ROSAT AND OPTICAL OBSERVATIONS OF PRE-MAIN SEQUENCE STARS OUTSIDE STAR FORMING REGIONS

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ABSTRACT.
With the spatially complete but flux-limited ROSAT All-Sky Survey (RASS), two-thirds of the previously known weak-line T Tauri stars (wTTS) and only one sixth of the classical T Tauri stars (cTTS) were detected in the near-by Taurus star forming region. With ground-based optical follow-up observations of unidentified RASS sources, many late-type stars with lithium 6708Å absorption were identified as RASS counterparts. High-resolution spectra confirm high lithium abundances in many of them, and also yield their rotational and radial velocities. Also, quite a number of older, more evolved - but still active - zero-age-main-seqeuence (ZAMS) stars are detected, which are not concentrated towards star forming clouds or the Gould Belt. So far, up to $\sim$ 100 new wTTS (and also a few cTTS) are found in any of the star forming regions studied: Taurus, Orion, Lupus, ScoCen, Chamaeleon, and R CrA. They do show more lithium than ZAMS stars of the same spectral types and rotational velocities. Hence, these new stars really are young, i.e. pre-main sequence stars. Most of the new wTTS are located on or near clouds, but some are isolated, i.e. several degrees off any remnant cloud material. We discuss possible sites and modes of origin of such objects.

1. Introduction

With ground-based optical follow-up observations of previously unidentified ROSAT X-ray sources, many new T Tauri stars (TTS), i.e. low-mass, late-type pre-main sequence (PMS) stars, have been discovered. Because most of them show weak $H\alpha$ emission, they were classified as *weak-line* TTS (wTTS), in contrast to *classical* TTS (cTTS), which show strong emission lines and strong infrared (IR) excess indicative of circumstellar disks, where planets may be forming.

After the discovery of many wTTS with follow-up observations of *Einstein Observatory* (EO) sources (Walter et al. 1988), it became clear – by placing the stars into the H-R diagram – that many wTTS are co-eval with the cTTS, i.e. are located on Hayashi-tracks – still contracting, i.e. being very young. Other wTTS are located on radiative tracks approaching the Zero-Age-Main-Sequence (ZAMS), and can thus be called post-TTS as originally proposed and expected by Herbig (1978). EO observations covered only small parts of the sky, were flux-limited, and – as TTS show variable X-ray emission – actually missed most of the wTTS, so that Walter et al. (1988) estimated that wTTS outnumber cTTS by factors of up to ten.

With the ROSAT All-Sky Survey (RASS), the whole sky has been observed, so that one could search for TTS anywhere. The RASS has been performed with the Positional Sensitive Proportional Counter (PSPC) onboard ROSAT and typical RASS exposure times lie around 500 seconds, so that the flux limit is $\sim 10^{-13} erg/sec/cm^2$; for details about ROSAT and its instruments, we refer to Trümper (1983). There are several near-by star forming regions at distances of ~ 140 pc, like Taurus–Auriga, Lupus, Scorpius, and CrA. Given the RASS flux limit, many TTS can be detected at this distance. Indeed, in the Taurus clouds, two thirds of the previously known wTTS have been detected with RASS (Neuhäuser et al. 1995a), so that one could expect to discover many new TTS.

To avoid taking spectra of all or even large portions of the $\sim 10^5$ RASS sources (Voges et al. 1997), a pre-selection of TTS candidates must be applied. This can be done as suggested and shown by Sterzik et al. (1995). Well-known and RASS detected non-TTS and TTS can be discriminated by four parameters known for any RASS source with near-by optical counterpart, e.g. in the HST GSC: The X-ray hardness ratios HR 1 and HR 2, the X-ray count rate, and the X-ray to optical flux ratio. Using these criteria, one can pre-select unidentified RASS sources, which resemble well the typical TTS properties, for which one can then take optical spectra. A potential RASS counterpart can then be identified as young star due to the Lithium 6708 Å absorption line, as Lithium is burned rapidly during the pre-MS phase in TTS, i.e. fully convective stars.

However, since ZAMS stars show similar optical and X-ray properties as TTS (e.g. Briceño et al. 1997), one can accept a counterpart as pre-MS stars only, if it shows Lithium stronger than a ZAMS star of the same spectral type. This Lithium criterion does not work for G-type stars, because G-type ZAMS stars still show the primordial Lithium like TTS. However, a fully convective M-type star with detected Lithium must be younger than $\sim 10^7$ yr anyway, and needs 50 to 100 Myr to reach the ZAMS. The Lithium criterion works quite well for K-type stars. For determining the Lithium equivalent width or abundance precisly, one has to take the optical spectrum with sufficiently high resolution in order to avoid blends with other near-by lines. Comparison of low- and high-resolution spectra of about 80 Lithium-rich stars in Chamaeleon has shown, that low-resolution spectra give reliable Lithium data for K- and M-type stars, but not so well for G-type stars (Covino et al. 1997; C97). To confirm the pre-MS nature of a star, one has to estimate its bolometric luminosity from multi-color photometry and spectroscopy in order to place the star into the H-R diagram. For doing this, one needs to know or assume a distance. One can estimate ages and masses by comparison with evolutionary track and isochrones.

