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EVOLUTIONARY STAGE AND PHYSICAL PARAMETERS OF NEARBY WEAK LINE T TAURI STARS [1]

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RESUMEN

Discutimos los resultados preliminares de un estudio fotométrico en el óptico y en el cercano infrarrojo de una muestra de estrellas T Tauri con líneas en emisión débiles (WTTS) y post T Tauri (PTTS) *nuevas* y brillantes asociadas a las regiones de formación estelar en Orion (71 objetos) y en el Toro (30 objetos). Estas estrellas fueron detectados por primera vez en el patrullaje de todo el cielo del *ROSAT* (RASS). Nuestras estrellas programa fueron seleccionadas de seguimientos en el óptico de las fuentes de rayos X hechos por Alcalá (1994) y Wichmann (1994).

ABSTRACT

We discuss preliminary results obtained from optical and near IR photometry of a sample of bright *new* weak–line (WTTS) and post (PTTS) T Tauri stars associated with the Orion (71 objects) and the Taurus/Auriga (30 objects) star forming regions (SFRs). They were first detected with the *ROSAT* all-sky survey (RASS). Our program stars were selected from follow-up optical observations of the X-ray sources by Alcalá (1994) and Wichmann (1994).

Key words: **STARS: FORMATION — STARS: FUNDAMENTAL PARAMETERS— STARS: PRE-MAIN SEQUENCE**

1. INTRODUCTION.

WTTS are characterized by the following:

(a) They are localized in star–forming regions (SFRs).
(b) Their X-ray emission is $\geq 10^2$ times the solar flux (e.g., Feigelson 1987; Walter et al. 1988).
(c) They have a late spectral type (G0 or later), and except for the Ca II H+K and the Hα lines, they do not have a line–emission spectrum (e.g., Bouvier & Appenzeller 1992).
(d) The Li I λ 6707 line is strong in absorption (Walter & Kuhi 1981).
(e) WTTS rotate faster than CTTS (e.g., Smith 1994; Edwards et al. 1993).
(f) Normally, no IR and/or UV flux–excesses are present in their SED–curves (e.g., Walter et al. 1994; Bouvier & Appenzeller 1992).
(g) They are more luminous than their main–sequence (MS) counterparts (e.g., Mundt et al. 1983).

Although most WTTS were discovered in nearby SFRs (d $\leq$ 500 pc, typically 150 pc), kinematic studies of the regions are lacking. Their association with a given SFR would be reinforced if such studies were available. The pre-main sequence (PMS) nature and youth of WTTS is established unambiguously with the help of (a), (c), (d), (e) and (g) above. The vast majority have been discovered from space because of (b), with some exceptions (e.g., the Ca II H+K line emission prism objective surveys, see Herbig, Bell, & Robbin 1988 for references). It is believed that when the mass accretion phase of a classic T Tauri star ends, a WTTS merges.

[1] based on observations made at the Observatorio Astronómico Nacional at San Pedro Mártir, B.C., México; at the German-Spanish Astronomical Center, Calar Alto, Spain; at European Southern Observatory, La Silla, Chile and at the 1.8-m telescope of the Ohio State University, Lowell Observatory, Flagstaff, Arizona, USA

1.1. The Post T Tauri Problem

In the current scenario of star formation, WTTS are considered more evolved than classic T Tauri star (CTTS) (e.g., Shu, Adams, & Lizano 1987). Assuming that star formation is a continuous process, at least for a time comparable to the lifetime of a molecular cloud, and from simple (geometric and kinematic) considerations of PMS stars associated with SFRs, the expected ratio of post T Tauri stars (PTTS) to CTTS could be as high as 10. Nearby SFRs (e.g., Taurus/Aurigae, Lupus, Chamaleon) have characteristic sizes of about 20 pc, their associated PMS stars have a large age spread (10^7 yr or more) and a velocity dispersion ≤ 2 km s^{-1}. All this supports the assumptions indicated above. However, recent observations indicate a lower WTTS to CTTS ratio of about 3 (e.g., Feigelson et al. 1993). This is the post T Tauri problem first discussed by Herbig, Vrba, & Rydgren (1986).

1.2. The Merger Problem of WTTS

An argument to increase the PTTS to CTTS ratio is that only the denser parts of the clouds were surveyed with the *Einstein* X–ray satellite for WTTS and, since they are more evolved than the CTTS, they had time to disperse to the outer parts of the cloud leaving the central regions where they formed. They were thus missed by the limited satellite field of view. But observational evidence already existed in the early 80's that did not support this idea (Mundt et al. 1983): CTTS and WTTS are found to share the same location in the (log L_*,log T_{eff}) diagram and, consequently, the latter have the same ages and masses as the former. If WTTS had time to disperse, so did the CTTS. But we do not see CTTS distant from the denser parts of the clouds.

