to note that the flux limit of the RASS agrees quite well with the magnitude limit of our spectroscopy. Assuming a ratio of $\log{(L_{\rm X}/L_{\rm bol})} \approx -3.5$ as typical for late type PMS stars, we can expect that most RASS detected PMS stars have $B \lesssim 14$.

2.2. X-ray quiet proper motion candidates

In order to search for possible X-ray quiet PMS stars in Upper Sco, we have observed a large sample of stars with magnitudes similar to those of the RASS candidates. X-ray quiet candidates were selected by the criterion that their proper motion is similar to that of the known early-type members in Upper Sco.

In our field we found 2014 stars listed in the PPM catalogue. Nearly all of the PPM stars are rather bright with $B \lesssim 11$ and thus much brighter than our RASS candidates. In order to get a comparable sample we needed fainter stars. An ideal source for proper motions of rather faint stars is the STARNET catalogue (cf. Röser 1996). This catalogue is based on a comparison between the Astrographic Catalogue and the Guide Star Catalogue (GSC 1.2, Röser et al. 1996), with an epoch difference of about 80 yrs. It contains 4.3 million stars with magnitudes down to about 14, and provides proper motions in the Hipparcos system with an accuracy of $\sim 3-5$ mas/yr. For 11 463 stars in our area proper motions are listed in the STARNET catalogue.

Since our field is rather large, we have to take projection effects into account in the kinematic candidate selection. In other words, a constant space motion of possible members of an association transforms into a proper motion depending on position. Therefore we performed the kinematic candidate selection separately for each of the 6 UKST survey fields in our area. For each $6.5^\circ \times 6.5^\circ$ UKST field we took all the B stars from the PPM Catalogue and averaged the proper motions of those B stars which clustered near the mean overall proper motion for the Upper Sco association of about $(\mu_\alpha, \mu_\delta) \approx (-11, -25)$ mas/yr (de Bruijne et al. 1997). We regarded every star in the PPM or STARNET Catalogue with a proper motion difference to the mean of the corresponding field of less than 7.5 mas/yr as possible kinematic member. For observational reasons stars brighter than $B \approx 11.5$ were excluded. After removing all stars which were detected in the RASS, we ended up with a sample of 648 X-ray quiet proper motion candidates.

We also investigated whether there are proper motion members among the RASS sources rejected as PMS candidates according to their X-ray properties. There are 418 rejected RASS sources but only 109 of them have an optical counterpart. For 71 of these stars we know the proper motions, and 17 stars meet our kinematic member criteria. With only one exception, all of these 17 objects are bright ($B < 11.5$) stars. Most of them are bright HD stars of spectral type A and F and therefore do not belong to the class of late type PMS stars we are looking for. We conclude that our RASS candidate selection procedure did not exclude a significant number of potential late type PMS members.

3. Optical spectroscopy with FLAIR and data analysis

For our observations, we used the wide-field multi-object spectrograph FLAIR II (fiber-linked array-image reformatter; see Parker & Watson 1995) on the UK Schmidt Telescope of the Anglo-Australian Observatory. This instrument has 91 fibers which are terminated with right-angled prisms. Each fiber has to be positioned in exact alignment with the selected target star visible on a film copy of the corresponding Schmidt plate and glued onto the film. The core diameter of each fiber is 100 μm, corresponding to $6.7''$ on the sky. The fibers guide the light into the floor-mounted spectrograph and finally to a CCD camera with 400×578 pixels.

FLAIR allows to observe up to 91 objects simultaneously in the $6.5° \times 6.5°$ field of view of the Schmidt plate. However, since adjacent fibers result in a cross-talk between the spectra on the CCD, we decided to use every second fiber only, reducing the number of available fibers to 46. In order to be able to subtract the sky background from the object spectra, 6 of these fibers were placed onto blank patches of the sky close to the objects. Thus, we could observe 40 target stars per field.