In any of the star forming regions studied, many new TTS were found: In Chamaeleon, Alcalá et al. (1995; A95) found 77 Li-rich stars with low-resolution spectroscopy, two thirds of which were confirmed to show more Lithium than ZAMS stars in high-resolution spectra (C97). In Lupus, Krautter et al. (1997) and Wichmann et al. (1997) found 164 Li-rich stars with low-resolution spectroscopy, most of which are confirmed, by high resolution spectroscopy, to have W_λ(Li) higher than in ZAMS stars of the same spectral type (Wichmann et al., in preparation). In Taurus, Wichmann et al. (1996) found 76 Li-rich stars with low-resolution spectra. Finally, Alcalá et al. (1996; A96) found 112 Li-rich stars in Orion with low-resolution spectroscopy. For a summary of the ROSAT follow-up studies, see Neuhäuser (1997).

Surprisingly, new TTS were not only found among ROSAT sources in star forming regions, but also several degrees away from the clouds, i.e. outside from active star forming sites. Neuhäuser et al. (1995b; N95) and Magazzù et al. (1997; M97) identified

33 Li-rich stars south of the Taurus clouds by medium-resolution spectroscopy. High-resolution spectra of the stars south of Taurus were obtained by Neuhäuser et al. (1997b; N97). Also, some of the Orion and Chamaeleon stars (A95, A96) are located several degrees away from clouds. For those stars, one cannot easily assume a distance for placing them into the H-R diagram. If they are tens of degrees, i.e. tens of pc, away from the cloud cores, then they may be located foreground to the clouds.

2. Ejection of run-away T Tauri stars

If the Li-rich stars (or at least some of them) found outside clouds, i.e. up to several degrees away from any nearby molecular cloud, are too young to have dispersed out of the Taurus clouds with velocities similar to the small velocity dispersions observed among TTS and clouds in central Taurus (2 to 3 $km\ s^{-1}$, Herbig et al. 1977, Jones & Herbig 1979, Hartmann et al. 1986), then the question arises: How and where did these young PMS stars form ? They may have formed locally (as suggested by Feigelson 1996), but we see no residual gas left over. Alternatively, they must have formed in the central cloud cores and were subsequently ejected with velocities larger than the typical dispersions in the radial velocities and proper motions (as suggested by Sterzik & Durisen 1995).

When Herbig (1977) found that TTS usually share the radial velocity of their nearby parent clouds, he also listed six TTS with locations outside dense clouds that have radial velocities off the Taurus mean. He suggested three possible explanations for this observation: Either (a) some stars might be accelerated as part of their formation process for instance, by ejection of one component of a multiple star system; or (b) there are many non-spherical cloud filaments with very low binding energy; or (c) the Taurus cloud geometry is not permanent. Ghorti & Bhatt (1996) modeled the ejection of protostars in encounters of protostars with clouds, and found that some protostars can indeed be ejected in such a way. Kroupa (1995) showed that several percent of the members of a cluster as rich as the Trapezium can be ejected by close encounters with velocities exceeding 5 $km\ s^{-1}$.

Sterzik et al. (1995) suggested that PMS stars found in follow-up observations of RASS sources outside the Orion molecular clouds have been ejected from their birth clouds with high velocities and called such stars 'run-away TTS' (raTTS). N95 showed that the (preliminary) radial velocity distribution of 15 Li-rich RASS source counterparts south of the Taurus clouds is consistent with (at least some of) them being such raTTS. Few-body encounters can happen early in the lifetime of a multiple protostellar system, so that they are also of relevance in establishing the fraction of binary (and triple) TTS and their parameters such as the separation. It has been observed recently that most (on-cloud) TTS are multiples and that the multiplicity parameters are established very early in the PMS phase (e.g., Leinert et al. 1993, Ghez et al. 1993, Mathieu 1994).

In encounters such as those studied by Sterzik & Durisen (1995), ejected raTTS are either single stars, or binaries where the separation depends on the encounter dynamics: The smaller the pericenter distance and the larger the relative encounter velocity, the higher is the binding energy of previously bound systems that can be broken apart. Hence, most raTTS should be single stars or close binaries. They also tend to be on average less massive than average TTS.

