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T Tauri Stars in the Scorpius-Centaurus OB Association

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Abstract:

We present the results from our intermediate resolution spectroscopic survey for T Tauri stars in the Scorpius Centaurus OB association. In a 160 square-degree area in Upper Scorpius, where 86 T Tauri stars were previously known, we could identify 46 new T Tauri stars by follow-up observations of X-ray selected stars.

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 ScoCen. We found that none of these stars is a T Tauri star. We conclude that our X-ray selected sample of T Tauri star seems to be rather complete for stars with $L_{\rm bol} \gtrsim 0.5\, L_{\odot}$.

1. Introduction

With a distance of only 160 pc the Scorpius Centaurus (ScoCen) association is the OB association nearest to the Sun. It contains several hundred B stars with ages between 5×10^6 yrs and 12×10^6 yrs (e.g., Blaauw 1978; de Geus et al. 1989). While the population of high mass stars in ScoCen is completely known and very well studied, virtually nothing was known about the low-mass pre-main-sequence stars, i.e., the T Tauri stars, until recently. This is due to the problem of finding the widespread population of T Tauri stars among the many thousands of foreground and background field stars in the huge area in the sky (several hundred square-degrees) covered by the association. Unlike the classical T Tauri stars, which can be rather easily found by their strong Hα emission, the weak-line T Tauri stars, which are the dominant part of the T Tauri population, cannot be easily distinguished from normal field stars.

Fortunately, most T Tauri stars display strong coronal activity and are copious X-ray emitters. Thus, follow-up observations of X-ray sources are a good way to find the T Tauri stars. Our aim is to get a representative sample of the T Tauri stars in the Upper Scorpius subgroup, the youngest part of ScoCen, which covers an area of about $20^\circ \times 20^\circ$ in the sky. This will finally allow us to study the initial mass function and the star formation history.

The first step to find T Tauri stars in ScoCen was taken by Walter et al. (1994), who could identify 28 T Tauri stars by optical follow-up observations of *Einstein* X-ray sources. However, the study of Walter et al. (1994) covered

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only an area of a few square-degrees, a tiny fraction of the whole association. They estimated that ScoCen contains at least 2000 more T Tauri stars.

The second step was a study by Kunkel (1997), who investigated ROSAT All Sky Survey X-ray sources in a 60 square-degree area in Upper Scorpius and could detect 65 new T Tauri stars. In order to increase the sample of T Tauri stars we extended the investigated region to 160 square-degrees (see Fig. 2).

2. T Tauri Star Candidate Selection

The data of the ROSAT All Sky Survey (RASS) provide us with a spatially complete sample of X-ray sources in this region and thus are the basis for our investigation. More than 900 X-ray sources have been found in ScoCen. From these sources we selected T Tauri star candidates by their X-ray hardness-ratios ("X-ray colors"), their flux ratio F_{X}/F_V, and the magnitude of the optical counterpart (see Sterzik et al. 1995 for a description of the selection method). This resulted in a sample of 275 X-ray selected T Tauri star candidates in the magnitude range $B \approx 10$ to $B \approx 15$. Additionally, we included the optical counterparts of 7 X-ray sources detected in deep pointed ROSAT observations only.

The aim of our study is not only to find more T Tauri stars, but also to investigate a very important question:

How complete is the X-ray selected sample of T Tauri stars?

The significance of this question has recently been demonstrated in a study of T Tauri stars in the Orion nebula region. Wolk (1996) found T Tauri 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 T Tauri stars there have much lower X-ray luminosities than typical for the X-ray detected T Tauri stars of similar bolometric luminosity. This surprising result implies the existence of a population of "X-ray quiet" T Tauri stars and shows that the X-ray selected sample of T Tauri stars in Orion is probably considerably incomplete.

