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On the evolutionary status of X-ray selected weak-line T Tauri star candidates in Taurus-Auriga*

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Abstract. We present lithium observations of 35 stars previously reported by Wichmann et al. (1996) to be possible new weak T Tauri stars (WTTS) discovered by *ROSAT* in the Taurus-Auriga star-forming region. These stars were identified on the basis of low-resolution optical spectra. We have used our higher resolution spectra for measuring the equivalent widths of the Li I 670.8 nm resonance line, and for revisiting the evolutionary status of these stars. Most (∼85%) of the stars in our sample coming from *ROSAT* pointed observations are indeed confirmed to be new WTTS, but only a minority (∼22%) of the stars coming from the *ROSAT* all-sky survey are confirmed as WTTS. There are two reasons why we reject some stars as WTTS. One is that seven of the stars do not have a detectable lithium line at all. The other is that we use a definition different from that Wichmann et al. (1996) for classifying stars as WTTS. In particular, we identify eight stars as post T Tauri stars (PTTS) on the basis of their moderate lithium depletion. Our results confirm that the widely dispersed RASS-selected candidate WTTS tend to be older than the T Tauri stars associated with dark molecular clouds. The presence of PTTS around central Taurus suggests that the clouds may have been forming stars for more than ∼10 Myr, although at a very low rate. On the basis of the PTTS identified in this work we discuss possible differences between them and the WTTS. We find that PTTS seem to have slightly lower Hα emission equivalent width than WTTS, but the small number of known PTTS prevent us from making a strong conclusion.

Key words: stars: abundances – stars: activity – stars: pre-main sequence – X-rays: stars

1. Introduction

Wichmann et al. (1996, hereafter W 96) identified 76 new T Tauri star (TTS) candidates in the direction of the Taurus-Auriga star-forming region. Most of these TTS (72) were classified as weak-line TTS (WTTS) on the basis of detection of lithium and weak (W_{H_α} $\leq$10 Å) Hα emission or absorption in low-resolution spectra. Stars with strong Hα emission were classified as classical TTS (CTTS), which are thought to have active accretion disks (e.g. Appenzeller & Mundt 1989). The high number of WTTS identified by W 96 led them to estimate a WTTS/CTTS ratio ≥6, which implies that most TTS are not actively accreting from their circumstellar disks. If confirmed, this result could have important consequences for our understanding of pre-main sequence (PMS) stellar evolution. W 96 used the following criteria for classification of a star as a WTTS: the Li I 670.8 nm absorption line is present with an equivalent width ≥100 mÅ, and the star has a spectral type F or later. However, the detection of lithium in a late-type star is a necessary but not sufficient condition for considering it as a WTTS because post-TTS (PTTS) and low-mass members of young open clusters with ages 30–200 Myr also show strong Li I lines (see Martín 1997a for a review). Thus, we do not agree with the classification criteria adopted by W 96. We prefer a more conservative classification scheme that would really convey the idea that WTTS are very young PMS stars.

Post T Tauri stars represent an evolutionary phase intermediate between the TTS and the zero-age main-sequence (ZAMS). They have not been found in significant numbers around molecular clouds, suggesting that they are difficult to detect, or they disperse away, or else they do not exist because the timescale for low-mass star formation is short (Herbig 1978; Palla & Galli 1997). The missing population of PTTS constitute an important key to understanding the history of star formation. A few PTTS were found as visual companions to early-type stars (Lindroos 1986; Martín, Rebolo & Magazzù 1992; Pallavicini, Pasquini & Randich 1992). These stars have strong lithium lines and weak Hα emission or absorption, and hence they could be confused with WTTS. Martín (1997b, hereafter M 97) proposed to use the equivalent width of the Li I 670.8 nm resonance line for distinguishing between WTTS and PTTS. This provides a spectroscopic method of classification between these two types of PMS stars, analogous to using the Hα equivalent width for separating CTTS and WTTS. The basic idea behind the M 97

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classification scheme is that WTTS are very young and consequently should not have depleted lithium. Theoretical models indicate that PMS lithium depletion does not start until an age of 5–10 Myrs (D'Antona & Mazzitelli 1997). The definition of M 97 for PTTS is that they are low-mass stars in the process of PMS lithium depletion. M 97 argued that WTTS and PTTS occupy different regions in a W(Li I) versus spectral type diagram. A related problem is how to differenciate between PTTS and other young stars like the members of open clusters with ages older than ∼30 Myr. There is a region occupied only by PTTS which M 97 called the 'PTT-gap'. Neuhauser et al. (1997) noted that they did not find a PTT-gap in Taurus, but this is mainly due to their incorrect use of lithium equivalent width measurements affected by optical veiling.

