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The Spatial Distribution and Origin of the Widely Dispersed ROSAT T Tauri Stars

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Abstract

With ground-based optical follow-up observations of previously unidentified ROSAT All-Sky Survey X-ray sources, many new young stars have been found, both in star forming regions as well as far away from dark clouds. Young low-mass pre-main sequence stars can be identified by $H\alpha$ *emission and lithium absorption. If they show more lithium than zero-age main-sequence stars of the same spectral type, then they are younger, i.e. pre-MS stars. In this paper, the proceedure of selecting and identifying new pre-main sequence stars among ROSAT sources is reviewed. Then, the question of their evolutionary status is outlined. Finally, the question of their origin is discussed in detail: There are several populations among the lithium-rich ROSAT counterparts, namely very young pre-MS stars near previously known star forming sites, members of the Gould Belt, and ejected run-away stars.*

1 Introduction: Low-mass star formation

Stellar mass functions show that low-mass stars contain most of the visible mass in the Galaxy (eg. Miller & Scalo 1979). Hence, the study of young low-mass stars is a main step towards the understanding of star formation in the Galaxy. Low-mass pre-main sequence (PMS) stars are referred to as T Tauri stars (TTS), first recognized as a separate class of stars by Joy (1945), studying the spectra of variable stars towards Taurus. From their high stellar density and the fact that such stars are usually, but not always, located close to high-mass (i.e. young) stars, Ambartsumian (1947) concluded that TTS are recently formed stars and introduced the new term T association for groups of low-mass PMS stars. One of the best studied regions of on-going low-mass star formation is the Taurus(-Auriga) area. This T association extends over tens of square degree on the sky (see, e.g., the CO map by Ungerechts & Thaddeus 1987) and its distance is estimated to be ~ 140 *pc* (Elias 1978, Kenyon et al. 1994, Preibisch & Smith 1997, Wichmann et al. 1998).

While it has been thought earlier that low- and high-mass stars form not only differently, but also in separate star forming clouds (bi-modal star formation), it is now clear that OB associations, i.e. region of on-going high-mass star formation, are also populated by a large number of TTS. This has been found not only in Orion (Walter et al. 1999), but also in Sco-Cen (Walter et al. 1994), IC1396 (Schulz et al. 1997), Mon R2 and Rosette (Gregorio-Hetem et al. 1998), and Cepheus OB3 (Naylor & Fabian 1999).

Until ~ 20 years ago, most TTS known were discovered in objective-prism surveys and, hence, display strong Balmer lines; see Herbig (1962) and Bastian et al. (1983) for early reviews. Nowadays, TTS with $W_\lambda(H\alpha) \geq 10$Å are called classical TTS (cTTS). They also show strong excess emission in the UV (from accretion, i.e. hot material falling onto the star) and in the infrared (from cold circumstellar material). Almost all cTTS are located inside or close to molecular gas clouds, in which they were born. Herbig (1977) found that TTS share the radial velocity of their parent cloud. Most members of a T association also share the same proper motion (Jones & Herbig 1979), so that T associations are groups of co-moving stars.

In the last ~ 20 years, several surveys aiming at the discovery of more TTS using proper motions (eg. Hartmann et al. 1991) and youth indicators like the Ca II H and K lines (eg. Herbig et al. 1986) or X-ray emission (eg. Feigelson et al. 1987 and Walter et al. 1988) have shown that there are more TTS than just the cTTS, namely weak-emission line TTS (wTTS). The usual separation between cTTS and wTTS at $W_\lambda(H\alpha) \simeq 10$Å can be somewhat misleading, as G-type TTS, e.g. SU Aur, with a small $H\alpha$ equivalent width in fact do show strong $H\alpha$ flux because of their high temperature. Most wTTS are bright X-ray sources, but lack UV and IR excess emission, as their circumstellar material either is optically thin, and/or it has accreted onto the star and/or planetesimals, and/or it has dispersed. For this reason, wTTS without IR excess are also called naked TTS (Walter 1986). From the (in-)completeness of the *Einstein Observatory* (EO) X-ray observations in Taurus, the results of their optical follow-up observations of unidentified EO X-ray sources, and the variability of X-ray emission in TTS, Walter et al. (1988) concluded that there are ~ 10 times more wTTS in Taurus than cTTS. For recent reviews we refer to Bertout (1989) and Appenzeller & Mundt (1989).

Because the sound-crossing time-scale of the clouds in a T association like Taurus is longer than the typical age of cTTS, there should be many somewhat older PMS stars, so-called post-TTS (Herbig 1978), not only inside the star forming clouds, but also around the clouds, as older TTS have had enough time to disperse within $\sim 10^7$ yrs – given the typical velocity dispersion within associations being 1 to 2 km/s (Herbig 1977, Jones & Herbig 1979, Hartmann et al. 1986, Frink et al. 1997). However, because many wTTS also populate the convective tracks, i.e. are just as young as cTTS, the discovery of wTTS did not solve this post-TTS problem. Palla & Galli (1997), however, noted that star formation is not a steady process, but runs slowly, i.e. less efficient in the first few millions years of the cloud life-time. Hence, their should be only few post-TTS, but many co-eval cTTS and wTTS.