1.3. On the Spatial Distribution of WTTS

The spatial distribution of WTTS in SFRs was, until recently, a completely open matter. Surveys previous to *ROSAT* were done in the pointed mode towards locations known to have CTTS. Nothing was known about the outer regions of clouds with ongoing star formation. The RASS has shed new light on this matter in at least 4 SFRs (Chamaleon and Orion by Alcalá 1994, Lupus and Taurus by Wichmann 1994; see also Krautter et al. 1994). Apparently, WTTS have a much broader and more homogeneous spatial distribution than CTTS.

1.4. The ROSAT All Sky Survey

The important advantages of the RASS are that its sampling is not spatially biased and covers an entire SFR with a sensitivity comparable to that of the much more spatially restricted *Einstein* observations. Supported by a follow-up optical survey of the X-ray sources found, the RAAS allows us to do the following:

(i) To extend the search of WTTS+PTTS to the outer parts of molecular clouds.
(ii) To derive the distributions in space and time of their basic stellar parameters.
(iii) To try to derive different inter-correlations between the parameters involved and with observations at other wavelengths and learn more about the star forming process at a cloud scale.

With these goals in mind, we have observed photometrically $\approx 1/3$ of the expected 300 new WTTS in Orion SFR, covering spatially about 450 square degrees. Something similar but in a less advanced stage is being done in Taurus/Aurigae SFR. Here we report preliminary results of an optical and near IR photometric study of 101 selected new WTTS in Orion and Taurus/Aurigae star forming regions.

2. THE DATA

Identification charts, coordinates and spectroscopic spectral types of the new WTTS in Orion and Taurus/Aurigae were available beforehand (Alcalá 1992, 1994; Wichmann 1992, 1994). The program stars resulted from follow-up spectroscopic observations of the RASS sources carried out at the 1.5-m and 2.2-m telescopes at La Silla (ESO), at the 1.8-m telescope of the Ohio State University at Lowell Observatory and at the 2.2-m telescope of the German–Spanish Astronomical Center at Calar Alto. Optical (*uvbyβ* and *UBV(RI)$_C$*) and near IR (*JHKLM*) photometry was done during several seasons in 1992–1994 at the 2.1-m, 1.5-m and 0.84-m telescopes of the Observatorio Astronómico Nacional. The *UBV(RI)$_c$* photometry of 8 stars done by Wichmann (1994) using the 1.23-m telescope at Calar Alto Observatory was also used in the present study. The optical and near IR photometry were reduced following the procedures outlined by Mitchell (1960). The resulting errors are typically $\leq 0^m.02$ and $\leq 0^m.05$ for the optical and near IR data, respectively.

3. RESULTS AND DISCUSSION

The PMS nature of the stars of the sample, derived earlier from key spectral features by Alcalá (1994) and Wichmann (1994), is confirmed by our photometry. Except for a couple of objects of the sample, the program stars fall above and to the right of the expected zero-age main sequence line in the (optical and near IR) magnitude-color diagrams of the regions. In general, we find that the stars suffer moderate IS-extinction, they are not significantly veiled and, for those stars in Orion that have optical *and* near IR data (20 stars), the bolometric corrections (BC) we derive by integration under the dereddened spectral energy distribution curves are normal. Therefore normal bolometric corrections were applied to derive the luminosities of the program stars.

From the *uvby-β* photometry of a subsample of WTTS (45 stars) and following procedures outlined by Neri, Chavarría-K, & de Lara (1993) we obtain (photometric) spectral types which are in good agreement with those derived spectroscopically, with a mean error ≤ 2 subclasses. We also obtain gravity values that are, on the mean, between dwarfs and giants. All this confirms the earlier results of the spectroscopic follow-up observations by Alcalá (1994) and Wichmann (1994).

Because of the low and uniform IS-extinction observed, we conclude that the Orion WTTS are probably located on the front face of the SFR, but this seems not to be the case for the Taurus/Aurigae WTTS, since in this case it was found that the IS-extinction varies considerably from star to star. Although *uvby-β* photometry permits us to obtain with little effort the luminosities and temperatures of the program stars, it is the spectroscopic survey that allows us to unequivocally determine their pre–main sequence nature.