The main advantage of the M 97 classification is that it relies solely on spectroscopic quantities that are independent of the distance and reddening of the stars. On the other hand, the identification of PTTS using the PTT-gap has two important shortcomings. As already stressed by M 97, we have to bear in mind that the number of stars in the PTT-gap is actually a lower limit to the total number of PTTS because only stars less massive than about 0.9 $M_\odot$ can occupy it, and because some PTTS may burn their lithium so efficiently that it becomes undetectable and so they are confused with ordinary dMe stars. Stars less massive than the Sun are still in the PMS evolution for an age of 30 Myr. Therefore the M 97 definition of PTTS, which we have adopted, is restricted to ages younger than ∼30 Myr.

The stars studied by W 96 were candidate optical counterparts of *ROSAT* X-ray sources. Most (89%) of them came from the *ROSAT* All-Sky-Survey (RASS), and the rest from pointed observations. They did not find any clustering towards the population of TTS known prior to *ROSAT*, and suggested that the new WTTS could be in part an older population of about 10 Myrs that had been dispersed from the clouds. If this is true, we might expect to find some PTTS amongst the W 96 sample. The observations of W 96 were not of sufficiently high resolution for providing reliable measurements of W(Li I). With the aim of studying the nature of the W 96 stars, we have obtained higher resolution (FWHM=0.8–1.6 Å) spectroscopic observations for 35 of these stars. We selected preferentially M-type stars. Most (83%) of the M-type stars of W 96 were observed by us because lithium is a sensitive age indicator for these cool stars (Briceño et al. 1997; Martín 1997a). On the other hand, lithium is not efficiently depleted during the PMS evolution of G-type stars and consequently we tried to avoid stars earlier than G8, although a few were finally observed because of extinction by passing clouds. In Sect. 2 we present the observations and we provide the results, and in Sect. 3 we discuss the properties of the different types of PMS stars and the history of star-formation in the Taurus-Auriga clouds.

2. Observations and results

The spectra were recorded using the Intermediate Dispersion Spectrograph (IDS) mounted on the Cassegrain focus of the 2.5 m Isaac Newton telescope on the nights from november 29 to december 4, 1996. We used the 235 mm camera and TEK 1024^2 CCD with the H1800V grating for stars brighter than V=11.5 and the R1200Y grating for fainter ones, giving FWHM resolutions of 1.0 and 1.6 Å, respectively. Three stars (W2, W7 and W36) were observed in an observing run with the 4.2 m William Herschel telescope on february 1997. The spectrograph was ISIS coupled with the R1200 grating and the detector a TEK 1024^2 CCD, yielding a resolution of FWHM=0.8 Å. The S/N of the IDS and ISIS spectra range from 80 to 200, averaging at ∼120. R. Wichmann (1997, private communication) has informed us that the W 96 observations were carried out with different telescopes and setups, and that their FWHM resolution ranged from 3.7 to 5.0 Å. Thus, our spectral resolution is significantly higher than that of the W 96 paper. We show the spectra of a few programme stars in Fig. 1. Note the different strength of the lithium feature for stars of similar spectral type.