Infrared protostars become optically visible when they cross the so-called birth-line in the H-R diagram (Stahler 1983). Then, as fully convective cTTS, they evolve down along their Hayashi-tracks. Except in the least massive TTS, radiative cores will develope next, so that the TTS will turn onto the radiative tracks to approach the zero-age main-sequence (ZAMS). Because lithium is depleted at the bottom of the convection cells by proton-proton capture (Bodenheimer 1965), the Li 6708Å absorption line can be taken as reliable youth indicator. The lithium depletion time-scale, however, depends on the depth of the convection cell, i.e. on the stellar mass. Late F- and G-type Pleiades ZAMS stars and TTS all still show their initial lithium abundance, also taken as measure for the primordial lithium. M-type ZAMS stars, on the other hand, have depleted all their lithium, so that any M-type Pleiades member with detectable lithium can only be a brown dwarf. According to both the lithium abundance and the loci of TTS in the H-R diagram – compared to theoretical evolutionary tracks (eg. D'Antona & Mazzitelli 1994) – the ages of TTS range from $\sim 10^5$ and $\sim 10^7$ yrs.

With the advent of the ROSAT All-Sky Survey (RASS) X-ray mission (Trümper 1982), it has become possible to search for TTS on the whole sky. Because many new wTTS had been found earlier with the EO X-ray mission, it was expected and confirmed that even more are detected by ROSAT. With optical follow-up observations of unidentified ROSAT sources, new Li-rich, i.e. young, star have not only been found in and close to star forming clouds, but also many degrees off the cloud boundaries, to be reviewed in this article; see Krautter et al. (1994), Krautter (1997), and Neuhäuser (1997a, 1997b) for earlier reviews.

In the next section, the proceedure of identifying TTS among previously unidentified ROSAT sources will be explained. Then, the nature and origin of the newly discovered TTS will be outlined. They consist of five different subsets, namely very young TTS in previously known star forming clouds, late-type members of the Gould Belt (sect. 3.1), TTS formed in small cloudlets which dispersed since the TTS formed (sect. 3.2), run-away TTS ejected from their original birth-places (sect. 3.3), and a galactic fore-ground ZAMS population.

2 Discoverying new T Tauri stars with ROSAT

Prior to the ROSAT mission, ~ 60 wTTS were known in Taurus, half of which were discovered by ground-based optical follow-up observations of previously unidentified EO X-ray sources (Feigelson et al. 1987, Walter et al. 1988). See Herbig & Bell (1988) and Neuhäuser et al. (1995b) for lists of TTS known prior to ROSAT. From their EO 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 RASSis the complete sky coverage with a flux limit sufficient to detect most TTS in nearby SFRs (Neuhäuser et al. 1995a).

2.1 Pre-selection and spectral identification

Prior to follow-up observations of RASS sources, TTS candidates were pre-selected 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 RASS X-ray sources, many late-type stars with Li 6708 Å absorption and Hα 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. 1995c, Wichmann et al. 1996, Magazzù et al. 1997, Neuhäuser et al. 1997), Orion (Alcalá et al. 1996, 1998), Lupus (Krautter et al. 1997, Wichmann et al. 1997a, 1997b), ScoCen (Preibisch et al. 1998), Chamaeleon (Alcalá et al. 1995, 1997, Covino et al. 1997), and CrA (Neuhäuser et al., in preparation).

Most of the ROSAT counterparts with lithium detected in spectra with low resolution (a few Å) were classified originally as 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 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 H-R 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. 1998, Briceño et al. 1997). Because ZAMS stars such as the Pleiades also show a high level of X-ray activity and optical spectra (with Li) similar to wTTS, it is clear that some (or many) of the Li-rich ROSAT stars could be young ZAMS stars rather than PMS stars (Briceño et al. 1997).

(2) It is possible to overestimate the Li 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 Li-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.

2.2 Lithium confirmation by high-resolution spectroscopy

Covino et al. (1997) have performed high-resolution spectroscopy for nearly all the Li-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 show 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 in lithium: Stars with much more lithium than ZAMS stars (bona-fide TTS), and stars with lithium as weak as in ZAMS stars (which are also ZAMS stars). Covino et al. (1997) find no intermediate lithium stars, i.e. no post-TTS. Another interesting point is that most of the Li-rich stars share the Chamaeleon radial velocity.

The spatial distribution of their stars is shown in their figure 7 (Covino et al. 1997). Obviously, many of the Li-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). 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, 1998).

In figure 1, we show a diagram of lithium equivalent width versus effective temperature of newly discovered Li-rich ROSAT counterparts. We compare their lithium line strength with those of ZAMS stars in the Pleiades. All those stars with more lithium than ZAMS stars of the same spectral type (or effective temperature) are younger than ZAMS stars, i.e. PMS stars.