While FLAIR is a powerful facility in terms of multiplex advantage and area coverage, it also imposes some observational restrictions which influence the selection of target stars. One factor is that the magnitude difference between the brightest and faintest stars observed simultaneously has to be kept relatively small ($\lesssim 4$ mag). Another factor is that not all individual fibers can be positioned fully as desired, since each fiber covers up an area of several square arcminutes on the plate. Furthermore, there is a minimum distance of about $1'$ between neighboring fibers on the plate. Thus, in those cases where more than one candidate star was visible within the X-ray error circle, we usually could observe only one star, and always preferred the brightest star. Finally, we did not observe candidates for which another star could be seen within about $5''$ on the Schmidt plate, since the fixed fiber aperture of $6.7''$ does not allow to exclude the light from such a companion.

It has recently been shown that the determination of the equivalent width of the 6708 Å Li line can be problematic if the spectral resolution is too low. Low resolution (4 – 8 Å) spectroscopy can lead to a serious overestimation of the Li line width (Covino et al. 1997). Intermediate resolution of at least 2 Å is necessary to measure the equivalent width reliably (cf. Neuhäuser et al. 1997). We therefore used a 1200 line/mm grating, the highest dispersion grating available for use with FLAIR, which gives a spectral resolution of $\sim$2 Å. The wavelength range covered in this configuration is quite small (6050 – 6850 Å), making it very hard to determine spectral types. We therefore took additional low resolution spectra using a 250 line/mm grating, which covered the wavelength range 3900 – 7200 Å with $\sim$7 Å resolution.

Our observing procedure was as follows: First we took bias and dome-flat frames and arc spectra with a Ne and a Hg-Cd calibration lamp. We started with the 1200 line/mm grating and took a series of 12×15 min exposures. Then, we changed the grating and took a series of 12×5 min exposures with the 250 line/mm grating.

During our first observing run in June 1996 we could only obtain the intermediate resolution spectra for the western-most field due to very bad weather conditions. During our second observing run in June 1997 we could obtain intermediate and low resolution spectra for the other 5 fields. During two nights up to three of the individual exposures contained only very low signal due to moving clouds. However, for each series of exposures we had at least 9 usable frames. In total we took spectra for 88 X-ray selected candidates, 136 proper motion candidates, and additionally for 13 known PMS stars from the list of W94 and K98 in order to use them as spectral standards.

Bias subtraction and flat-fielding was done in the usual way with the corresponding standard IRAF[1] routines. Then the individual frames of each series were summed and cosmic rays removed. We used the IRAF task dohydra for subtraction of scattered light, extraction of the spectra, and for wavelength calibration. The dome-flat frames were used for the throughput correction during the sky subtraction. Nearly all spectra have at least 10 000 counts per pixel in the continuum around 6700 Å. As an example for our data we show parts of several intermediate resolution spectra in Fig. 2.

From our FLAIR data we could obtain usable spectra ($\gtrsim$ 10 000 counts per pixel) for 78 X-ray selected candidates (69 RASS sources, 9 sources from pointed ROSAT observations) and 115 X-ray quiet proper motion candidates. From the normalized intermediate resolution spectra we determined the equivalent width of the 6708 Å Li line with the IRAF task splot. In order to avoid misidentifications due to possible blending with other nearby lines, especially the 6705 Å and 6710 Å Fe lines, we measured the central wavelength of the Li line and computed the wavelength difference to the 6717 Å Ca line. The true wavelength difference between these lines is 9.7 Å, and if the measured difference deviated from this value by more than 1 Å, we used the measured Li equivalent width as upper limit only.

The equivalent width was measured in two ways, first by integrating over the line profile, and second by fitting a Gaussian to the line profile. The mean of both values was used as the final equivalent width. For nearly all spectra the two values agree to within $\sim$10% and we assume this to be the uncertainty of our measurement. For the few spectra with slightly less than 10 000 counts per pixel the uncertainties are higher; they are marked with ':' in Tables 1 and 2. Spectra with a considerably smaller number of counts (mainly due to problems with the fiber transmission) were not analyzed.