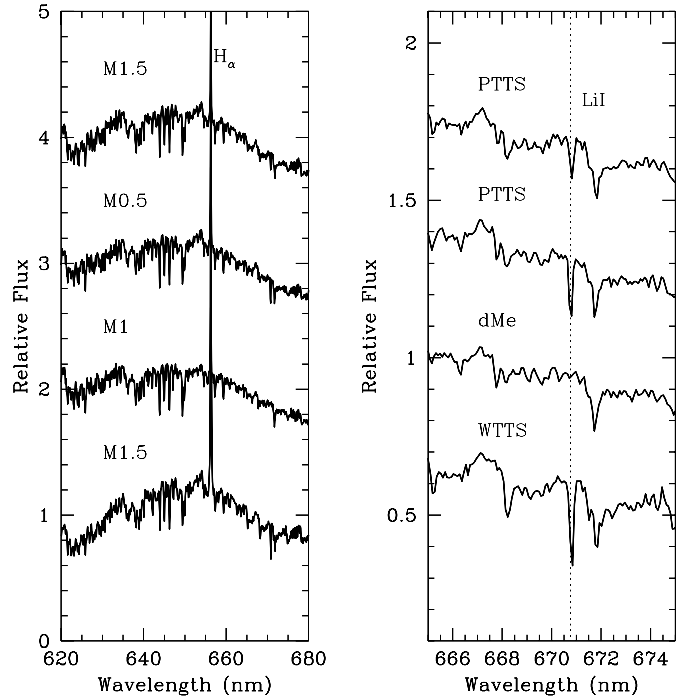

Fig. 1. Spectra of the programme stars (from top to bottom) W12, W43, W56, and W59. *Left panel*, wide spectral range; *right panel*, zooms around the Li I 670.8 nm resonance line. Note that the dMe star has a nondetection of the lithium feature, while the two PTTS have detectable Li I lines but weaker than that of the WTTS of similar spectral type.

We measured the equivalent widths (EW) of Hα and Li I in our spectra with gaussian fitting and direct integration. Both methods gave similar results except in a few cases, which were looked at more carefully. They turned out to be two double-lined spectroscopic binaries (DLSB) and one ultra-fast rotator (UFR, vsin$i\geq$30 km/s), which are noted in the rightmost column of Table 1. The UFR star was found to have a very short photometric period by Bouvier et al. (1997), which is consistent with our observation. In order to be more objective about establishing the continuum, both of us measured the equivalent widths independently and averaged the results. None of our measurements

Table 1. Spectroscopic results

W 96	RXJ	SpT	W_{H_α} (Å)	$W_{Li\,i}$ (Å)	Class	Comment
2	0403.3+1725	K3	−0.5	0.42	WTTS	UFR
3	0405.1+2632	K2	0.4	0.22	PMS?	
7	0406.8+2541	K7-M0	−3.0	0.59	WTTS	
8	0407.8+1750	K4	−0.2	0.27	PMS?	
9	0408.2+1956	K2	0.5	<0.07	dK	
12	0409.8+2446	M1.5	−1.8	0.29	PTTS	
13	0412.8+1937	K6	−0.6	0.39	PTTS	
14	0412.8+2442	G9	1.1	0.17	NA	DLSB
15	HD285579	G1	2.6	0.13	NA	
16	0413.3+1810	M3.5	2.7	<0.09	dMe	
20	0416.5+2053A	M5	−5.3	0.58	WTTS	XP
21	0416.5+2053B	M6	−5.5	0.57	WTTS	XP
22	0419.4+2808	G9	2.8	0.09	NA	XP
24	0420.8+3009	K7-M0	−5.9	0.42	PTTS	
25	0422.1+1934	M4.5	−19.2	0.58	WTTS	XP
28	BD+26 718	K1	0.2	0.38	WTTS	
29	BD+26 718 B	K0	0.6	0.34	WTTS	
33	0431.3+1800	M5	−29.0	0.61	CTTS	XP
34	0431.4+2035	M4	−4.4	0.30	PTTS	
35	0432.6+1809	M5	−5.7	0.63	WTTS	XP
36	0431.4+2035	K1	0.1	0.22	PMS?	XP
37	0432.8+1735	M2	−1.9	0.65	WTTS	XP
39	0433.7+1823	G6	2.7	<0.05	NA	
42	0437.4+1851A	K6	−0.9	0.41	PTTS	
43	0437.4+1851B	M0.5	−2.4	0.38	PTTS	
45	0438.2+2302	M1	−2.4	0.32	PTTS	
49	0441.4+2715	G8	2.6	0.21	NA	
53	0444.4+1952	M1	−0.3	<0.07	dMe	
56	0446.8+2255	M1	−0.9	<0.05	dMe	
59	0451.8+1758	M1.5	−6.6	0.57	WTTS	
60	0451.9+2849A	K4	1.5	0.10	PMS?	DLSB
61	0451.9+2849B	K2	2.2	0.19	PMS?	
69	0456.7+1521	M3.5	−7.0	<0.04	dMe	
72	0457.0+3142	K2	0.9	<0.09	dK	
75	0458.7+2046	K7	0.0	0.43	PTTS	