Many raTTS are expected to have been ejected with velocities larger than a few $km\ s^{-1}$, so that this mechanism can easily explain the appearance of very young (10^5 to 10^7 yrs) TTS several degrees away from the molecular clouds. The model also makes predictions that can be tested by observations such as the mass and velocity distributions of raTTS and the fraction and parameters of binaries among them. Brandner et al. (1996) have searched for binaries among Li-rich PMS stars in and around the Chamaeleon clouds discovered among RASS source counterparts (A95). Interestingly, Brandner et al. (1996) report a larger binary fraction among new on-cloud PMS stars (18.0 ± 4.2 %) compared to off-cloud (8.4 ± 3.0 %), as predicted by the raTTS hypothesis.

3. RATTS as transition systems between cTTS and wTTS

Ejections of TTS from molecular clouds have also been studied by Armitage & Clarke (1997). They investigate in particular the effect of close encounters on circumstellar disks, which are frequent among very young low-mass protostars. Studying the encounter between a TTS without disk and a TTS with disk, they find that, the smaller the pericenter distance of encounter is, the more violent is the disruption of the disk, i.e. the smaller the outer radius of the surviving disk. E.g., for ejection velocities between 3 and 10 $km\ s^{-1}$ implying pericenter distances of 2 to 25 AU, they find outer remnant disk radii of tyically less than 10 AU. This effect reduces the viscous evolution of the disk, so that accretion rapidly ceases (Armitage & Clarke 1997). Hence, this mechanism turns TTS with accretion disks (most of which are cTTS) into TTS without observable disks (most of which are wTTS). For their subsequent studies, they distinguished between TTS with high and low magnetic fields. For ejected TTS with low magnetic fields, the duration of the cTTS phase can still be relatively long, so that they predict the existence of ejected TTS (without accretion but with IR excess emission) located outside molecular clouds. For the case of strong stellar magnetic dipole fields, which can couple with the inner disk region effectivly braking the stellar rotation rate (e.g., Bouvier 1993), the ejected cTTS will very rapidly turn into a wTTS without $H\alpha$ and near-IR excess emission, which however should still be detectable at wavelengths $> 5\ \mu m$ due to emission from outer disk material.

Armitage & Clarke (1997) predict that such transition systems should rotate with periods similar to cTTS. This can be tested by observation. While wTTS usually rotate with periods shorter than a few days, cTTS show rotation periods of four to nine days. All of the so-called 'naked' TTS found by Mundt et al. (1983) and Walter et al. (1988) among previously unidentified EO sources show weak $H\alpha$ emission, and there is only one star also detected at mm wavelengths, namely V836 Tau (Skinner et al. 1991). With a rotation period of 7.0 days (Vrba & Rydgren 1984), this star is one of the slowest rotating wTTS. (The slow rotation of V836 Tau is probably not tidally forced by its companion, as the period of seven days is longer than the transition period between circular and eccentric orbits among PMS stars, which should also be the dividing line between synchronized and non-synchronized systems.) Hence, it may be possible to use the rotation period of a wTTS to estimate the time that has elapsed since the (inside-out) disk dispersal begun; a fast rotating wTTS has cleared its disk completly, while a slowly rotating wTTS is just dispersing its disk.

A95 have performed optical and IR photometry of Li-rich PMS stars among RASS source counterparts in and around the Chamaeleon clouds. Most of their stars show spectral energy distributions consistent with black bodies, i.e. could be called naked TTS. Two stars, however, show strong HKLM excess emission typical of cTTS, one with weak $H\alpha$ emission and one with highly variable $H\alpha$ emission (Alcalá et al. 1993, A95). Both of these stars lie on-cloud but may be transition systems – as described by Armitage & Clarke (1997) – with low accretion but still strong emission from the outer disk.

Three other stars in A95 show weak $H\alpha$ emission, no near-IR excess, but L and/or M excess emission, one of which lies several degrees off the nearest cloud, namely RXJ1001.1-7913 with spectral type M0, i.e. a low-mass raTTS candidate. By comparing its locus in the H-R diagram (assuming a distance of 150 pc) with D'Antona & Mazzitelli (1994) tracks, Alcalá et al. (1997) found its age to be just $1.57 \pm 0.56 \cdot 10^6$ yrs. With high-resolution spectroscopy, C97 confirmed that this star shows Lithium, i.e. is very young, irregardless of any distance assumption. Also, C97 measured its rotational velocity to be $\sim 15\ km/s$, i.e. relatively low for a wTTS. Its radial velocity being $\sim 12\ km/s$ (C97) indicates that it slowly moves towards us relative to the Chamaeleon clouds. Its proper motion relative to the other Chamaeleon TTS, when it becomes available, may be able to show whether it could have been ejected from any of the Chamaeleon clouds.