For all stars with strong Li lines we determined the spectral type from the low resolution spectra by comparison with the standard stars. We assume our spectral types to be accurate to ± 1 subclass in most cases.

[1] IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

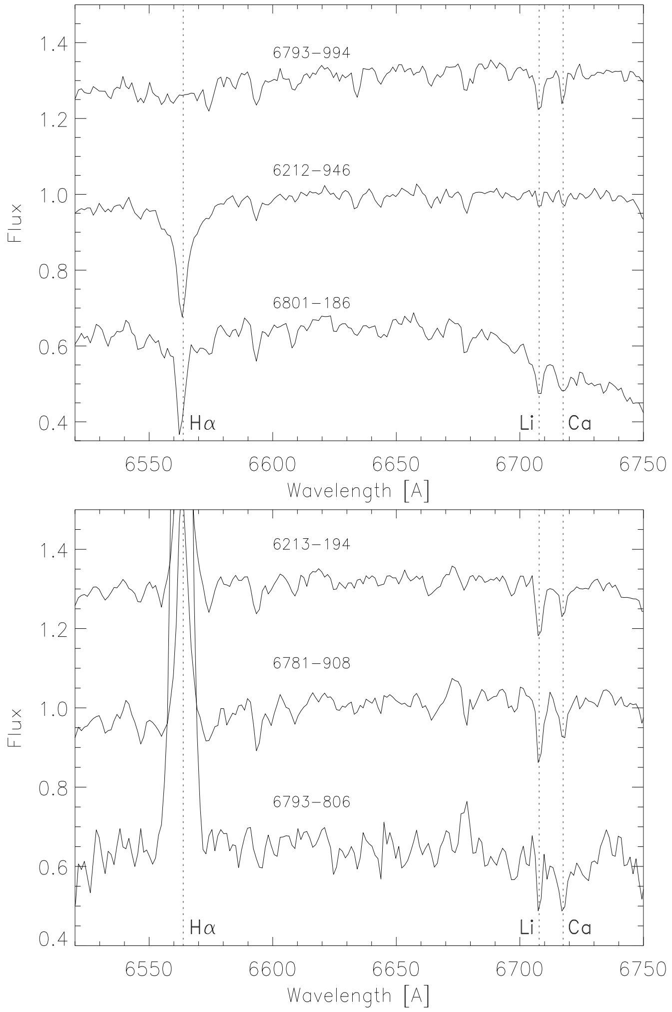

Fig. 2. Examples of our FLAIR spectra. Each plot compares spectra with similar spectral type but different S/N ratio and Li line strength. The spectra are arbitrarily scaled, the uppermost spectrum has the highest S/N ratio. Important lines are marked by the dotted lines. The upper plot compares three G type stars, the lower plot three M type stars.