Note: Negative values of W_{H_α} indicate that the line is in emission.

diverged by more than 5%. In Table 1, we have also flagged (XP) the stars coming from the pointed observations, in order to distinguish them from those detected in the RASS stars.

3. Discussion

3.1. Spectroscopic classification

The main physical difference that we are concerned with between stars hotter and cooler than about 5200 K, is that the hotter stars do not deplete lithium efficiently during PMS evolution. Our classification scheme and discussion refers only to stars cooler than about 5200 K. Hence, in the classification column of Table 1 we have denoted as NA the G-type stars for which our criteria do not apply. Nevertheless, we note that they are unlikely to be very young because none of them shows H_α in emission.

Many of the stars proposed as new WTTS by W 96 do not have strong enough lithium to be considered as such. Using the diagramme shown in Fig. 2, we identified 11 TTS (1 CTTS and 10 WTTS) out of the 30 stars cooler than about 5200 K observed by us. It is interesting to note that the ratio of TTS versus older stars is much higher in the sample coming from the pointed X-ray observations (6:1) than in the RASS selected sample (5:18). We believe that this is due to an observational bias. The pointed observations were more sensitive than the RASS and are generally located around known TTS (W 96). Therefore, they tend to detect lower-mass TTS. We note that most of the WTTS cooler than M4 in the W 96 sample were detected in the pointed observations rather than in the RASS data. The pointed observations revealed a population of new very low-mass WTTS. This is very important because the census of very low-mass stars in Taurus-Auriga is probably incomplete (e.g. Briceño et al. 1998).

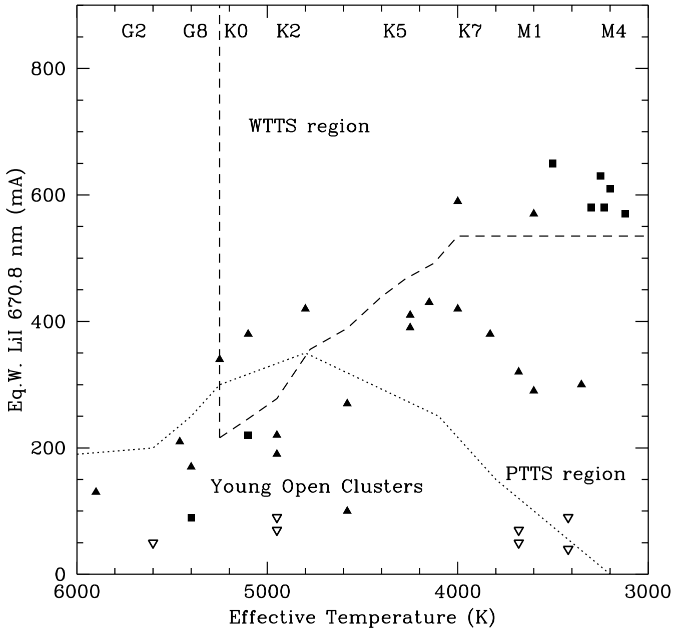

Fig. 2. A lithium versus spectral type diagram showing schematically the regions occupied by different types of young stars (M 97). The stars observed by us are plotted as filled triangles (RASS) and filled squares (pointed). The empty inverted triangles are stars with lithium non-detections.

