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# Kinematics of Lithium-Rich Stars South of Taurus

R. Neuhäuser[1], S. Frink[2], G. Torres[3], M.F. Sterzik[1], S. Röser[2], and S. Randich[4,5]

**Abstract:**

We have obtained single-order echelle spectra for 106 late-type stars found with *ROSAT* south of Taurus, including some 30 stars that have been claimed to be low-mass pre-main sequence (PMS) stars. 19 stars are located on the $\lambda$ Ori cloud, nine of which are K-type stars with lithium in excess of the zero-age-main-sequence (ZAMS) level; i.e., are PMS stars. At least 40 of the remaining off-cloud stars display detectable lithium, 24 of which show lithium at least as strong as IC 2602 stars with the same spectral types and, therefore, are probably not older than IC 2602 ($\sim 3 \times 10^7$ yr). Of those 24 stars, nine (25% of the off-cloud stars with detectable lithium) are PMS stars isolated from cloud material; all have spectral type K, and three of them are spectroscopic binaries. The remaining 15 off-cloud stars have spectral type G and lithium comparable to IC 2602 stars, i.e., may have arrived already on the ZAMS, as the G-type IC 2602 stars have. However, these 24 off-cloud lithium-excess stars are probably not older than IC 2602 ($\sim 3 \times 10^7$ yr).

For 18 of the lithium-excess stars south of Taurus, we have determined proper motions with a typical accuracy of 5 mas/yr from the STARNET catalog, a combination of the HST GSC1.2 and the Astrographic Catalog. Most of these 18 stars have spectral type G. Their 3D space velocity is different from the 3D velocity distribution of bona-fide T Tauri stars in central Taurus. We conclude that the new G-type stars among the lithium-excess population may be young Gould Belt members. Since both the GSC and the AC are magnitude-limited, only the brightest stars (i.e., the G-type stars) are listed in STARNET. Runaway T Tauri stars, however, should be most frequent among lower-mass stars. We also discuss alternative modes of origin of the isolated PMS stars south of Taurus.

## 1. Introduction

Prior to the *ROSAT* mission, $\sim 60$ weak-line T Tauri stars (wTTS) were known in Taurus, half of which were discovered by ground-based optical follow-up observations of previously unidentified *Einstein Observatory* X-ray sources (Herbig

[1]Max-Planck-Institut für extraterrestrische Physik, D–85740 Garching, Germany
[2]Astronomisches Rechen-Institut, Mönchhofstr. 12–14, D–69120 Heidelberg, Germany
[3]Harvard-Smithsonian Center for Astrophysics, 60 Garden St., MA 02138
[4]European Southern Observatory, Garching, Germany
[5]Osservatorio Astrofisico di Arcetri, Florence, Italy

& Bell (1988) and Neuhäuser et al. (1995a) for lists of TTS known prior to *ROSAT*). From their *Einstein Observatory* studies, Walter et al. (1988) concluded that there should be as many as $\sim 10^3$ wTTS in the Taurus clouds.

Among the advantages of the *ROSAT* All-Sky Survey (RASS) is the complete sky coverage with a flux limit sufficient to detect most TTS in nearby SFRs (Neuhäuser et al. 1995a). A total of $\sim 70$ lithium-rich stars — claimed to be wTTS — have been discovered among RASS sources in the central parts of the Taurus T association (Wichmann et al. 1996). Most X-ray discovered TTS are wTTS located on or very close to molecular clouds, but they do show a more wide-spread spatial distribution compared to classical T Tauri stars (cTTS), which are still closely associated with their parent clouds.

Prior to follow-up observations of RASS sources, we pre-selected TTS candidates using the X-ray data of the unidentified RASS sources following Sterzik et al. (1995). With ground-based optical follow-up observations of previously unidentified X-ray sources from the *ROSAT* All-Sky Survey (RASS), many late-type stars with lithium 6708 Å absorption and H$\alpha$ in emission (or filling in the absorption) were identified as optical counterparts. They were found in all of the star forming regions investigated: Taurus (Neuhäuser et al. 1995b, Wichmann et al. 1996; Magazzù et al. 1997; Neuhäuser et al. 1997), Orion (Alcalá et al. 1996), Lupus (Krautter et al. 1997; Wichmann et al. 1997a, b), and Chamaeleon (Alcalá et al. 1995, 1997; Covino et al. 1997).