2.3 Is there a post-TTS gap?

Martín (1997) suggested that PMS stars, which have depleted some amount of lithium, are post-TTS. One can plot iso-lithium-abundance lines into the diagram EW(Li) versus temperature, see figure 1. Stars falling below a particular line would then be post-TTS, e.g. stars below the line for lithium abundance half the primordial value are post-TTS. Now, while this concept might be usefull in principle, it has not been possible so far to draw such iso-abundance lines for M-type stars, because our understanding of lithium depletion is not sufficient in this temperature regime, yet. However, Martín (1997) needs this

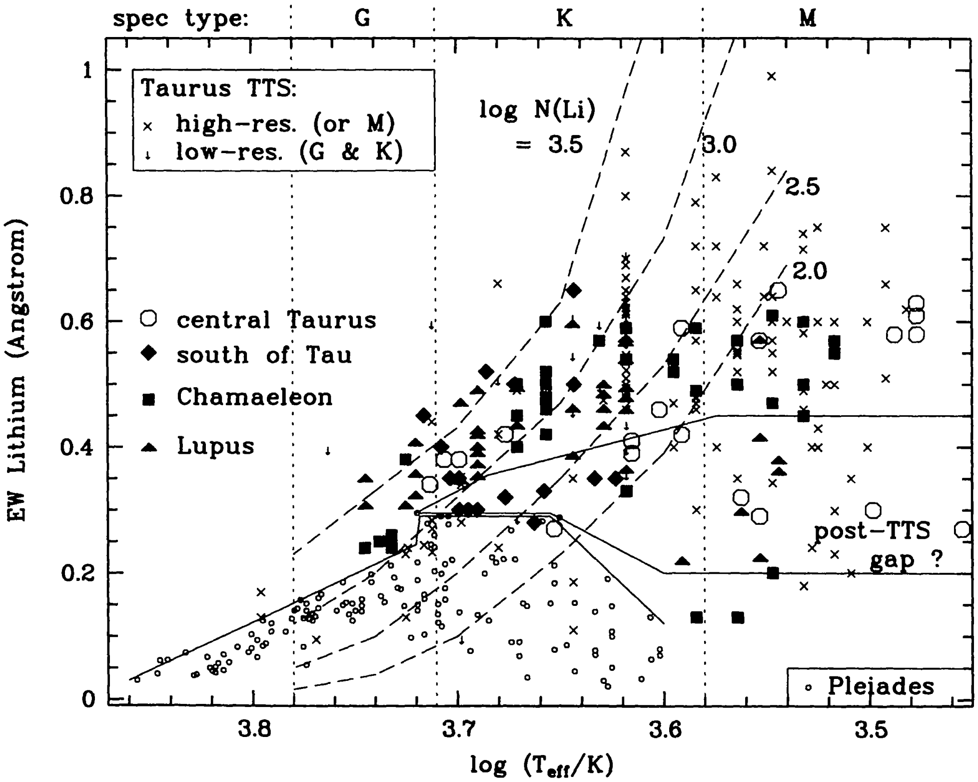

Figure 1. Lithium versus temperature for new ROSAT TTS.
Lithium equivalent width (in Ångstrom) versus (log of) effective temperature (in Kelvin) for Pleiades (small circles), high-resolution data for previously known bona-fide TTS in central Taurus as crosses (low-resolution data for G- and K-type TTS as upper limits), and new ROSAT TTS south of Taurus (diamonds, Neuhäuser et al. 1997), in central Taurus (open circles, Wichmann et al. 1996), around the Lupus clouds (triangles, Krautter et al. 1997) and around the Chamaeleon clouds (squares, Alcalá et al. 1995). This figure has been adapeted from Neuhäuser (1997a). Also shown are upper envelopes to Pleiades data as well as lithium iso-abundance lines (from Pavlenko & Magazzù 1996). Whether there exists a post-TTS gap in the lower right is discussed in the text. For references for lithium data of Pleiades and pre-ROSAT TTS, see Neuhäuser et al. (1997).

line for his post-TTS definition, but he can only assume where this line lies. How was his assumption regarding the placement of this line motivated? *I have chosen a constant value for M-type stars, which was shown by Martín (1997) to provide a reasonable fit to the lower envelope of the Li EWs observed in WTTSs located within the Taurus molecular clouds* (Martín 1998).

Hence, the M-type PMS stars known in Taurus prior to ROSAT (by definition) were all above Martín's line with EW(Li)$\geq$ 0.58. However, the sample of PMS was and still is very incomplete, even in Taurus, before and even after ROSAT. There is no reason whatsoever to use an incomplete (pre-ROSAT) sample of stars to define a class of stars, namely the wTTS and post-TTS. Martín (1997) used an incomplete sample of PMS stars in Taurus to define post-TTS is a way, that there are no post-TTS in that sample. According to his definition, post-TTS are those stars with EW(Li) lower than the lower envelope of the previously known PMS stars in Taurus. And because the wTTS and post-TTS samples according to the Martín definitions do not overlap, all of the previously known PMS stars in Taurus with weak Hα emission would be wTTS.

Additionally, it should be pointed out, that the so-called post-TTS gap, which Martín (1997) claims to exist, is not really empty in Taurus, see figure 1. Even some of the PMS stars known before ROSAT populate that area in the EW(Li) versus temperature plot, as shown by Neuhäuser et al. (1997). Martín (1997) as well as Briceño et al. (1997) plotted only a limited number of lithium measurements. If one plots all of them, and preferentially the higher resolution ones if several are available for a given star, then the post-TTS gap is not empty in Taurus. In Chamaeleon, however, even when including the ROSAT PMS stars, there is a post-TTS gap in about the area defined as such by Martín (1997), and this seems to be the case because star formation did not last long enough in Chamaeleon to fill that gap (Covino et al. 1997).

