Astron. Astrophys. 321, 492–496 (1997)

ASTRONOMY
AND
ASTROPHYSICS

Quantitative spectroscopic criteria for the classification of pre-main sequence low-mass stars

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Received 1 October 1996 / Accepted 7 November 1996

Abstract. The discovery of hundreths of X-ray emitting stars possibly associated with pre-main sequence (PMS) low-mass stars far from molecular clouds, makes it necessary to adopt quantitative spectroscopic criteria for classifying them. T Tauri stars have young ages (< 10 Myr) and low masses ($M<2M_\odot$). As a consequence, it is shown that they must verify two spectroscopic conditions: (1) spectral type in the range K0-M6, and either (2a) strong emission lines and UV-optical-NIR continuum excesses, or (2b) weak-emission lines and a photospheric Li I λ670.8 absorption feature with a "minimum" equivalent width which depends on its spectral type. Classical T Tauris meet criteria (1) and (2a), while weak T Tauris (WTTS) meet criteria (1) and (2b).

T Tauri stars occupy a different region in the $T_{\rm eff}$ – W_{LiI} diagramme than the low-mass members of young open clusters. Post T Tauri stars (PTTSs) later than about K2 can be clearly identified in the same diagramme because they fill an empty region (PTT-gap), intermediate between the T Tauris and the young cluster stars. The application of the spectroscopic criteria defined in this work to the PMS stars claimed to have been discovered in recent X-ray surveys of molecular clouds is hampered by the lack of high-resolution optical spectra for most of them. On the basis of the sparse and modest-resolution data that is available, the preliminary results indicate that the majority of these stars (∼60%) are not WTTSs. Only ∼25% of the non-WTTS X-ray discovered stars are clearly PTTSs according to this study. The PMS status of the remaining stars is dubious. It seems unlikely that the PTTSs indentified in X-ray surveys outnumber the T Tauri stars. Far away from molecular clouds, the number of WTTSs and PTTSs appear to decrease significantly.

Key words: stars: pre-main sequence; fundamental parameters – X-rays: stars

1. Background

T Tauri stars (TTSs) were discovered more than 50 years ago (Joy 1945) and were soon recognized as very young low-mass stars (Ambartsumian 1947). Their observational properties have been subject of extensive reviews (Herbig 1962, Haro 1983, Appenzeller & Mundt 1989, Bertout 1989). Presently, there is general agreement that TTSs can be divided in two groups; the classical TTSs (CTTSs), and the weak TTSs (WTTSs)[1], depending on the strength of their optical emission lines. The most commonly used criterion for distinguishing between these two categories is the equivalent width of Hα in emission. While some authors use W(Hα)<10 Å for defining the WTTS (Appenzeller & Mundt 1989), others use W(Hα)<5 Å(Herbig & Bell 1988). The quantitative Hα boundary between CTTSs and WTTSs remains somewhat arbitrary.

The classification of TTSs into two subtypes became necessary only after the launch of the Einstein Observatory (EO). A number of X-ray sources associated with molecular clouds were discovered occupying the same region in the H-R diagram as the previously known TTSs (e.g. Walter et al. 1988). However, they did not show the spectroscopic characteristics which defined the T Tauri class (Herbig 1962). The coverage provided by the EO of the nearest star-forming regions was very incomplete. This problem was solved with the advent of the ROSAT All-Sky Survey (RASS), which is spatially unbiased and has similar sensitivity than typical EO pointings. It was expected that RASS would reveal new WTTSs towards molecular clouds, but it came as a surprise the finding of hundreths of WTT candidates very far from the clouds (Alcalá et al. 1995, 1996; Neuhauser et al. 1995; Wichmann et al. 1996). Whether these new stars are really WTTSs, or post TTSs (PTTSs), or even young main-sequence (YMS) stars, is still an open question and a matter of ongoing debate (e.g. Briceño et al. 1997, Feigelson 1996). This paper revisits the classification of pre-main sequence (PMS) low-mass stars, trying to be as quantitative as possible on the basis of PMS evolution physics, with the ultimate goal of clarifying the nature of the young stars discovered by X-ray satellites.