Most of the *ROSAT* counterparts with lithium detected in spectra with low resolution (a few Å) were classified originally as "weak-line" T Tauri stars (wTTS). Surprisingly, some of the young stars are located even outside the commonly accepted borders of the star forming regions.

However, there are two major problems with this interpretation, i.e., the question of whether they really are pre-main sequence (PMS) stars, namely:

1) In particular, for stars which can no longer be associated with their parent clouds (like wTTS), it is difficult to determine or assume a distance. However, knowing the distance is crucial for placing the stars onto the HR diagram for estimating their ages by comparison with theoretical isochrones. The usual practice is to adopt the same distance as the clouds. However, if the star is really foreground to the clouds, one would underestimate the age (Alcalá et al. 1997; Briceño et al. 1997). Since ZAMS stars such as the Pleiades also show a high level of X-ray activity and optical spectra (with lithium) similar to wTTS, it is clear that some (or many) of the lithium-rich *ROSAT* stars could be young ZAMS stars rather than PMS stars (Briceño et al. 1997).

2) It is possible to overestimate the lithium equivalent width in spectra with low resolution (as used in most RASS follow-up studies) due to blends with nearby iron lines and the assumption on the continuum level. Hence, some (or many) of the "lithium-rich" *ROSAT* counterparts may actually have very weak lithium or no lithium at all (Briceño et al. 1997). Even ZAMS stars show a wide range in lithium strength due to different masses and rotational velocities.

To overcome these two mayor problems, one should

- investigate distance-independent age indicators (such as lithium, and perhaps even surface gravity), and one should observe the stars with high spectral resolution to determine whether lithium is indeed stronger than in ZAMS stars of the same spectral type;

- investigate the three-dimensional space motion (proper motion and radial velocity) of the stars to check for kinematic membership to the associations;

- make efforts to obtain trigonometric parallaxes which, although very difficult to do from the ground for stars more distant than 100 pc, may be possible for stars foreground to the clouds.

## 2. The Lithium Argument

Covino et al. (1997) have performed high-resolution spectroscopy for nearly all the lithium-rich *ROSAT* counterparts classified as "wTTS" by Alcalá et al. (1995). Their comparison of high- and low-resolution lithium equivalent widths — as displayed in their Figure 3 — clearly shows that lithium can be overestimated in late-F and G-type stars by large amounts. The reasons are the low lithium equivalent width (so that the relative errors in Li equivalent widths from low-resolution spectra are large) and the strong iron lines in G-type stars. In K-type stars, the overestimate decreases in relative terms with decreasing effective temperature because the Fe/Li ratio in cooler stars get smaller, as the lithium equivalent width is much more sensitive to the temperature than the Fe lines. In absolute terms the effect is smaller than 0.1 Å in K-type stars in any case. With two exceptions, lithium was not overestimated at all in M-type stars.

Hence, while it is difficult to estimate the true lithium equivalent width in G-type stars just from low-resolution spectra, this is very well possible for K- and M-type stars. Lithium data from low-resolution spectra are reliable for K- and M-type stars, but not for G-type stars.

Covino et al. (1997) also compare the lithium data for their stars with those of the Pleiades. They clearly show that many K-type *ROSAT* stars in Chamaeleon show stronger lithium than K-type ZAMS stars. Also, the M-type Chamaeleon stars with lithium are clearly younger than ZAMS stars, as they burn all their lithium quite rapidly (no M-type Pleiades shows lithium; only the much cooler brown dwarfs do). However, G-type ZAMS stars still show primordial levels of lithium, just as G-type TTS do, so that it is not possible to confirm their pre-MS nature using the lithium data alone. In Chamaeleon, Covino et al. (1997) find a bi-modal distribution of lithium: stars with much more lithium than ZAMS stars (bona-fide TTS), and stars with lithium as weak as in ZAMS stars. Covino et al. (1997) find no intermediate lithium stars, i.e., no post-TTS. Another interesting point is that most of the lithium-rich stars share the Chamaeleon radial velocity.

The spatial distribution of the Covino et al. stars is shown in their Figure 7 (Covino et al. 1997). Obviously, many of the lithium-rich stars are located on or very close to the clouds. In addition, there are several TTS far off the clouds, including M-type stars with lithium, which must be younger than 10 Myr. These stars are too young to have traveled the distance from the nearest clouds in their short life-time, if one adopts the canonical velocity dispersion in T associations (1 to 2 km s$^{-1}$). Hence, they may either have formed locally (in small cloud-lets which have dispersed since then; cf., Feigelson 1996), or they may have been ejected from the clouds with high velocities, and would be so-called run-away TTS (Sterzik & Durisen 1995).