2.4 Hipparcos observations

Recently, Neuhäuser & Brandner (1998) have cross-correlated the list of ROSAT-discovered Li-rich stars with the Hipparcos catalog. Out of $\sim$ 500 Li-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 Li-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. They cannot be post-MS stars, because the ROSAT stars all have more lithium than typical post-MS stars and they rotate much faster than post-MS stars. Only two of the stars are located on the Hayashi-tracks, whereas the other 13 are post-TTS, located on radiative tracks, with relatively low lithium abundance.

Even more recently, Zickgraf et al. (1998) have reported the results of their program to identify an unbiased complete set of ROSAT sources in an area south of the Taurus clouds, which happens to overlap partly with the area studied by Neuhäuser et al. (1995c, 1997) and Magazzù et al. (1997). They have identified several M-type stars with strong lithium far south of the Taurus clouds. These stars being of spectral type M cannot be older than a few million years, so that they are certainly pre-MS objects. The space density of these Li-rich M-type stars is larger than expected from galactic models, so that there clearly is an enhancement of pre-MS stars in that area. Hence, Zickgraf et al. (1998) have finaly confirmed the early claim that there is a pre-MS population south of the Taurus clouds (Neuhäuser et al. 1995c).

3 The origin of the widely dispersed T Tauri stars

Because the PMS status of most of the newly discovered Li-rich ROSAT counterparts has clearly been established, one can now study and discuss their origin. Those new PMS stars which are located on or near known star forming clouds, most certainly have formed in those clouds. This is particulary the case of many of the youngest new PMS stars found in Chamaeleon (Alcalá et al. 1995), Orion (Alcalá et al. 1996), Taurus (Wichmann et al. 1996), and Lupus (Krautter et al. 1997). It is different for the isolated new PMS stars, which are *isolated* in the sense that they are located far (i.e. several degrees) away from known star forming sites. Did they form near their present locations, e.g. in clouds which have dispersed since the stars formed? Or did they form somewhere else and where ejected to their present location? These questions will be discussed below. Many of the new ROSAT PMS stars outside star forming clouds appear to be members of the Gould Belt, some others have most certainly formed in small cloud-lets which either still exist (but were not known so far) or have dispersed recently, and some other fraction of stars has been ejected from the birth place. The latter are called run-away TTS (raTTS), which will be discussed below in some more detail.

3.1 Late-type PMS members of the Gould Belt

The Gould Belt (Gould 1874) was recognized as a band of O-, B-, and early A-type stars inclined by some 18° to the galactic plane and within ~ 1 *kpc* of the Sun. The Sun is inside, but not in the center of the Belt. Several SFRs are part of this Belt, e.g. Orion, Lupus, and ScoCen. However, the Taurus cloud is not a member of the Belt. The origin of this structure, e.g. by an impact of a high-velocity cloud (HVC) onto the galactic plane, or triggered by many simultaneous supernovae, or as instability of the Carina spiral arm, is still a matter of debate. Several independent age estimates yield roughly 3 to $5 \cdot 10^7$ years. See Pöppel (1997) for a review about the Gould Belt.

Guillout et al. (1998a, b) have cross-correlated the RASS source list with the Tycho catalogue. The overlapping sample is a sample of X-ray bright, i.e. young stars in the solar neighbourhood. Studying their spatial distribution clearly shows an enhancement along the Gould Belt: There are more X-ray detected stars projected within the Gould Belt boundaries than outside, even when considering biases due to different RASS exposure times and when excluding known star forming cloud regions. Whether these young stars *projected* onto the Gould Belt really are part of the Belt, i.e. at the correct distances, can be investigated by checking the photometric distances available from Tycho. Guillout et al. (1998b) have verified not only that those Tycho photometric distances agree well with Hipparcos distances, but also that the young stars which appear to be projected onto the Gould Belt, really are part of Belt, i.e. at the correct distances. They also found that the Gould Belt really is a plane filled with young stars which may be empty in its center, see figure 2. Such a *Gould Plane* filled with young stars was expected from the HVC impact scenario put forward to explain the origin of the whole structure (e.g. Comerón et al. 1994).