We have investigated this question for ScoCen 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 to the Upper Scorpius association because of their proper motions being similar to the ones of the known early-type members. The procedure for our selection of these "X-ray quiet proper motion candidates" was the following:

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 Scorpius 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 (Röser 1996) Catalogue with a proper motion difference to the mean of less than 7.5 mas/yr as possible kinematic member. For observational reasons stars brighter than $B \approx 11$ mag were excluded, just like stars which were already included in the list of possible early-type members of Upper Scorpius by de Geus et al. (1989). This left us with 805 proper motion candidate stars with magnitudes between $B \approx 11$ and $B \approx 13$ in Upper Scorpius.

3. Observations

We have used the wide-field ($6.5^\circ \times 6.5^\circ$) multiobject spectrograph FLAIR (see Parker & Watson 1995) on the UK Schmidt Telescope at the Anglo-Australian Observatory. We selected 6 slightly overlapping fields in Upper Scorpius and obtained optical medium-resolution ($R = 3800$) spectra for 240 stars in these fields. For the determination of spectral types we also took low-resolution ($R \approx 800$) spectra for most of the stars. These observations resulted in high quality spectra for 76 X-ray selected stars and 115 proper motion selected stars. Additionally, we included 6 of the T Tauri stars found by Walter et al. (1994) in order to use them as spectral standards.

We determined the pre main sequence (PMS) nature of a star by the strength of its 6708 Å lithium line. Since lithium is strongly diminished in the first few million years of the life of a star, a high lithium content is a clear indication for the youth of a star (e.g., Herbig 1962; D'Antona & Mazzitelli 1994). However, not all stars that display a strong lithium line actually are PMS stars: For example, many of the 7×10^8 years old Pleiades stars, that are young main sequence stars and thus not PMS stars, show rather strong lithium lines (Soderblom et al. 1993). Therefore, we classify a star as PMS if the equivalent width of its lithium line is at least 0.1 Å and larger than typical for Pleiades stars of the same spectral type (see Fig. 1).

It has recently been shown that the determination of the lithium equivalent width can be problematic if the spectral resolution is too low. For example, Covino et al. (1997) performed high (0.3 Å) resolution echelle spectroscopy for a sample of stars in the Chamaeleon star-forming region that had been classified as T Tauri stars in previous low (4 – 8 Å) resolution spectroscopy and could show that the line widths determined from the low resolution spectra tend to overestimate the true line widths by up to a factor of 2. However, intermediate resolution of at least 1 – 2 Å seems to be sufficient to measure reliable lithium line widths (see Neuhäuser et al. 1997).

For our observations we have used the highest spectral resolution possible with FLAIR, 1.8 Å. Since nearly all of our spectra have a S/N ratio of at least 100, the lithium line can be reliably discerned from other nearby lines in most spectra. Thus, we expect no significant problems for our determination of equivalent widths. This expectation is confirmed by comparison to the equivalent widths determined by Walter et al. (1994) for the 6 stars in common, which shows no significant systematic deviations. In a few of our spectra the lithium line appears to be significantly blended with other lines; in these cases we regarded the measured equivalent widths as upper limits only.

4. Results

The results of our observations are shown in Fig. 1. For 46 of the X-ray selected stars the lithium line width is above the maximum found for Pleiades stars of the same spectral type; these 46 stars are classified as new T Tauri stars. In contrast to this high success rate for the X-ray selected candidates, most of the X-ray quiet proper motion candidates show no detectable or very week lithium lines (W(Li) $\leq$ 0.1 Å) and none of them can be classified as a T Tauri star.