## 3. Kinematics of New TTS in and Around the Taurus Clouds

Magazzù et al. (1997) present lithium results for over 100 RASS sources in an area just south of the Taurus clouds. They find 33 stars south of Taurus with lithium stronger than Pleiades members of similar spectral types. These stars display the spectral signatures typical of weak-line TTS.

Neuhäuser et al. (1997) have obtained high-resolution spectra for most of the Magazzù et al. (1997) stars. They conclude that 15 late F- and G-type stars with lithium comparable to G-type IC 2602 stars may just be arriving on the ZAMS. Most of the K-type stars among them show stronger lithium than K-type ZAMS stars, while it is difficult to classify the G-type stars either as ZAMS or PMS stars solely on the basis of the lithium strength. Nine other stars show large lithium excess above the ZAMS level and are located in the $\lambda$ Ori area, a region of ongoing star formation. These are PMS stars, possibly associated to that region. The remaining nine lithium-rich stars south of Taurus have spectral type K and lithium at least as strong as IC 2602 stars; these nine stars are also PMS stars, but are located far from any cloud.

High-resolution echelle spectra have also been used for determining radial velocities (RV), and also projected rotational velocities $v \times \sin i$; observations and data are presented in Neuhäuser et al. (1997).

The heliocentric radial velocities of "bona-fide" TTS in central Taurus peak at $17.4 \pm 2.1$ km s$^{-1}$ (Hartmann et al. 1986). One may consider the RV of a lithium-rich star to be consistent with central Taurus if the RV lies between 13.5 km s$^{-1}$ and 21.5 km s$^{-1}$, which represents a 2 $\sigma$ interval around the mean.

The 33 lithium-excess stars in the sample south of Taurus display a RV distribution that peaks near 17 km s$^{-1}$, the same as that of previously known TTS in central Taurus (see Figure 6 in Neuhäuser et al. 1997). The complete sample of objects studied, however, shows a wider RV distribution due to the contribution of older field ZAMS stars. The RV distribution of non-PMS stars (i.e., stars without lithium excess) is quite uniform and does not show any peak, which is consistent with these stars belonging to a foreground population of somewhat older stars.

In summary, the RV data of many lithium-rich stars south of Taurus are consistent with membership to the Taurus association, which seems to suggest that the stars south of Taurus are PMS stars, like those in central Taurus. In order to check whether these stars might have been ejected from the Taurus clouds, one must investigate their proper motions. Ejected stars should move south relative to the Taurus clouds and TTS.

In addition to having a sharp peak in heliocentric RV, TTS in the Taurus T association also populate a narrow box in the proper motion ($\mu_\alpha \times \cos \delta$, $\mu_\delta$) plane (Jones & Herbig 1979), and they share the RV of the nearby clouds (Herbig 1977). The internal velocity dispersion in both RV and proper motion is only 2 to 3 km s$^{-1}$ (Hartmann et al. 1986; Jones & Herbig 1979). However, these studies were restricted to small samples consisting almost exclusively of young cTTS. As soon as older, more evolved and dispersed stars are included with the cTTS, these internal dispersions are expected to become larger.

Frink et al. (1997) list the proper motions of TTS found in the STARNET catalog: Bona-fide TTS in central Taurus, *ROSAT* TTS in central Taurus (Wichmann et al. 1996), and the lithium-rich stars south of Taurus. As seen in their Figures 1 and 2, none of the young stars south of Taurus move south relative to Taurus, i.e., none of them appear to have been ejected from Taurus. However, this can be said only for about 10 of the stars listed in STARNET. These are G-type stars, since STARNET is magnitude-limited. The proper motions of the K-type stars are not known, and we point out that run-away TTS ejected from the central regions should be more frequent among the lowest mass TTS.

Very few of the stars south of Taurus are younger than 10 Myr, as judged from their lithium being much stronger than in IC 2602 stars. Most lithium-rich K-type stars south of Taurus show as much lithium as IC 2602 stars, i.e., are approximately 30 Myr old. They are also located on the Gould Belt, so that we may conclude that they are members of that structure. Interestingly, no such stars were found in Chamaeleon, where there is no Gould Belt.