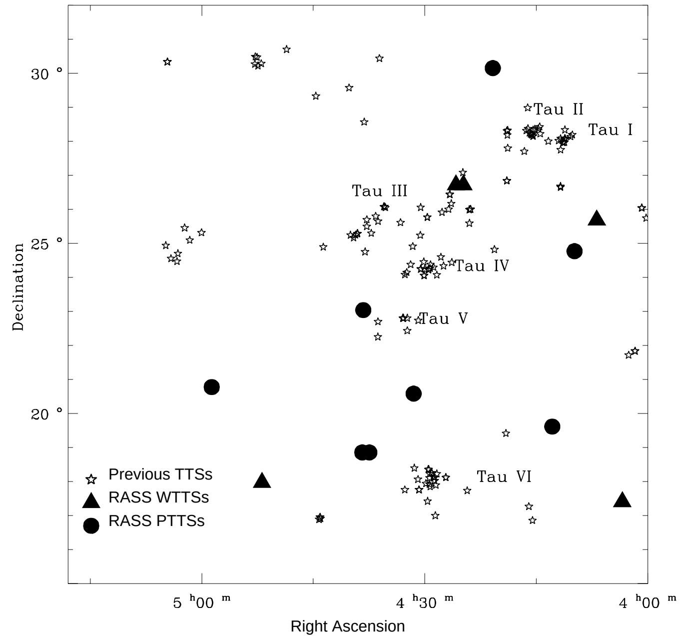

Fig. 3. The distribution of T Tauri stars in Taurus. Previously known members included in the Herbig & Bell (1988) catalog and from the recent surveys of Briceño et al. (1993, 1998) are shown as starred symbols, RASS-selected stars classified by us as WTTS are filled triangles and RASS-selected stars classified by us as PTTS are filled circles. The groups identified by Gomez et al. (1993) are indicated with roman numerals.

The 19 RASS-selected stars cooler than about 5200 K that are not TTS have been classified as follows: 8 PTTS, 4 stars with lithium below the open cluster upper envelope (PMS?), and 7 stars with lithium non-detections, which are presumably older. We have confirmed 5 new WTTS out of 23 stars coming from the RASS, i.e. 22% detection rate. For PTTS the detection rate among the RASS sources is 35%, i.e. somewhat higher than for WTTS. We interpret this result as evidence that the W 96 RASS sample is on the average older than the PMS population associated with molecular clouds. We would like to emphasize again that our definition of WTTS is a new one which differs from that one previously used by W 96 and other papers dealing with this subject.

Alcalá, Chavarría & Terranegra (1998) have found using gravity-sensitive narrow-band *uvby*-β photometry that about half of their RASS-selected WTTS candidates in the direction of Orion are probably ZAMS stars, even though they would appear as very young in an H-R diagram. Martín (1998) found that about half of the WTTS candidates reported by Walter et al. (1994) from an *EINSTEIN* survey of the Upper Sco OB association are older stars. All these results in different star-forming regions indicate that X-ray surveys that cover large areas outside dark molecular clouds are likely to find many young X-ray emitting stars that are older than TTS. On the other hand, deep X-ray surveys that concentrate around dark molecular clouds tend to find a majority of genuine new TTS, as illustrated recently by the spectroscopic classification of *ROSAT* PSPC-selected stars in the ρOphiuchi region (Martín et al. 1998). Our finding that most of the W 96 stars selected from pointed *ROSAT* observations are indeed new TTS supports this conclusion.

3.2. Spatial distribution of the new PMS stars around Taurus-Auriga

There are only three RASS-selected confirmed new WTTS that are far-away from already known TTS (Fig. 3). We have observed 35 stars, which corresponds to 46% of the W 96 total sample. Statistically, our results have to be considered as tentative until the other 54% of the stars are observed. At this point, we can only say that it is likely that the wide spatial distribution of the W 96 stars is largely due to the presence of stars older than WTTS. T Tauri stars tend to concentrate in groups (Gomez et al. 1993), but the PTTS do not appear to concentrate (Fig. 3). Martín et al. (1998) obtained a similar result in ρOphiuchi. This is probably due to the older age of the PTTS which have had enough time to move away from the molecular clouds.