Our photometry and the spectroscopic types by Alcalá (1994) and Wichmann (1994) enable us to fix the position of the program stars on a ($\log L_*$,$\log T_{eff}$) diagram. From simple eye inspection it stands out that the WTTS + PTTS share the same region in the diagram with the classic T Tauri star counterparts associated with these two SFRs. From their location in the diagram and from comparison with models of contracting stars (D'Antona & Mazzitelli 1994), we derive ages and masses for the WTTS. Most Orion WTTS lie between the 1×10^5 yr and the 3×10^6 yr isochronous lines, with 7×10^5 yr as a representative age for the sample. Their mass range is $0.3\ M_\odot \leq M_{star} \leq 3.1\ M_\odot$, with $M_{star} \approx 1.5\ M_\odot$ as its representative value. Their luminosities and temperatures fluctuate between $\log (L_{star}/L_\odot) \approx 0$ and ≈ 2 and $\log T_{eff} \approx 3.55$ and ≈ 3.9 with a mean of $\log (L_{star}/L_\odot) \simeq +0.68$ and $\log T_{eff} \simeq 3.664$ (K2/K3 IV). The data is in agreement with the hypothesis that the formation of the T Tauri stars was triggered by the formation of the OB stars.

Similarly, we find that the physical parameters of the Taurus WTTS and PTTS vary in the ranges $-1.4 \leq \log (L_{star}/L_\odot) \leq +0.7$, $3.54 \leq \log T_{eff} \leq 3.74$, $0.3\ M_\odot \leq M_{star} \leq 2\ M_\odot$ and 1×10^5 yr $\leq \tau_{age} \leq 3 \times 10^7$ yr. The average values for $\log (L_{star}/L_\odot)$, $\log T_{eff}$, M_{star} and τ_{age} are -0.24, 3.645 (K3/K4 IV), 0.9 $M_\odot$ and 1.1×10^7 yr, respectively. The Taurus/Aurigae sample suggests that star formation has been occurring for 3×10^7 yr. But the data are also in agreement with the interpretation that it could also have occurred in two outbursts: one 1×10^6 yr ago (11 stars) and the other 1.7×10^7 yr ago (9 stars). In order to be conclusive in this matter, more WTTS have to be observed.

From this first inspection, we find no obvious dependence of the mass, age or spectral type of the program stars with their position in the cloud. On the other hand, one has to be aware that the sample is biased in luminosity since the objects were originally X-ray flux-limited and hence our results are insufficient to draw definitive conclusions about *all* WTTS+PTTS in the SFRs. (We did not observe stars with $\log (L_{star}/L_\odot) \leq 0$ and ≤ -0.8 in Orion and Taurus/Aurigae, respectively). Here the (deeper) pointed mode observations of the regions with *ROSAT* are an important complement to our results. Except for one star, the upper bound for $\log (L_{star}/L_\odot)$ in Taurus/Aurigae was found to be 0 (i.e., $L_{star}/L_\odot \approx 1$). The more luminous stars of the region, if any, were missed in the present study. This was caused by the selection of program stars: the X-ray sources with bright optical counterparts were not considered by the original spectroscopic surveys of Taurus/Aurigae by Wichmann (1994) and of Orion by Alcalá (1994).

Interesting indeed is the fact that the spectral type, mass, luminosity and age distributions of the WTTS in Taurus/Aurigae and in Orion differ from one another, and that this is most probably due to the absence or presence of O and early B stars in the regions. This result compares well with similar results of other SFRs without and with OB stars present in them (e.g., Alcalá 1994 and Wichmann 1994 in the former case, Walter et al. 1994 in the latter case). Another result is that, for a given region, the WTTS of our sample have, on the mean, earlier spectral types and are more massive than the CTTS counterparts, and that the Orion WTTS are hotter and more luminous than the WTTS in Taurus/Aurigae. But this result could be spurious since we have a bias in luminosity. Here again, the pointed mode observations will play a decisive role.

Contrary to the normally adopted (one branch) evolutionary scheme (e.g., Shu, Adams, & Lizano 1987), our observations suggest a two branching evolutionary sequence, where the WTTS do not necessarily have a CTTS as predecessors. Schematically the evolutionary sequence looks like this:

Condensations in MC → protostar → bipolar sources → CTTS → WTTS → dwarf star
↘ → embedded source → WTTS ⟶ ⟶ ⟶ ↗

The branch that a newly born star will follow should depend on the initial conditions of the collapse, in particular, on the angular momentum of the collapsing condensations. Note that Montmerle & André (1989) give a different interpretation based on results which are similar to ours.

Another important property of our program stars is that, in contrast to CTTS which tend to concentrate in the proximity of the denser parts of the molecular clouds ($\leq 1^\circ$), the WTTS and PTTS occupy more or less homogeneously a significantly more extended area in the sky. We have found WTTS up to 7.5° from the cores of the molecular clouds in Orion and Taurus/Aurigae.

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