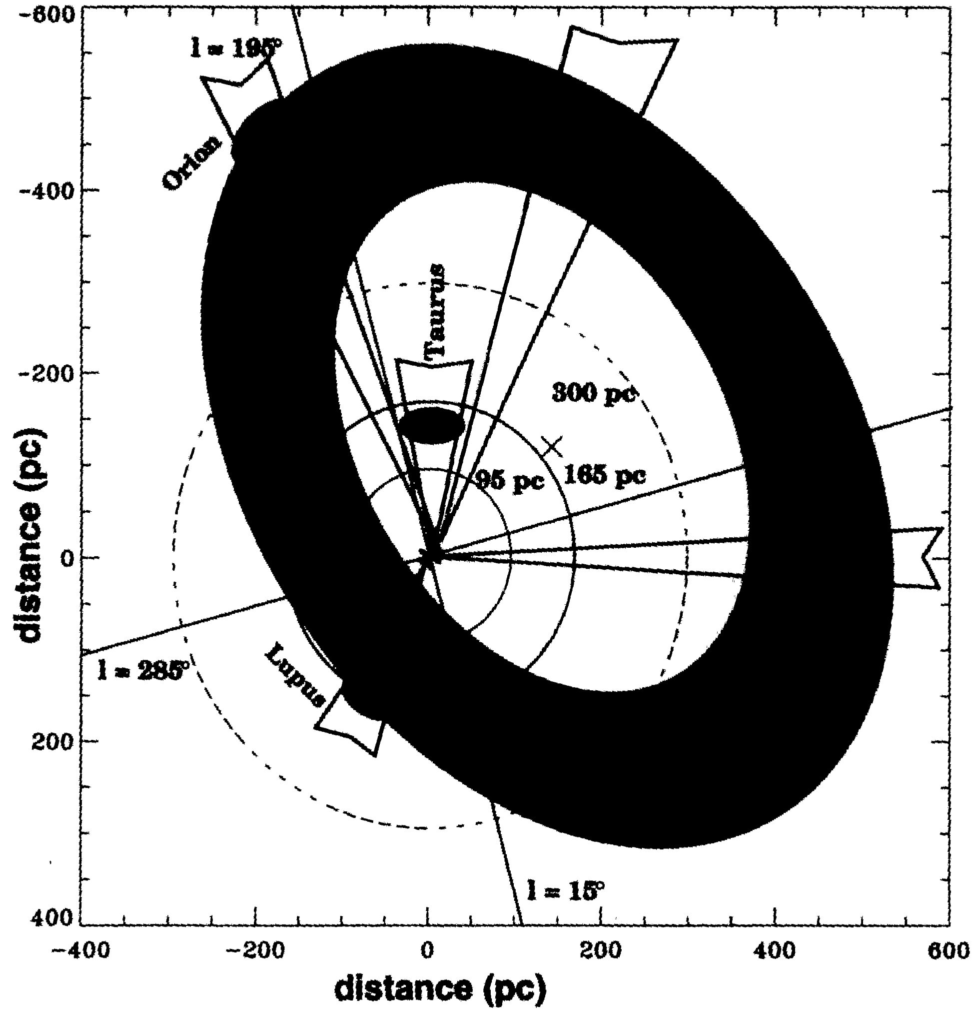

Figure 2. The Gould Belt scenario.
The Gould Belt geometry projected on the Galactic plane as assumed from the literature. It consists of an ellipsoidal shaped ring with semi-major and minor axes of 500 and 340 pc, respectively. The Sun (asterisk) is displaced from the center (cross), which is located at ~ 200 pc towards $l = 130°$. Gould Belt members are assumed to be located near the outer edge of belt (solid thick circle). The concentric circles of radii 95, 165 and 300 pc centered on the Sun show the X-ray horizon at a PSPC count-rate threshold of 0.03 cts/sec for stars with X-ray luminosities of $\log(L_x/erg/s)$ = 29.5, 30.0 and 30.5 respectively. The optical horizon of a G5 ZAMS star at the Tycho completness threshold (10.5 mag) is at 160 pc. The grey shaded area sketches an alternative picture of the Gould Belt, a filled plane which may be empty in the center. Also shown are the directions towards Lupus, Orion, Taurus, Cygnus, and an additional area, where distant Gould Belt members are expected to be found in a deep ROSAT pointed observation. This figure has been adapted from Guillout et al. (1998b).

Because the early-type stars of the Gould Belt were known for some time, it was expected to find many late-type stars as well. With the cross-correlation of RASS and Tycho, Guillout et al. finally found the late-type population of the Gould Belt.

Many of the widely dispersed Li-rich PMS stars found by ROSAT around the Orion, Lupus, and ScoCen clouds can well be explained by the Gould Belt. E.g. towards Orion, the Gould Belt is more distant than towards Lupus. Hence, there should be a lot of foreground Gould Belt PMS stars in Orion, but much less in Lupus. This is exactly as observed (Alcalá et al. 1998, Wichmann et al. 1999). Towards Cygnus, the Gould Belt is even further away, so that the RASS flux limit is too small to detect TTS. Hence, no Li-rich counterparts were found among Cygnus RASS sources (Motch et al. 1997). Such Gould Belt members are expected to be found in deep ROSAT pointings which are currently investigated.

However, the widely dispersed Li-rich ROSAT PMS stars found around the Chamaeleon clouds (Alcalá et al. 1995) and south of the Taurus clouds (Neuhäuser et al. 1997) cannot be explained by the Gould Belt. Hence, there must be some additional component.

3.2 T Tauri stars formed in small cloud-lets

Feigelson (1996) suggested that the majority of the widely dispersed PMS stars found by ROSAT have not been ejected from somewhere else, but were formed near their present location, e.g. in small cloud-lets, each of which gave birth to a few TTS. Those small clouds either are unknown to the present time (and unseen in the IRAS data) or have dispersed since the stars have formed. Hence, there should be many small groups of TTS and the TTS of a particular group should be co-moving with the same kinematics as their parent cloud-let.