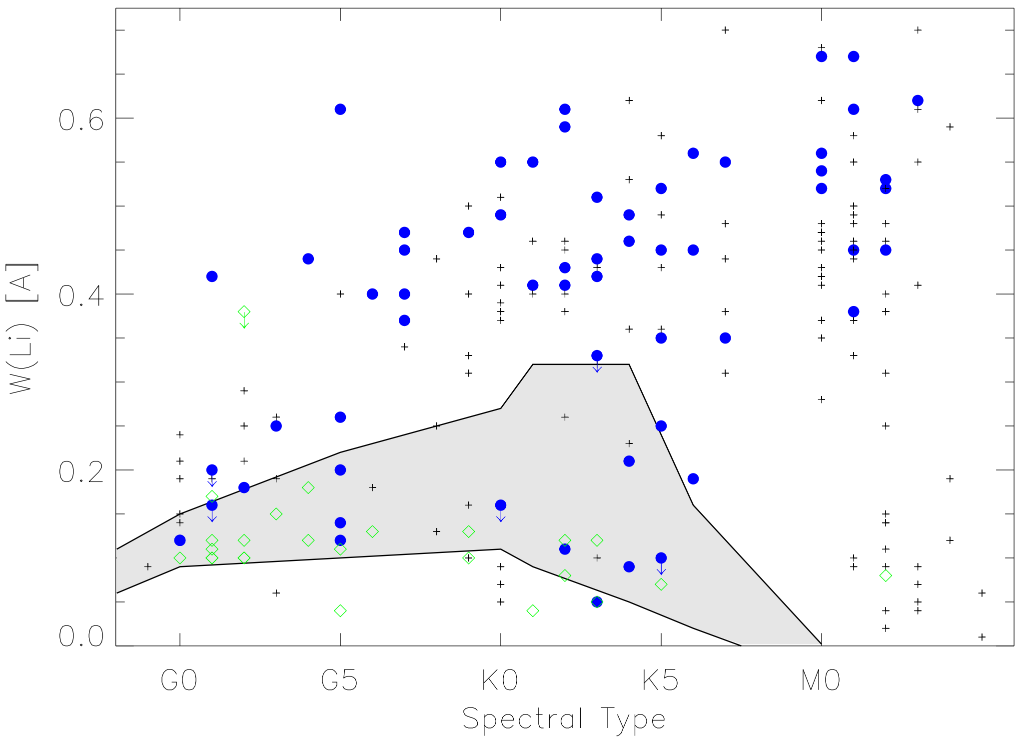

Figure 1. This plot shows the equivalent width of the 6708 Å lithium line and the spectral type of the stars in ScoCen determined from our FLAIR spectra. The solid dots show the X-ray selected stars, the open diamonds show the X-ray quiet proper motion candidates for which the lithium line could be measured. Symbols with downward arrows denote upper limits to the line width due to blending. The stars observed by Walter et al. (1994) and Kunkel (1997) are shown as small crosses for comparison. The shaded area marks the range of typical lithium equivalent widths for Pleiades stars from Soderblom et al. (1993). (An interactive version of this figure using the Ov applet is contained on the companion CD–ROM.)

In Fig. 2 we show the spatial distribution of T Tauri stars in Upper Scorpius. One can see a clear gradient in the spatial density of T Tauri stars when going from the center of our area towards the north-east and the south-west corners. At the eastern boundary of our area the spatial distribution of the T Tauri stars overlaps with the outer parts of the ρ Ophiuchi star forming region.

For 38 of the observed X-ray selected candidates we know the proper motions from the STARNET catalogue. They are shown in Fig. 3 together with the proper motions of the other stars in the field. One can see that nearly all of our new T Tauri stars among these candidates have proper motions consistent with membership, while most candidates without lithium detection have proper motions typical for field stars.