2. T Tauri stars

The two defining qualities of a TTS are extreme youth and low mass. Appenzeller & Mundt (1989) quoted 10 Myr as the upper

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[1] Naked T Tauri is an alternative name to weak T Tauri (e.g. Walter et al. 1988) but it is not as frequently used in the literature as WTTS

age limit, and 3 $M_\odot$ as the upper mass limit. However, PMS evolution is strongly mass dependent. Stars with masses in the range 2–3 $M_\odot$ have reached the ZAMS in less than 10 Myr (D'Antona & Mazzitelli 1994, Palla & Stahler 1993), becoming late B and early A-type stars. Most works on low-mass PMS evolution are concerned with stars with masses $\sim$1 $M_\odot$ or less. Therefore, it seems more adequate to use for TTSs an upper mass limit of 2 $M_\odot$, instead of 3 $M_\odot$. Moreover, since mass is not a direct observable (except in eclipsing binaries, of which none has yet been discovered amont TTSs), it would be better to use a $T_{\rm eff}$ or a spectral type. According to recent PMS evolutionary tracks (D'Antona & Mazzitelli 1994, Forestini 1994, Martín & Claret 1996, Palla & Stahler 1993) a convenient upper limit to the $T_{\rm eff}$ of a TTS (T^{TTS}_{limit} hereafter) would be around log T=3.7 (5011 K). The most widely used $T_{\rm eff}$ – spectral type scale for TTSs is the one adopted by Cohen and Kuhi (1979), in which 5080 K corresponds to K1-type. Other scales are also found in the literature (see discussion in Martín et al. 1994) which differ from the one of Cohen & Kuhi by up to $\sim$150 K for luminosity class V. Furthermore, spectral types are usually determined to an accuracy of half a spectral subclass. It is conservative to adopt a spectral type of K0 for the hot limit of TTSs, and a T^{TTS}_{limit} of 5250 K, which is the hottest value among the different calibrations.

The models of Martín & Claret (1996) with updated opacities and including rotation are cooler than those of Forestini (1994), which in turn are cooler than D'Antona & Mazzitelli's (1994). Despite such systematic differences, the models agree that the entire fully convective (Hayashi) tracks of stars less massive than 2 $M_\odot$ are cooler than our adopted T^{TTS}_{limit}. For stars less massive than $\sim$1.4 $M_\odot$, all PMS evolution for ages shorter than 10 Myr takes place at $T_{\rm eff}$ lower than T^{TTS}_{limit}. The original definition of the T Tauri class includes stars of spectral type late-F and G (Joy 1945, Haro 1983). However, less than 5% of the TTSs listed in the comprenhensive Herbig & Bell (1988) catalogue have spectral types earlier than K0. It is convenient to consider objects intermediate in mass between the TTSs and the Herbig Ae/Be stars as a new class of young stars, which could be called PMS Fe/Ge stars. Thé, de Winter & Pérez (1994) denominated a few of such stars "PMS F-type stars".

The lower limit in the spectral type of a TTS is close to the substellar limit. Recent works have shown that in the Pleiades cluster (age $\sim$ 100 Myr) brown dwarfs have spectral types later than M6.5 (e.g. Martín, Rebolo & Zapatero-Osorio 1996). Very young brown dwarfs are expected to have similar $T_{\rm eff}$ than their Pleiades-age counterparts as they follow fully-convective evolutionary paths. Therefore, it seems reasonable to set a spectral subclass of M6 as the cool limit for a TTS. This constraint does not exclude any TTS listed in the Herbig & Bell catalogue, which are all earlier than M6. The latest type of a known TTS, namely UX Tau C, is $\sim$M6 (Magazzù, Martín & Rebolo 1991).

CTTSs can be easily identified because of their characteristic emission-line spectrum (Herbig 1962, Appenzeller & Mundt 1989) and non-photospheric continuum excesses (Kenyon & Hartmann 1987, Bertout 1989). Such properties cannot be explained by conventional stellar activity. The equivalent width of Hα should not be used as the only criterion to classify a TTS as classical or weak, because it can vary depending on spectral type, binarity, flare activity, etc. Additional criteria, such as UV and near-IR excesses and presence of forbidden emission lines, should also be used. However, for lack of other data, it is sometimes convenient for statistical purposes to rely on Hα as the only criterion for classifying CTTSs. In such case, the CTT Hα threshold should be set at such an equivalent width that for higher values chromospheric activity is unlikely to be the source of the emission. For K-type stars a high enough value is 5 Å because chromospherically active single and binary stars do not show higher Hα equivalent widths (Strassmeier et al. 1990, Montes et al. 1995). However, for M-type stars, the value has to be risen, because M-stars in young open clusters and the field do show Hα equivalent widths stronger than 5 Å (Prosser 1994, Zapatero-Osorio et al. 1996). Safe enough values are $\sim$10Å for early-M and $\sim$20Å for late-M types.