Recently, Mizuno et al. (1998) performed a 13CO and C18O survey of the area investigated by Alcalá et al. (1995), in order to check Feigelson's hypothesis. Mizuno et al. found small cloud-lets within a few pc near two thirds of the Alcalá et al. (1995) PMS stars confirmed by Covino et al. (1997) with high-resolution spectroscopy. And these newly discovered cloud-lets do share the same radial velocities as the PMS stars near-by. Hence, they may very well have formed in those small clouds, as suggested by Feigelson (1996). The existence of many small and turbulent cloud-lets around the Chamaeleon dark clouds is consistent with HVC scenario: A high (or intermediate) velocity cloud has hit the galactic plane (coming from the north) and triggered star formation. Then, the cloud with its newly formed stars moved through the galactic plane and afterwards continued to move south relative to the plane, to arrive at the present location. The filamentary structure of the Chamaeleon clouds is very well consistent with this picture. Also, Frink et al. (1998) and Terranegra et al. (1999) found that most of the Chamaeleon TTS (including the ROSAT TTS) tend to move towards the direction expected from this scenario.

The remaining third of the seemingly dispersed TTS either may have formed in cloud-lets which have dispersed since they gave birth to these stars, or those TTS did form somewhere else.

3.3 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, 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, 1998).

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). Neuhäuser et al. (1995c) 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, 1998), 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 (Alcalá et al. 1995). Interestingly, Brandner et al. (1996) report a larger binary fraction among new on-cloud PMS stars ($18.0 \pm 4.2\,\%$) compared to off-cloud ($8.4 \pm 3.0\,\%$), as predicted by the raTTS hypothesis.

3.3.1 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 Hα 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 Hα 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.

Alcalá et al. (1995) 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 Hα emission and one with highly variable Hα emission (Alcalá et al. 1993, 1995). 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 Alcalá et al (1995) show weak Hα emission, no near-IR excess, but L and/or M excess emission, one of which lies several degrees off the nearest cloud, namely RXJ 1001.1-7913 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.

3.3.2 Run-away TTS south of Taurus?

The new PMS stars found south of the Taurus clouds (Neuhäuser 1995c, Magazzù et al. 1997, Neuhäuser et al. 1997) are located as far as 10° south of the southern border of the IRAS 100 μm contours, i.e. up to 24° south of the southern border of the known Taurus CO clouds, see Neuhäuser (1997b) for details. 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, 1998), which constitute the majority in the sample.

At face value, these data would therefore seem to suggest that there are not more than $\sim$ 10 % raTTS among PMS stars outside molecular clouds. Interestingly, Neuhäuser et al. (1997) have shown that $\sim$ 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, because their greater distance would have made them too faint for detection in the RASS.

The Taurus clouds are not part of the Gould Belt, but located south of the Belt and south of the galactic plane and may have originated by an HVC impact (e.g., Franco et al. 1988, Lépine & Duvert 1994). This may provide an alternative explanation for the spatial distribution and kinematics of our lithium-excess stars. If a HVC impacted from the north side onto the galactic plane, then stars formed in this event would first move south, and then fall back down to the plane. Subsequently, the clouds and stars would oscillate around the plane. Because the Taurus clouds and their TTS are moving south, we conclude that this structure is not falling back.

Alternatively, the HVC might have hit the plane coming from the south, formed stars, and reversed its direction. Following Lépine & Duvert (1994), we then have the following scenario: The HVC hit the plane coming from the south and formed stars; clouds and stars reversed their direction and fell back onto the plane. While the clouds feel the friction from galactic plane material, the stars do not, so that they effectively got separated from their parent cloud (combing-out effect).

From the galactic gravitational potential (e.g. Stothers & Tech 1964) and the observed velocity of the Taurus clouds and associated TTS (4 km s^{-1} to the south, away from the galactic plane) and their location (40 pc south of the plane), it is possible to infer the dynamics of the oscillations around the galactic plane. Assuming negligible resistance from interstellar material, the cloud passed through the galactic plane $\sim 8 \cdot 10^6$ yrs ago, and the maximum distance from the plane that will be reached is $\sim$ 65 pc, i.e. 25 pc south of the present Taurus cloud center. The combing-out of stars by passing through the galactic plane takes place every 3 to $4 \cdot 10^7$ yrs (cf. Jones & Herbig 1979).

The stars that we observe south of the Taurus clouds may be those stars that were separated from their parent clouds during the last passage of the Taurus clouds through the galactic plane. They formed when the HVC hit the galactic plane coming from the south, which – given the calculation above – happened $\sim 3 \cdot 10^7$ yrs ago, consistent with our age estimate for the lithium-excess stars. We find these stars on average at $\delta \simeq 10°$, i.e. $\sim 10°$ south of the Taurus cloud center. At a distance of 140 pc, ten degrees correspond to 25 pc, i.e. exactly where the Taurus clouds and their TTS would reverse their oscillatory motion around the galactic plane. Stars just reversing their motion should show negligible proper motion. This can be tested using the proper motions listed by Frink et al. (1997). Although, as stated above, many of the lithium-excess stars do roughly share the mean Taurus proper motion, their mean proper motion in the north-south direction is $\mu_\delta = -9.7 \pm 2.1$ mas yr^{-1}, while the mean proper motion in the north-south direction of previously known TTS in central Taurus is -19.7 ± 1.6 mas yr^{-1}, i.e. significantly different. These data are consistent with the southernmost PMS stars being about to reverse their motion. We note that such a combing-out effect may also be observable in other SFRs, if they formed by HVC impacts. For example, Alcalá et al. (1997) do not observe new PMS stars in the eastern part of their study area surrounding the Chamaeleon clouds, as expected from the HVC impact scenario (Lépine & Duvert 1994).