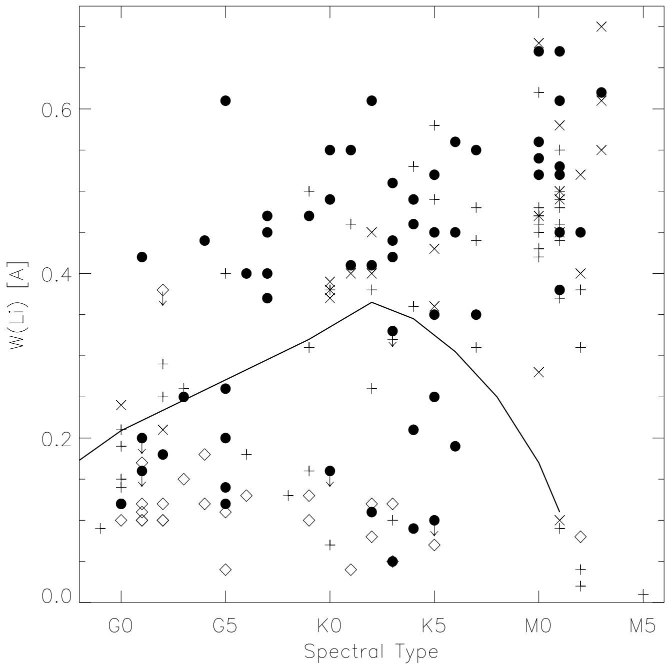

Fig. 3. This plot shows the equivalent width of the 6708 Å Li line versus the spectral type of those stars observed with FLAIR for which a strong Li line could be found. The black dots denote X-ray selected stars, the open diamonds X-ray quiet proper motion candidates. The stars observed by W94 and K98 are shown as '×' and '+' resp. The solid line shows the upper envelope for the Li line widths of stars in several young clusters (see text for details).

4. Results

In Fig. 3 we show the spectral types and Li line widths for all stars with detectable Li lines. The corresponding data are given in Tables 1 and 2 in the appendix.

We determined the pre-main sequence nature of a star by the strength of its 6708 Å lithium line. Since Li is strongly diminished in very early phases of stellar evolution, a high Li content is a good indication for the youth of a star (e.g. Herbig 1962, D'Antona & Mazzitelli 1994). However, Li depletion is not only a function of stellar age, but also of stellar mass and presumably even depends on additional factors like stellar rotation (cf. Soderblom 1996). Not only PMS stars, but also older stars which have already reached the main sequence, e.g. the G and K type stars in the $\sim 10^8$ years old Pleiades (c.f. Soderblom et al. 1993a), can display quite strong Li lines. In order to classify stars as PMS, we thus have to define a spectral type dependent threshold for the Li line width.

4.1. Classification criteria

We are interested in late type (G – M) PMS stars, and according to PMS stellar evolution models (e.g. D'Antona & Mazzitelli 1994), the PMS phase for these stars last for at least ~ 30 Myrs. We therefore use the available data on Li line widths of stars in several well-known young clusters which have ages in the range $\sim 30-50$ Myrs. We have collected Li data from the young clusters IC 2601 (~ 30 Myrs; Randich et al. 1997), IC 4665 (~ 35 Myrs; Martin & Montes 1997), IC 2391 (~ 40 Myrs; Stauffer et al. 1989), and α Per (~ 50 Myrs; Balachandran et al. 1996). Furthermore, we also have included Li data for the Pleiades from Soderblom et al. (1993a), Garcia Lopez et al. (1994), and Jones et al. (1996). The solid line in Fig. 3 shows the upper envelope for all Li measurements in these young clusters. Any star with a Li line width considerably above this threshold should be younger than ~ 30 Myrs and can therefore be classified as a PMS star. We note that similar classification schemes are now widely used in studies of young stars (e.g. Neuhäuser et al. 1997) and are thought to be very reliable for K and M type stars, while there might be some uncertainties for G type stars.

39 of our X-ray selected stars satisfy our Li criterion and thus are classified as new PMS stars. Most of the X-ray quiet proper motion candidates show no detectable or at best very weak Li lines and none of them can be classified as PMS.

For most of our new PMS stars the Li line widths are in the typical range found for bona-fide T Tauri stars (e.g. Basri et al. 1991, Magazzu et al. 1992). We therefore believe that most of our PMS stars are T Tauri stars with ages not exceeding a few Myrs, while others might be somewhat older. However, here we will not try to divide our PMS stars into T Tauri stars and "post T Tauri stars", since there is no general agreement on how to define theses classes of PMS stars (cf. discussion in Caillault 1998). We would like to note that $\sim 75\%$ of our new PMS stars show the Hα line in emission or completely filled in. Nearly all new PMS stars with Hα in absorption show considerably weaker Hα absorption lines than stars of similar spectral type classified as non-PMS.