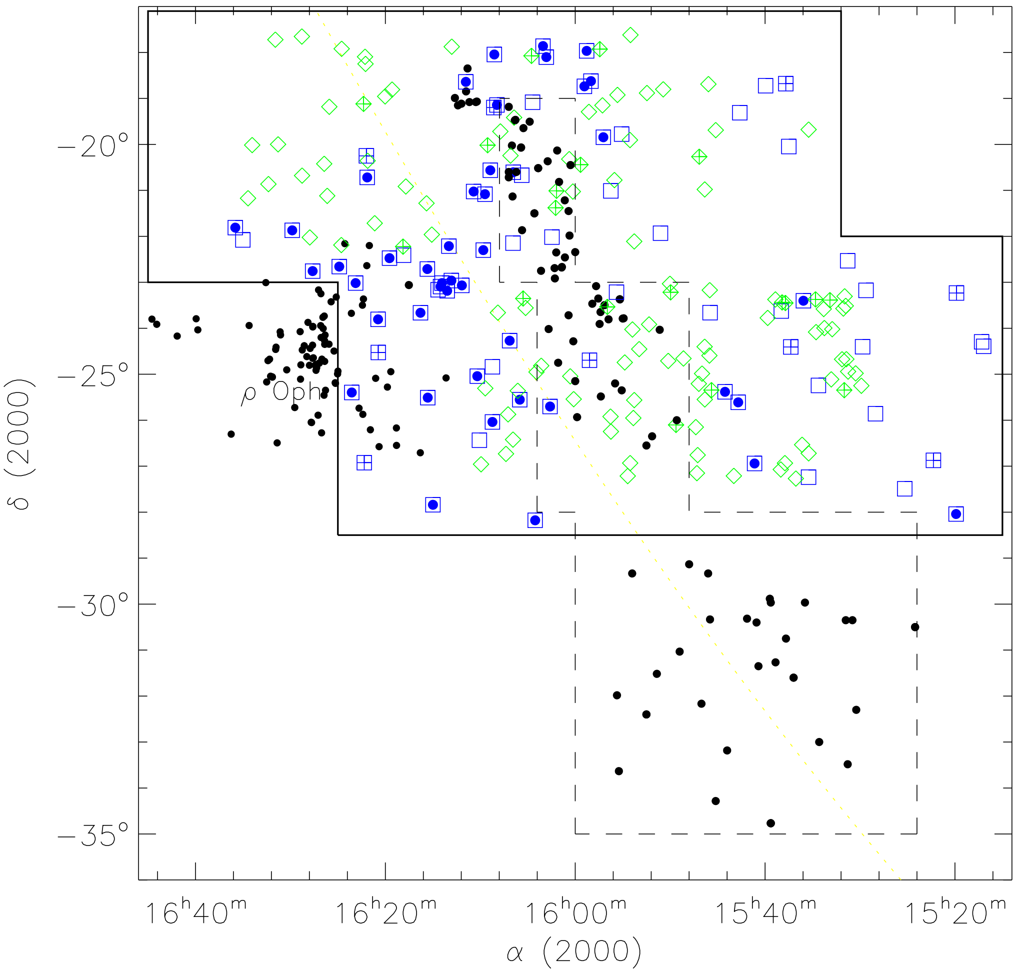

Figure 2. Map of the Upper Scorpius region. The dashed line marks the region studied by Kunkel (1997). Previously known T Tauri stars are marked as filled dots, the dotted line shows Gould's Belt. The area investigated in our study is marked by the solid line. The positions of X-ray selected candidates we have observed are show by open squares, those of the X-ray quiet proper motion candidates by open diamonds. Stars which have been classified as T Tauri stars are marked by a black dot within the symbol, stars with lithium lines comparable to Pleiades are marked by crosses. (An interactive version of this figure using the Ov applet is contained on the companion CD–ROM.)

Among the X-ray selected stars as well as the X-ray quiet proper motion candidates a fraction of about 15% show lithium lines with similar strength as typical for Pleiades stars. These are presumably young (zero-age?) main-sequence stars or perhaps post T Tauri stars. As can be seen from Fig. 2, these stars are distributed rather uniformly in our area. They might be related to