One of the new PMS stars south of Taurus can be identified as a very promising raTTS candidate, namely RXJ 0511.2+1031 (Neuhäuser et al. 1997).

3.3.3 Run-away T Tauri stars in Orion

Parenago (1954) presented a list of Orion nebula stars which included star number 1724, now called P1724, that has subsequently been shown to be one of the most active TTS known, as evidenced by the detection of a very powerful X-ray flare (Gagné et al. 1995; Preibisch et al. 1995). P1724 is a relatively bright ($V \simeq 10.6$ mag) star located only $15'$ north of the Trapezium cluster in Orion. There have been a number studies of the proper motion of P1724, and the probability of membership to the Orion association according to different authors has ranged from 0 % and 97 %. Preibisch et al. (1995) presented a low-resolution spectrum showing $W_\lambda(\mathrm{H}\alpha) = 4$ Å and $W_\lambda(\mathrm{Li}) = 0.47$ Å. P1724 does not show excess infrared emission, and there is no IRAS source in the vicinity (Weaver & Jones 1992). Hence, one can classify this star as wTTS.

Recently, Neuhäuser et al. (1998) have studied this star in great detail, with the following results:

Based on deep R-band imaging, no companion is found down to a separation of $\sim 1''$ and a magnitude difference of $\Delta R = 7$ mag. With hundreds of V, R, and I measurements obtained within twelve weeks, its rotation period is confirmed to be about 5.7 days. Repeated high-resolution spectra show very low amplitude radial velocity variability. This series of high-resolution, high S/N spectra exhibit variations in the line profiles that are common in spotted stars. Data reduction by Doppler-imaging techniques yields an image showing a pronounced dark feature at relatively low latitude. Its derived size and temperature indicate that it can easily produce the observed photometric and spectroscopic variability.

Multiple high-resolution spectra yield a projected rotational velocity of $v \cdot \sin i = 71$ km/s, and a mean radial velocity of $+23$ km s^{-1} that is consistent with kinematic membership to the Orion star forming region. Therefore, the distance to P1724 is most likely also ~ 460 pc. Based on the proper motion of P1724 as listed in STARNET (a catalog of positions and proper motions of all stars which are listed in both the HST GSC 1.2 and the AC, Röser 1996), the derived 3D space velocity shows that P1724 moves north relative to the Trapezium cluster (see figure 3); in other words, its proper motion differs from most Trapezium stars, which is the reason why some earlier proper motion studies concluded that P1724 may not belong to the Orion star forming region.

Optical ($UBVRI$) and infrared (JHK) photometry of P1724 as well as the spectral energy distribution are presented, showing that P1724 is a naked (weak-line) T Tauri star. The bolometric luminosity is estimated to be 51 $L_\odot$, the spectral type to be K0, and the radius to be 9.0 $R_\odot$ (from both the Stefan-Boltzmann law based on the luminosity and temperature, and from the Barnes-Evans relation, which is consistent with a nominal distance to P1724 of ~ 460 pc).

Although P1724 has lost all its circumstellar material, its bolometric luminosity places it very close to the birth-line at an age of only $\approx 2 \cdot 10^5$ years, with a mass of ≈ 3 $M_\odot$ (consistently found from four different sets of pre-main sequence tracks and isochrones). This age is consistent with its present location and 3D space motion (~ 10 km s^{-1} relative to the Trapezium) under the assumption that it was ejected from the Trapezium $\approx 10^5$ yrs ago.

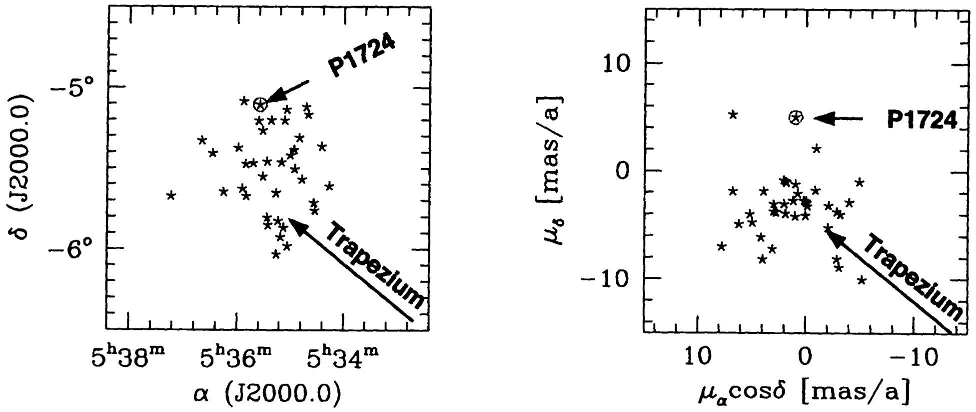

Figure 3. Position and proper motion of P1724 compared to members of the Trapezium cluster.
In the left panel, T Tauri star members of the Trapezium cluster which are listed in the STARNET catalog (see text) are plotted showing that this sample constitutes a cluster. On the right panel, the proper motions from STARNET are shown for the same stars showing that this cluster is a moving group. P1724 is located north of the cluster center and moves north relative to the cluster. This figure has been adapted from Neuhäuser et al. (1998).