Many of our non-PMS stars show weak but detectable Li lines. Since stars older than a few hundred Myrs generally show only very week Li lines (for example, the ~ 300 Myrs old stars in the Ursa Majori Group (Soderblom et al. 1993b) as well as the ~ 600 Myrs old Hyades stars (Thorburn et al. 1993) generally have $W(\mathrm{Li}) \leq 0.1$ Å), our non-PMS stars with $W(\mathrm{Li}) \geq 0.1$ Å probably are quite young with ages not exceeding a few 100 Myrs.

4.2. The new PMS stars

37 of the new PMS stars are the counterparts of RASS sources, 2 are the counterparts of sources from pointed ROSAT observations. One of these two sources is star 6770-655. Its count rate in the pointed observation is well above the RASS detection limit. Indeed, this source was also detected in the RASS, but due to its rather soft hardness ratios the discrimination probability is $P = 0.46$, slightly below our cutoff. The other source is star 6214-210. Its count rate in the pointed observation is only slightly above the RASS limit and it was not detected in the RASS.

In Fig. 5 we show the spatial distribution of the previously known and our new PMS stars in Upper Sco. One can see a clear concentration of PMS stars in the center of our area. Their spatial distribution is in good agreement with that of the early type probable members from de Geus et al. (1989), and also with that of the Hipparcos members (see Fig. 2 of de Bruijne et al. 1997). This means that the population of PMS stars is spatially coincident with that of the early type members.

For 37 of the observed X-ray selected candidates we know the proper motions from the STARNET catalogue. They are shown in Fig. 4 together with the proper motions

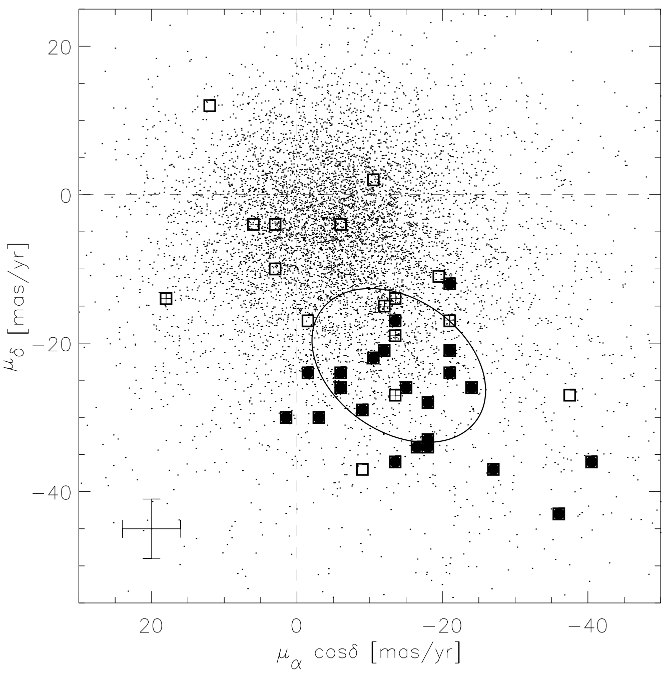

Fig. 4. The proper motions of the stars in our area as listed in the STARNET catalogue. The data points have been slightly randomized in order to avoid overlapping of points. All our X-ray quiet proper motions candidates lie within the ellipse. Note that this ellipse is drawn for illustration only; the proper motion candidate selection was based on stricter and position dependent criteria as described in section 2.2. The squares show the observed X-ray selected candidates with known proper motions. New PMS stars with known proper motions are marked by filled symbols. The cross in the lower left edge shows the typical size of the errors. Two RASS selected stars (both classified as field stars) have very high proper motions and are outside of the plot region.

of the other stars in the field. 8 of the new PMS stars fully satisfy our kinematic criteria for proper motion members. Another 12 of the new PMS stars have proper motions that miss our, very strict and conservative, kinematic selection criteria only very slightly. Thus, 20 of the 22 new PMS stars with known proper motions can be considered as probable kinematic members. In contrast to this, the non-PMS stars in our X-ray selected sample are evenly distributed in the proper motion space and most of them have proper motions typical for field stars.