A WTTS lacks the exotic properties of a CTTS. It has a spectral energy distribution similar than a MS star, and spectroscopically only the strong Li I λ670.8 feature might be a signal of identity. In fact, papers claiming to have found new WTTSs have usually relied on the detection of the Li I feature. The use of this line is justified because of its accessibility using modern spectrographs with CCD detectors and the well-known property of Li[2] as an age indicator (Herbig 1962, Bodenheimer 1965, Magazzù, Rebolo & Pavlenko 1992, Martín et al. 1994). One of the main conclusions of the last two works is that PMS stars are formed with a homogeneous "initial" Li abundance of log N(Li)=3.1$\pm$0.1 (in the usual scale of log N(H)=12), which is similar to the abundance found in the interstellar medium. Martín et al. (1994) also concluded that PMS stars do not show significant Li depletion until they are relatively evolved. No Li depletion larger than the uncertainties has been found in any CTTS, whereas some low-luminosity WTTSs clearly showed Li depletion.

Theoretical models agree that Li depletion is less than 50% for ages younger than 5 Myr, independently of mass (D'Antona & Mazzitelli 1994, Forestini 1994, Martín & Claret 1996, Bildsten et al. 1996). For masses $\leq$0.5 $M_\odot$, Li depletion is not significant until ages larger than 10 Myr. A typical TTS has a mass of 0.5 $M_\odot$ and has preserved most of its "initial" Li content, implying the presence of a strong Li I λ670.8 feature in the spectrum. Quantitatively, the "minimum" Li I equivalent width (W_{LiI}) of a TTS is determined by the line formation for "minimum" Li abundance as a function of mainly temperature. Gravity and microturbulence are only second-order effects. In order to derive the "minimum" W_{LiI} shown in Fig. 1, I have used the grid of NLTE curves of growth of Pavlenko et al. (1995), and I have adopted the following values: a "minimum" Li abundance for a TTS of log N(Li)=2.8, i.e., 50% lower than the "initial" value; the highest $T_{\rm eff}$ for each spectral type among those available from different calibrations (Martín et al. 1994

2 The term Li is used here to refer to lithium's most abundant isotope ^{7}Li. The rarer ^{6}Li isotope burns at lower temperature and it's therefore consumed more rapidly inside the stars.

and references therein); a gravity of log g=4.0 for spectral types in the range K0–K5 and log g=3.5 for cooler temperatures; and finally a microturbulent velocity of 2 km s^{-1}. For T_{eff} cooler than 4000 K the Pavlenko et al. (1995) computations are not very reliable because of problems with the model atmospheres and the blending effects of molecular features. Hence, a constant "minimum" W_{LiI} value has been used for M-type stars in Fig. 1. It is important to note that CTTSs may present apparently small Li I equivalent widths due to the blurring effect of optical veiling (Basri, Martín & Bertout 1991, Magazzù et al. 1992). Hence, the "minimum" W_{LiI} values of Fig. 1 can be used for WTTSs without veiling correction, and for CTTSs with veiling correction. Nevertheless, a CTTS can be identified from its extreme emission lines and continuum excess, without needing to accurately unveil the photospheric spectrum.

3. Post T Tauri stars

Herbig (1978) remarked that the T Tauri phase represents only about 10% of the PMS evolution of solar-type stars. He used the term PTTS for a PMS star which has lost its T Tauri properties. However, with the recognition of the WTTSs it has become unclear how to characterize observationally the PTTSs. Some authors have suggested that PTTSs are only distinguished from WTTSs because they lie closer to the ZAMS in the H-R diagram (Martín, Magazzù & Rebolo 1992; Pallavicini, Pasquini & Randich 1992). The caveat of this criterion is that it relies on an asssumption of the distance to the star and on comparison with theoretical isochrones. It would be desirable to define the PTTS from phenomenological properties rather than from comparison with models.