P1724 thus appears to be a single, very young, naked, weak-line TTS moving north relative to the Trapezium, but sharing the Orion radial velocity. All the observations are consistent with P1724 being a run-away TTS, ejected from its birth place, the Trapezium cluster, only $\approx 10^5$ years ago (Neuhäuser et al. 1998).

Although the relatively large mass of this star, neither the Sterzik & Durisen (1995, 1998) nor the Kroupa (1995) scenario rule out the ejection of such massive stars, they are just a priori less likely. However, due to observational biases, it may even be more likely to find such a massive (and, hence, luminous) raTTS.

Another similar object is Par 1540, a 13th mag star with spectral type K3. It is a double-lined spectroscopic binary with γ velocity consistent with membership to Orion, but proper motion different from the clusters mean. Its space motions points away from the Trapezium cluster, where it might have been formed and from which it might have been ejected $\sim 10^5$ years ago (Marschall & Mathieu 1988).

One of the newly-discovered PMS stars south of Taurus, RXJ 0511.2+1031, has been identified as a very promising raTTS candidate. It was identified as a TTS with follow-up observations of ROSAT sources south of the Taurus clouds (Magazzù et al. 1997, Neuhäuser et al. 1997). This star has a spectral type K7 with Hα emission (Magazzù et al. 1997) and $W_\lambda(\mathrm{Li}) = 0.65$ Å (which is the largest in the Magazzù sample). It is located on the λ Ori cloud. If it originated in Orion, it is now moving towards us with a radial velocity of ~ 10 km s^{-1} relative to the Orion clouds. This velocity translates into ~ 10 pc per million yrs, so that one would still expect the star to be more distant than ~ 400 pc if it originated in λ Ori, at ~ 460 pc. Unfortunately, its proper motion has not yet been measured. Repeated high-resolution spectra show no indications of binarity (Neuhäuser et al. 1997), and Sterzik et al. (1997) found no visual companions down to 0.6″ separation and ΔR up to 7 mag. The small observed rotational velocity of only ~ 5 km s^{-1} for this star (Neuhäuser et al. 1997) is consistent with the predictions for recently ejected raTTS (Armitage & Clarke 1997). This star has $V \simeq 14$ mag (from the GSC), while many other stars in the sample south of Taurus have $V \simeq 11$ to 12 mag (Magazzù et al. 1997). Such a difference in brightness is consistent with the difference in distance between Taurus and Orion.

The near-by M0.5 dwarf Gl 182 (V1005 Ori) shows very high lithium abundance ($\log N(\mathrm{Li}) = 2.8$) as determined by high-resolution spectroscopy (Favata et al. 1997). The rapid lithium depletion expected for such a late-type star makes it a good PMS candidate. Hipparcos measured its distance to be just 26.7 pc (Micela et al. 1997), which places this star well above the ZAMS at an age between 10 and 30 Myrs. Although not related to the Orion clouds itself (which did not exist that long ago), this is a striking example of a young, isolated PMS star far (over 100 pc) from known sites of star formation. In fact, this star is probably the youngest known star in the immediate vicinity of our Sun (see Sterzik & Schmitt 1997 for more details).

All these examples show that there are indeed very young stars very far away from star forming clouds, some even show space motion pointing back to clouds with on-going star formation. This shows that raTTS most certainly do exist.

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Space Research at the Threshold to the 21st Century – Aims and Technologies –

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Abstract

Testing the Equivalence Principle, detecting gravitational waves and observing the evolving Universe in X-rays are aims of scientific space missions that are envisaged at the threshold of the 21st Century. To address this kind of science, one requires advanced systems, like drag-free satellites and giant X-ray telescopes that are based on replicated optics.

Missions called STEP (Satellite Test of the Equivalence Principle), LISA (Laser Interferometric Space Antenna) and XEUS (X-ray Evolving Universe Spectroscopy), that can fulfil these aims are not yet approved, but are under study within ESA's Science Programme. Similarly, the required technologies are being explored and, in part, under development. STEP and LISA, i.e. the missions addressing topics in the new area of Fundamental Physics in space will be based on a transatlantic collaboration.

To give the context of these missions within ESA, the framework of the "Horizons 2000" long-term science programme and in particular the current and recently completed missions, as well as the projects under development are described in the first part of the paper. Later sections present the scientific rationale, the resulting science requirements and the means for technical implementation of the advanced missions referred to above in today's perspective, as the 20th Century draws to a close.

1 Introduction

When we approach a (perceived) threshold in time – and in the present case, this is the start of a new century[1] – we usually assess the potential of the current state of affairs, express our wishes and present the results as our vision. Here we predict that Fundamental Physics will emerge early in the 21st century as a powerful new field of space science – provided, of course, that

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[1] We do not consider the start of the 3rd millenium – this would be pretentious.