Two of the PMS stars have rather large proper motions with $\mu_\alpha \cos\delta < -30$ mas/yr. It is interesting to compare their proper motions and positions. Star 6784-1219 seems to be coming from the direction to the ρ Oph clouds. For star 6770-655 (located at the extreme south-western edge of our field) the proper motions suggest that it might have been located in the central cluster of PMS stars about $1-2$ Myrs ago. This might indicate that this star has been ejected from there and perhaps is a run-away TTS (cf. Sterzik & Durisen 1995). However, this scenario has to be treated with some caution, since we do not know

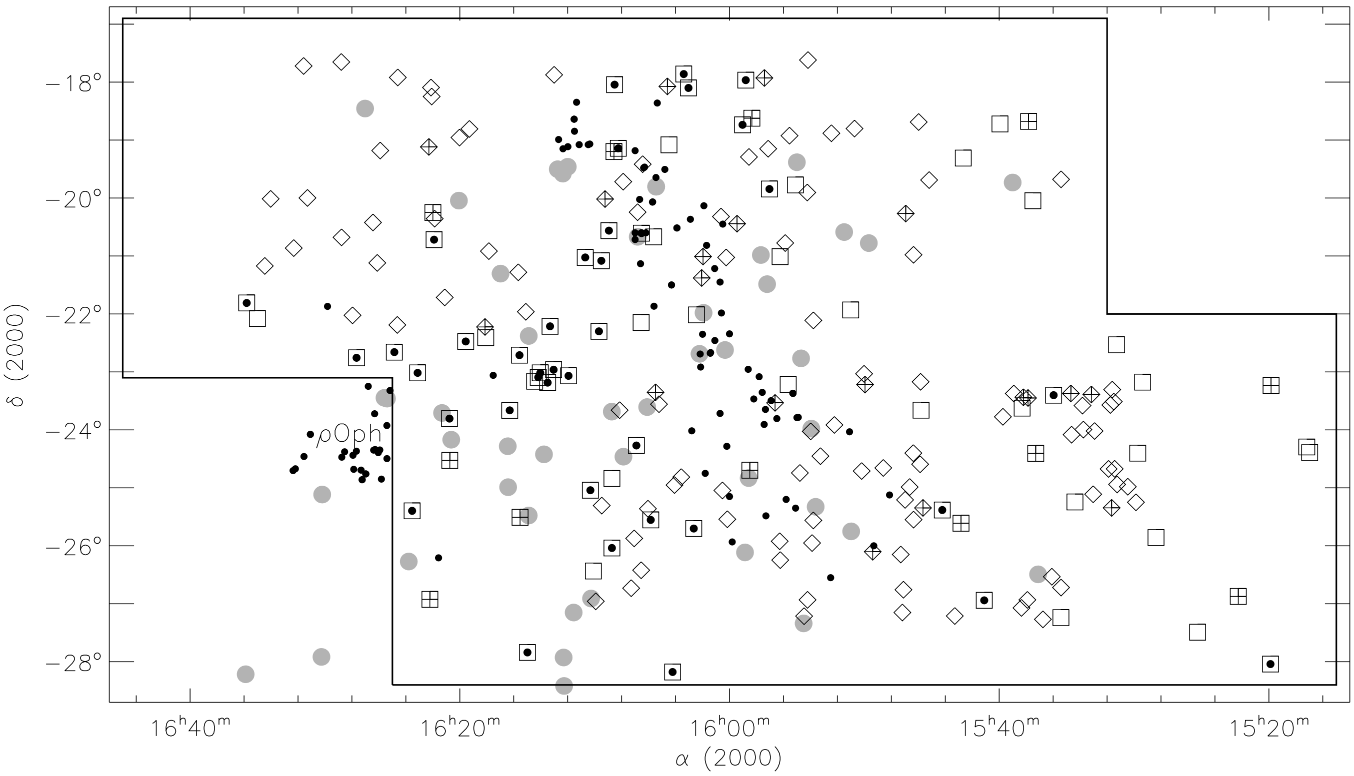

Fig. 5. This map shows the same region as Fig. 1. The small solid dots indicate the PMS stars detected by W94 and K98, big grey circles mark the B star members. The positions of the stars for which we obtained spectra are shown by open squares for the X-ray selected candidates and open diamonds for the X-ray quiet proper motion candidates. Stars which have been classified as PMS are marked by a solid dot within the symbol, stars with Li lines comparable to young cluster stars are marked by a cross within the symbol.

the actual age of this star. In fact, the rather weak Li line width close to our threshold and the rather strong Hα absorption line might indicate that this star is older than only a few Myrs.

4.3. The non-PMS stars

31 of the 69 RASS selected stars show Li lines too weak to be classified as PMS stars. It is well-known that many young active main sequence stars, e.g. Pleiades stars, have X-ray properties quite similar to those of PMS stars and can also meet our X-ray selection criteria for PMS candidates (Sterzik et al. 1995). Therefore, these 31 stars are probably active field stars. It is interesting to compare their number with the model for the stellar content of soft X-ray surveys of Guillout et al. (1996). For our source count rate limit of 0.02 counts/sec and galactic latitude $b \sim 30°$ this model predicts that we should detect ~ 0.65 active field stars per square-degree. This means that about 100 RASS sources in our ∼160 square degree area in Upper Sco should be active field stars. This is consistent with our number of 29 field stars if we keep in mind that not all field stars will meet our X-ray selection criteria.