Stars with masses $\geq$1 $M_\odot$ do not deplete Li during PMS evolution (Martín & Montes 1996), and therefore this element cannot be used as a PMS age indicator for those masses. Activity and rotation can neither be used because they do not behave fundamentally different in PTTSs than in WTTSs and YMS stars (Bouvier et al. 1996, Jeffries et al. 1996). A distinguishing quality of PTTSs is that they evolve towards the ZAMS on partially radiative evolutive tracks, and thereby they increase their T_{eff} . Stars in the mass range 2–1 $M_\odot$ evolve from T_{eff} 5100–4500 K (K1–K5) at the bottom of their fully convective PMS paths to 8600–5600 K (A3–G6), respectively, on the ZAMS. Therefore, the population of PTTSs with masses $\geq$1 $M_\odot$ consists of A, F and G-type stars. Possibly, the only way of discriminating such PTTSs from field YMS stars is to very accurately place them in an H-R diagram by measuring their trigonometric parallax.

For stellar masses <1 $M_\odot$, Li is depleted during PMS evolution and it could be used as an age indicator. This is illustrated in Fig. 1, where the Li I equivalent widths of TTSs and members of young open clusters are plotted as a function of T_{eff} or spectral type. 64 equivalent widths coming from Basri et al. (1991), Magazzù et al. (1992) and Martín et al. (1994) of both CTTSs (corrected for veiling) and WTTSs are shown. The X-ray discovered stars (Table 8 of Martín et al. 1994) have not been included. 89% of the TTSs fall on or above the lithium isoabundance line which represents the locus of "minimum" W_{LiI} values. The

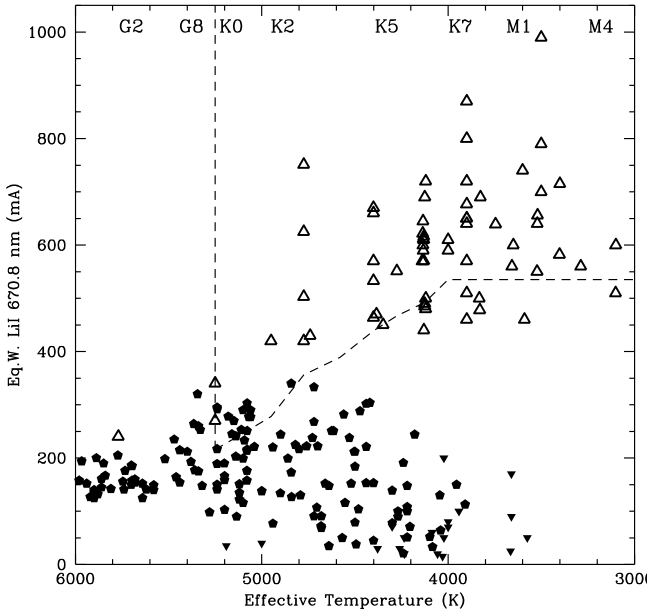

Fig. 1. Li I λ670.8 equivalent widths of TTSs (empty triangles) and low-mass members of the young open clusters IC 2602, IC2391, IC 4665 and the Pleiades (filled pentagons or, for upper limits, inverted filled triangles) plotted as a function of T_{eff} . 89% of the TTSs fall on or above the dashed line, which represents the T^{TTS}_{limit} cutoff at 5250 K, and the Li isoabundance line for log N(Li)=2.8 ("minimum" abundance for TTSs). Note the empty region between the TTSs and the cluster stars for T_{eff} $\leq$4800 K (PTT-gap).

few TTSs with smaller W_{LiI} could be PTTSs or 1-σ statistical deviations. The open cluster stars include 214 members of the Pleiades with equivalent widths (upper limits for 9 of them) measured by Soderblom et al. (1993) and García López, Rebolo & Martín (1994); 19 stars of IC 2602 (Randich et al. 1996); 9 members of IC 2391 observed by Stauffer et al. (1989); and 14 members of IC 4665 (Martín & Montes 1996). According to Mermilliod (1981), the age of these three IC open clusters are younger (36 Myr) than that of the Pleiades (78 Myr). Uncertainties in equivalent width vary from star to star, but in general they are in the range 10–80 mÅ. For T_{eff} in the range 5250–4800 K, the TTSs are not clearly separated from the cluster stars, but for decreasing temperature the separation becomes larger. PTTSs can be identified unambigously if they fill the empty space in Fig. 1 between TTSs and K,M-type young cluster stars. This region is what I call hereafter PTT-gap. PMS calculations predict that low-mass stars should spend a few Myr in the PTT-gap, but unfortunately the models cannot yet be used quantitatively because they fail to reproduce the pattern of Li abundances in young open clusters (Martín & Montes 1996 and references therein). The number of stars located in the PTT-gap that are found in a given survey can be used as a lower limit to the total number of PTTSs present in the surveyed area.