Frink et al. (1997) have provided proper motion data for many WTTS candidates in Taurus. Four of our confirmed RASS WTTS and three of our PTTS have available proper motions. The 3 PTTS with available kinematic information have proper motions that are not typical of Taurus TTS. Two of the PTTS (W42 and W43) were considered by Frink et al. to be candidate members of the Pleiades cluster. Oppenheimer et al. (1997) identified two late M-type stars much younger than the canonical Pleiades age ($\sim$75 Myr) among a sample of proper motion cluster members. They suggested that those stars could be result of a recent low-mass star formation event in the "Pleiades Supercluster". This is an association recently discussed by Eggen (1995) of both cluster and non-cluster stars with ages in the

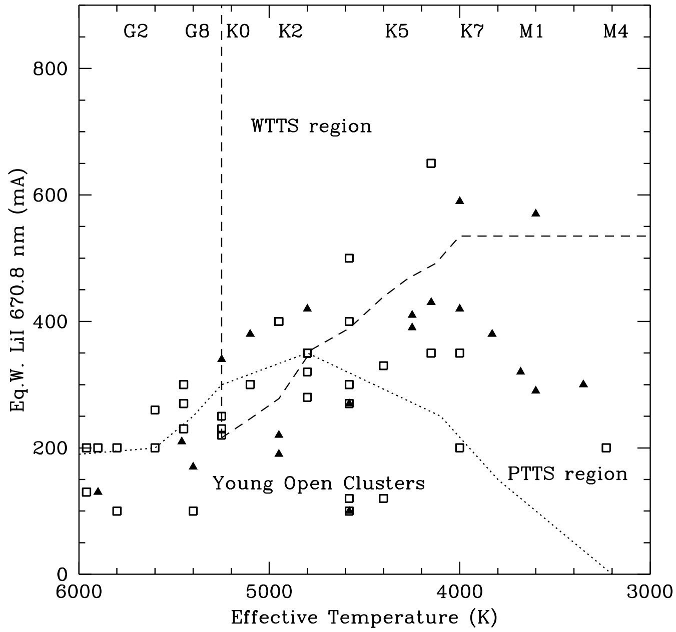

Fig. 4. A lithium versus spectral type diagram analogous to that of Fig. 2. The RASS stars observed by us are plotted as filled triangles and the RASS stars south of Taurus from Magazzù et al. (1997) are denoted as open squares.

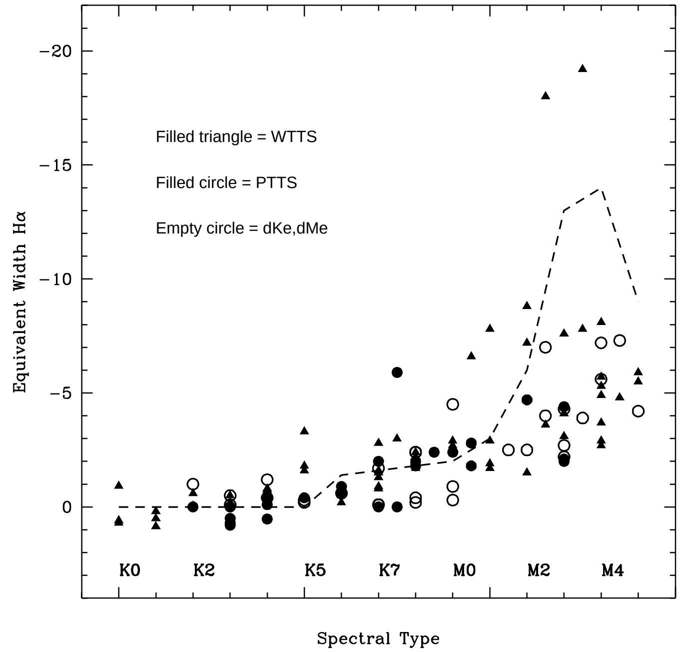

Fig. 5. The equivalent widths of Hα versus spectral type for X-ray selected WTTS (filled triangles), PTTS (filled circles) and emission-line stars with lithium non-detections (open circles). The dashed line is the upper envelope of Hα emission equivalent widths among members of the young α Persei open cluster (age ∼65 Myrs).

range from about 2 to 50 Myr. The RASS-selected PTTS identified by us with proper motions similar to the Pleiades cluster could be new members of this supercluster.