## 4. *Hipparcos* Results for New TTS

More recently, Neuhäuser & Brandner (1998) have cross-correlated the list of *ROSAT*-discovered TTS with the *Hipparcos* catalog. Out of $\sim 500$ lithium-rich *ROSAT* counterparts, which were presumed to be low-mass PMS stars, 21 stars have been observed by *Hipparcos*. These 21 stars include three wTTS from the Wichmann et al. (1996) sample in central Taurus, and one new PMS stars found south of Taurus by Magazzù et al. (1997).

The proper motions of these four Taurus TTS are consistent with membership to the Taurus T association and also agree well with proper motion data from the STARNET (or PPM) catalogue (Frink et al. 1997). Also, the distances of these stars — based on *Hipparcos* parallaxes — are in agreement with the mean distance of the Taurus TTS and clouds, which is $\sim 140$ pc.

For one of these four stars (HD 283798) precise photometry is available, and Neuhäuser & Brandner (1998) have combined the spectral type, the photometry, and the *Hipparcos* parallax to compute its absolute bolometric luminosity in order to place it on the H-R diagram. By comparison with evolutionary tracks and isochrones (D'Antona & Mazzitelli 1994), they determined for HD 283798 a mass of $\sim 1.3\ M_\odot$ and an age of $\sim 12$ Myr. It lies clearly above the ZAMS.

Using the available photometry, Neuhäuser & Brandner (1998) were able to place a total of 15 *ROSAT*-discovered lithium-rich stars on the H-R diagram using the *Hipparcos* parallaxes. All of them lie above the ZAMS and thus are indeed PMS stars with ages ranging from 1 to 15 Myr. Only two of the stars are located on the Hayashi-tracks, whereas the other 13 are post-T Tauri stars, located on radiative tracks, with relatively low lithium abundance.

## 5. Summary: How Many *ROSAT* Counterparts are Pre-MS Stars?

The number of true pre-MS stars among Lithium-rich *ROSAT* counterparts certainly varies from region to region. Four different types of regions must be distinguished:

- on-cloud and on the Gould Belt: e.g., Taurus, Lupus, Orion,
- on-cloud, off-Belt (i.e., outside of the Belt): e.g., Chamaeleon,
- off-cloud, on-Belt: e.g., south of Taurus,
- and off-cloud, off-Belt: e.g., far south of Taurus, far off Lupus.

The table below summarizes the fraction of the different kinds of stars (truly young pre-MS stars, 30 Myr old post-TTS, and ZAMS stars) in the different regions. The numbers given are very rough estimates and do not take into account differences between the different star forming regions, like star formation efficiency and history. The estimates given are fractions found in the respective sample of *ROSAT* counterparts with detected Lithium in low-resolution spectra.

| Area | | Li > IC 2602<br>wTTS $\leq 10^7$ yr | Li $\sim$ IC 2602<br>pTTS $\sim 3 \times 10^7$ yr | Li $\sim$ Pleiades<br>ZAMS $\sim 10^8$ yr |
|---|---|---|---|---|
| on cloud, on Belt | (1) | 1/3 | 1/3 | 1/3 |
| on cloud, off Belt | (2) | 2/3 | ... | 1/3 |
| off cloud, on Belt | (3) | 1/8 | 3/8 | 1/2 |
| off cloud, off Belt | (4) | 1/20 | 1/20 | 9/10 |

Remarks: (1) On the Taurus, Lupus, and Orion clouds; (2) On the Chamaeleon clouds; (3) Slightly south of Taurus; (4) The areas and stars referred to here in the strips far south of the Taurus clouds (Neuhäuser et al. 1995b, 1997) and near Lupus (Wichmann et al. 1997b) are only the areas outside the relevant (Taurus or Lupus) clouds and outside the relevant part of the Gould Belt, i.e., the stars on the clouds and the Belt studied in those papers are not included.

To summarize, the most important results of the follow-up studies of the *ROSAT* sources in and around the star forming regions are:

- In any of the regions investigated, we find Lithium-rich stars among the optical counterparts of *ROSAT* sources, a mixture of young pre-MS stars, ZAMS stars and young MS stars.
- Hundreds of new T Tauri stars are found in star forming clouds in the *ROSAT* sample.
- Few pre-main sequence stars are found far away from clouds (possibly ejected run-away T Tauri stars or born in cloudlets?).
- Among the post-TTS, some may be low-mass Gould Belt members.
- The ZAMS population expected from galactic models is also seen.

We refer to the recent review by Neuhäuser (1997) for more details.

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