The model furthermore predicts that about half (~ 50) of these RASS detected field stars are younger than 150 Myrs. Many of these young field stars should show Li lines with similar strength as the young cluster stars. This is consistent with our finding that 11 of the non-PMS RASS sources show Li line in that range.

Our sample of X-ray quiet proper motion candidates contains 19 stars which show Li lines comparable to those of the young cluster stars. These stars also probably are rather young main sequence stars. The other X-ray quiet proper motion candidates probably are older ($\gtrsim 100$ Myrs) field stars.

5. Discussion

5.1. How many X-ray quiet proper motion candidates might be PMS stars?

All proper motion selected stars observed have magnitudes in the range $B \approx 11.5 - 13.5$. To get a rough idea about the bolometric luminosities of these stars, we note that assuming a distance of 145 pc and a mean extinction of $A_V \approx 0.5$, this magnitude range transforms into a range of bolometric luminosities of $0.5\,L_\odot \lesssim L_{\rm bol} \lesssim 3\,L_\odot$ for a K5 star. Of course, earlier or later spectral types would give lower or higher luminosities, respectively. In the following, we restrict our analysis to this magnitude range. The total number of X-ray quiet proper motion candidates in this magnitude range is 442.

We observed 115 of these 442 X-ray quiet proper motion candidates and could not find any PMS stars among them. This information can be used to derive an upper limit on the possible number of PMS stars in the X-ray quiet proper motion candidate sample. For a statistical description of the problem we can use the hypergeometric distribution: We have a sample of $N = 442$ stars, from which we have randomly selected and observed $n = 115$ stars. If we assume that there are M PMS stars among the N stars, then the probability P of finding k PMS stars among the n observed stars is given by

$$P = \frac{\binom{M}{k}\binom{N-M}{n-k}}{\binom{N}{n}}$$

With $k = 0$ we find $P \leq 0.1$ for $M \geq 8$ and $P \leq 0.01$ for $M \geq 15$. This means that at the 90% (99%) confidence level the number of PMS stars in the sample of X-ray quiet proper motion candidates is smaller than 8 (15).