Magazzù et al. (1997) studied the optical counterparts of RASS sources located about 20 degrees south of Taurus. They covered an area slightly larger than W 96 (300 deg^2 vs 280 deg^2), and selected the TTS candidates following similar criteria. In Fig. 4 we present a classification diagramme for the RASS stars in our study and in that of Magazzù et al. (1997). We do not see a large number of WTTS that could have formed isolated or that might have been ejected from the clouds (run-away T Tauri stars). Preliminary results suggesting the presence of many WTTS (Neuhauser et al. 1995) widely dispersed around Taurus-Auriga are not confirmed when considering a larger sample of stars. Our results support the suggestions made by Briceño et al. (1997) and M 97 that a significant fraction of the RASS-selected stars are not very young WTTS but older stars like PTTS and solar-type ZAMS stars.

As shown in Fig. 4, the number of RASS-discovered stars filling the PTT-gap in central Taurus (filled triangles) is slightly larger than in the southern region (open squares), suggesting that some of the PTTS may have formed in the Taurus molecular clouds and have subsequently dispersed away. The number of known PTTS is too small to conclude that there is a significant difference in the density of PTTS between central and south Taurus. It is very important to carry out more sensitive studies in order to reveal a larger number of PTTS. Star formation in Taurus-Auriga may have lasted longer than ∼10 Myrs, but the star formation rate was probably much lower in the past than it is now observed, because otherwise we should observe more PTTS than TTS when considering a large area. Martín et al. (1998) have also found evidence for a strong time dependence of the star formation rate in the ρ Oph clouds.

3.3. PMS evolution of stellar activity

Assuming that the RASS-selected stars were at the distance of the Taurus clouds, W 96 derived X-ray luminosities for them. Unfortunately, it is not possible to assume that PTTS are at the same distance as the molecular clouds because they have had time to move relatively far away. Thus, the lack of distance information prevents us from deriving X-ray luminosities for PTTS. Furthermore, the RASS sample of PTTS is probably biased toward stronger X-ray emitters. It is possible that there are PTTS with lower X-ray luminosities which have not been found yet because they were below the threshold detection of the RASS. Randich (1997) did not find a significant decrease in the X-ray luminosity from the age of the IC2391 and IC2602 clusters (30–40 Myr) to the age of αPersei (∼65 Myr). The PTTS are younger than the IC clusters according to the classification of M 97. Hence, it is reasonable to expect that PTTS are relatively strong X-ray sources and that deep X-ray surveys should be a very good way of detecting them. We note that a search for PTTS should cover a wide area of the sky because these stars have presumably dispersed away from star forming regions.

In Fig. 5 we display the strength of Hα emission as a function of spectral type for WTTS, PTTS and dMe stars. We have merged the X-ray selected samples in central Taurus (this paper), south of Taurus (Magazzù et al. 1997) and in ρOph (Martín et al. 1998). The upper envelope of Hα emission equivalent widths in stars of the young (age$\sim$65 Myr; Basri & Martín 1999) open cluster α Per (Prosser 1994; Zapatero Osorio et al. 1996) is shown as a dashed line. The WTTS can have Hα emission above or below the dashed line, but most PTTS are below it. WTTS tend to have stronger Hα emission than PTTS. For the M-type X-ray selected WTTS in Taurus we find an average W_{H_α} of -7.4 Å, with a 1 σ dispersion of 2.1 Å, while for the M-type PTTS we find and an average W_{H_α} of -2.8 Å, with a 1 σ dispersion of 0.5 Å. Thus, there is some evidence of an evolutionary sequence for decreasing chromospheric activity from WTTS to PTTS, although we caution that the total number of known PTTS is rather small. On the other hand, PTTS appear to have similar Hα activity levels than young open cluster stars, indicating that there is not a strong decrease in chromospheric activity during PMS evolution. This is consistent with our previous discussion of the X-ray activity.

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