4. Run-away TTS south of Taurus ?

The new PMS stars found south of the Taurus clouds (N95, M97, N97) are located as far as 10° south of the southern border of the IRAS $100 \mu m$ contours, i.e. up to 24° south of the southern border of the known Taurus CO clouds (c.f. figure 8 in N97). Their birthplace could be anywhere on the clouds in Taurus. To have moved 20° (i.e. 50 pc at a distance of 140 pc) in $\leq 10^7$ yrs implies a line-of-sight velocity dispersion $\geq 5/\sqrt{3}\ km\ s^{-1} \simeq 3\ km\ s^{-1}$, which is consistent with the observed radial velocity dispersion of 2.8 $km\ s^{-1}$. At a distance of 140 pc, a proper motion of 10 mas per year corresponds to 6.7 $km\ s^{-1}$.

Any ejected raTTS south of Taurus should have proper motions indicating that they are currently moving to the south relative to the motion of the Taurus cloud complex as a whole. Among the 17 Li-rich stars in the sample south of Taurus that have known proper motions from Frink et al. (1997), none is moving south relative to Taurus. The catalogs from which these proper motions were extracted (STARNET and PPM) are magnitude-limited, and, hence, are biased against low-mass stars. However, raTTS should be more frequent among the lowest-mass TTS, but may be less frequent among G- and K-type TTS (Sterzik & Durisen 1995), which constitute the majority in the sample.

At face value, these data would therefore seem to suggest that there are not more than ~ 10 % raTTS among PMS stars outside molecular clouds. Interestingly, Neuhäuser et al. (1997a) have shown that ~ 10 % of the bona-fide TTS in central Taurus do show either proper motion or radial velocity inconsistent with kinematic membership. These stars may also be raTTS – just ejected.

Of the pre-MS stars south of Taurus with proper motions from Frink et al. (1997), six have radial velocity very different from the Taurus mean, but all six share the Taurus proper motion. Hence, their 3D space motions are consistent with them having been ejected from Taurus along the line of sight. Interestingly, their radial velocities are all *smaller* than the mean of Taurus, indicating that they are moving towards us, relative to the clouds. The probability of this happening by chance is less than 2 %. Instead, this is simply because if they had been ejected in the opposite direction, we would probably not have detected them, since their greater distance would have made them too faint for detection in the RASS.

One of the new PMS stars south of Taurus can be identified as a very promising raTTS candidate, namely RXJ0511.2+1031, c.f. N97 or elsewhere in this proceedings (Neuhäuser et al.) for details.

5. Discussion

Using the HIPPARCOS data of those ROSAT discovered Li-rich stars which happened to be observed by HIPPARCOS, Neuhäuser & Brandner (1997) could identify several more raTTS candidates. Two more candidate raTTS, namely P1724, and RXJ0511.2+1031 will be discussed in detail elsewhere in this proceedings (Neuhäuser et al.).

South of the Taurus clouds as well as off the Chamaeleon, Lupus, and Orion clouds, many new pre-MS stars have been discovered among RASS sources; they show more Lithium than ZAMS stars and, hence, are younger, i.e. pre-MS. Some are kinematic members of the near-by associations.

However, with the data in hand it is, as yet, in most cases not possible to distinguish unambiguously between (a) old and slowly drifting post-TTS; (b) Gould Belt members; (c) rapidly moving raTTS ejected from the cloud cores; or (d) young TTS formed in turbulent cloudlets. To do this would require either measuring their distance precisely in order to place them correctly on the H-R diagram, or determining accurate ages by other means. While the radial velocities – like those in N97 – should be sufficiently precise, proper motions with better precision than those in Frink et al. (1997) are needed in order to trace the 3D space motion of these lithium-rich stars back to their place of origin.

There have also been searches for star formation in high-latitute translucent clouds (e.g., the so-called MBM clouds, Magnani et al. 1985), which may be useful to investigate the suggestion by Feigelson (1996), that few TTS can be formed in small cloud-lets (like MBM clouds) which disperse subsequently. However, in the cloud MBM 40, no TTS at all have been found among IRAS and ROSAT sources, although the total mass of the cloud is several tens of solar masses (Magnani et al. 1996). Also, no young stars associated with the clouds MBM 7 and MBM 55 could be found among ROSAT sources (Hearty et al., in preparation). On the other hand, there are several isolated TTS known (like those around TW Hya, see Kastner et al. 1997 for a list) and also, a few young stars have been found on MBM 12 (Herbig & Bell 1988, Gameiro et al. 1993, Magnani et al. 1995, Caillault et al. 1995).

While several very promising raTTS candidates have been found already, it would be surprising, if most of the new PMS stars found outside molecular gas were ejected raTTS. For example, in Chamaeleon there are as many new PMS stars off the clouds as on the clouds (A95), so that the star formation efficiency and ejection rate would have to be very high. Accurate 3D kinematics, as well as an investigation of the rotational periods and spectral energy distribution along with binary statistics on larger samples, may eventually show how frequent raTTS are.

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