5.2. Completeness of the X-ray selected sample

If we want to estimate the completeness of our X-ray selected sample, we have to take two effects into account. First, Fig. 4 shows that the distribution of proper motions of the new PMS stars is considerably wider than our (very strict) selection criterion for the X-ray quiet proper motion members. This means that our selection criterion was somewhat too strict, since stars with proper motions similar to those of the new PMS stars also have to be regarded as possible members. Thus the number of possible proper motion members is probably larger than 442.

On the other hand, it is important to realize that not all stars with proper motions indicating membership actually are related to Upper Sco. It is clear that some fraction of our proper motion sample, like every proper motion sample, will be made up of field stars, having similar proper motions as the member stars just by chance. This fraction will be larger when the mean proper motion of the association is very near to the mean of the background population of field stars, i.e., when the convergent point is very near to the solar antapex.

Unfortunately, this is the case for the Upper Sco association. In the direction of Upper Sco the reflex motion of the Sun corresponds to proper motions of $(\mu_\alpha \cos\delta,\ \mu_\delta) = (-14, -26)$ mas/yr for $D = 100$ pc, $(-7, -13)$ mas/yr for $D = 200$ pc, and $(-3, -5)$ mas/yr for $D = 500$ pc. This means that field stars at distances between 100 pc and 200 pc tend to have proper motions very similar to the Upper Sco members and thus our sample of proper motion candidates contains many field stars. This effect can be seen in Fig. 4. However, with the available data it is not possible to disentangle the field stars from the proper motion members.

Nevertheless, we can try to roughly estimate the number of possible members in a very conservative way in order to get a reliable upper limit for the fraction of PMS stars among them. We note that all our proper motion candidates and all new PMS stars have $\mu_\alpha \cos\delta < 0$ and $\mu_\delta < -13$ mas/yr. There are 1518 stars fulfilling this requirement and we regard these stars as possible members. In order to take the field star pollution at least partially into account, we subtract the number of 512 stars with $\mu_\alpha \cos\delta > 0$ and $\mu_\delta < -13$ mas/yr. In this way we can roughly correct for the pollution with field stars showing random proper motions. The resulting number of 1006 possible members is a secure upper limit to the number of actual proper motion members, since it still is contaminated by field stars due to the solar reflex motion.

We now can perform the same kind of calculation as above and find that with 90% confidence this sample of 1006 possible members contains no more than 18 PMS stars. This is a secure upper limit on the number of X-ray quiet PMS stars in the magnitude range considered. The number of known PMS stars in this magnitude range is 56. This means that the X-ray selected sample contains at least 75% of all PMS stars.

It should be noted that the completeness of 75% is a very conservative lower limit; our sample is probably complete to a considerably higher degree. On the other hand, we already know that our RASS selected sample cannot be 100% complete, since we have found 2 PMS stars among the stars selected from pointed ROSAT observations. Our best guess for the completeness of the RASS selected sample is 80% – 90%. It would be very hard to obtain a better estimate of the completeness since this would require optical spectroscopy of many hundred stars.

6. Summary

We have performed a search for PMS stars in a 160 square-degree region in the Upper Sco association. We identify 39 new PMS stars by their strong 6708 Å Li lines, increasing the number of known PMS stars in this area to 108. The PMS stars cluster in the center of our area and seem to be spatially coincident with the early type members of the Upper Sco association.

We find new PMS stars only among the X-ray selected candidate stars, not among X-ray quiet proper motion candidates. Our result provides no evidence for the existence of a significant population of X-ray quiet T Tauri stars in Upper Sco. We conservatively estimate that our sample of RASS selected PMS stars in the magnitude range $11.5 \leq B \leq 13.5$ is at least 75% complete.

This study is the first step in our project to investigate the low-mass PMS population of the Upper Sco association. Further steps will include photometry for the new PMS stars, analysis of the HRD and finally the investigation of the mass function and star formation history of this interesting association.

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