4. The PMS population found by X-ray surveys

The spectroscopic criteria discussed in the previous sections are useful for clarifying the nature of the stars found by the EINSTEIN and ROSAT satellites towards star-forming regions. For simplicity, the following convention will be used: class FG for F,G-type stars, which are either intermediate-mass PMS stars, or PTTSs, or else YMS stars; class KM for K,M-type PTTSs or YMSs; class PT for *bona fide* K,M-type PTTSs because they fall on the PTT-gap; class WT for WTTSs.

Starting with Taurus-Auriga, I have classified the NTTSs reported by Walter et al. (1988) using their spectral types and the W_{LiI} values of Martín et al. (1994) as follows: 7 FG, 6 KM, 4 PT and 10 WT. The percentage of WTTSs over observed EINSTEIN X-ray sources in this sample is 25%. A lower limit to the PTTS/WTTS ratio is 0.4. From ROSAT observations, Wichmann et al. (1996) have identified many more possible WTTSs, but their low-resolution optical spectra did not allow them to measure W_{LiI}. The classification of these stars awaits higher-resolution data. Neuhauser et al. (1995) and Magazzù et al. (1996) investigated with higher-resolution spectra 115 RASS sources in a region of 300 deg^2 south of Taurus and reported 35 new PMS stars. Their stars are classified in this work as follows: 14 FG, 10 KM, 3 PT, 8 WT. The WTTSs represent only 7% of the X-ray sources they observed, which is a significantly lower fraction than for the Walter et al. (1988) sample. This indicates the number of WTTSs decreases with increasing distance to the clouds. The ratio of PTTS/WTTS is at least $\sim$0.4 and, surprisingly, does not seem to change as the surveys move far away from the clouds.

Walter et al. (1994) studied EINSTEIN images of the Upper Scorpius OB association. They found 28 low-mass PMS stars. Using the data given in their Table 7, the classification of their stars is: 2 FG, 3 KM, 8 PT and 15 WT. Hence, the WTTS represent 53% of their sample. The PTTS/WTTS ratio is at least 0.5. This result is not consistent with their conclusions, based on isochrone fitting, that their low-mass PMS stars are systematically younger than the massive B stars, and that they have a very small dispersion of ages. The apparent ages based on the HR diagramme could be in error due to observational uncertainties in distance, reddening or effective temperature, and theoretical uncertainties in the calculations of PMS low-mass isochrones.

In Chamaeleon and Orion, Alcalá et al. (1995,1996) studied RASS sources and claimed to find 77 and 112 new WTTSs, respectively. They published W_{LiI} values which should be taken with caution because the resolution of their spectra (3.5–8.1 Å) is too low for resolving the Li I λ670.8 feature from nearby atomic and molecular lines. Using their W_{LiI}, my tentative classification of their stars in Chamaeleon/Orion is the following: 23/30 FG, 13/18 KM, 13/13 PT, and 28/51 WT, respectively. It is particularly interesting that the ratio of X-ray discovered PTTSs versus WTTSs is similar in Chamaeleon, Taurus and Upper Scorpius, but lower in Orion. However, this result remains preliminary until higher-resolution spectra for improving the W_{LiI} measurements of many stars become available.

To summarize, spectroscopic quantitative classification criteria applied to X-ray discovered stars allow to identify genuine WTTSs and PTTSs. The global fraction of WTTSs among the PMS candidates identified from previous qualitative criteria is $\sim$40%. The fraction of stars in the PTT-gap is $\sim$15%, which is a lower limit to the total number of PTTSs. However, it appears unlikely that the remaining 55% of X-ray emitting stars are all PTTSs outside the PTT-gap. Most of them are F and G-type stars with a detectable Li I feature. Briceño et al. (1997) have estimated that a significant number of solar-type young (but not PMS) stars could be contaminating the X-ray surveys. The results of this work seem consistent with their suggestion. There does not seem to be compelling evidence in the X-ray surveys for a large PTTS population. It is of great importance to obtain reliable W_{LiI} measurements on the basis of high-resolution spectroscopy for all the K and M-type X-ray discovered stars, in order to improve the estimate of the fraction of PTTSs over WTTSs.

Acknowledgements. I thank Drs César Briceño and Nick Kylafis for stimulating conversations. E.M. acknowledges financial support from EU grant ERBCHBG-CT93-0315 for visiting FORTH in Heraklion (Crete).

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