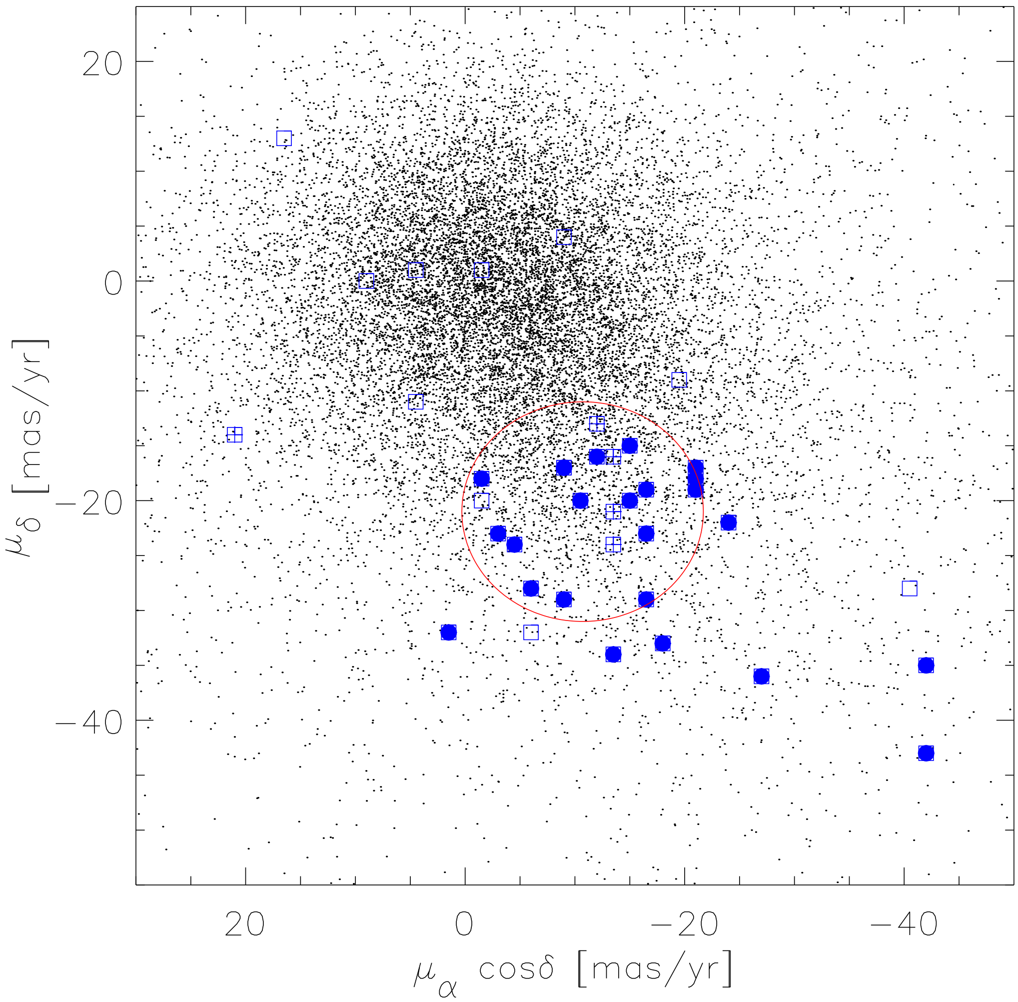

Figure 3. The proper motions of the stars in our area as listed in the PPM and the STARNET catalogues. All proper motions candidates lie within the ellipse. The squares show the proper motions of the X-ray selected candidates which we have observed with FLAIR. The new detected T Tauri stars are marked by filled symbols. (An interactive version of this figure using the Ov applet is contained on the companion CD–ROM.)

Gould's Belt, a system of young (30 – 60 Myrs old) stars within 1 kpc of the Sun (cf. Neuhäuser 1997).

5. Conclusions

Our observations have revealed 46 new T Tauri stars in Upper Scorpius. We find no evidence for the existence of a significant population of X-ray quiet T Tauri stars in ScoCen. Since we cannot find any T Tauri star among the 115 *non*-X-ray detected stars in the magnitude range $B \approx 11$ to $B \approx 13$, essentially all ScoCen T Tauri stars in this magnitude range must have X-ray luminosities above the RASS detection threshold. This means that essentially all T Tauri stars with $0.5\,L_\odot \lesssim L_{\rm bol} \lesssim 3\,L_\odot$ have X-ray luminosities exceeding 10^{30} erg/sec. This high level of X-ray activity is quite surprising: In other star forming regions, for example IC 348 (Preibisch, Zinnecker, & Herbig 1996) or Chamaeleon (Feigelson et al. 1993) at least 30% – 40% of the T Tauri stars in that bolometric luminosity range have X-ray luminosities considerably below 10^{30} erg/sec. Further investigations to understand this effect are in progress.

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