REVIEW

The results of the search and study of young stellar objects with Hα emission in the Byurakan Observatory

E. H. Nikoghosyan

NAS RA V. Ambartsumian Byurakan Astrophysical Observatory (BAO), Armenia
E-mail: elena@bao.sci.am

Abstract

One of the main observational properties of young stellar objects in the optical range is the presence of emission lines, in particular Hα (6563 Å). Therefore, detection of Hα emission is the most common spectroscopic means for identification of young stars. The paper presents the results of searching and studying of young stellar objects in several star forming regions carried out on the 2.6 m telescope in Byurakan observatory. The quantitative relationships between objects with different stage of activity are considered. In addition, a statistical analysis of Hα activity and other manifestations of PMS activity (X-ray, IR excess), as well as an evolutionary age of the Hα emitters in several star-forming regions is provided.

Keywords: *method: slit-less - young stellar objects: Hα emission - star formation regions: individual: L1340, NGC 7129, GM 1-64, GM 2-4, LkHα 326, GM 2-41, Cep OB3, IC 348*

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1. Introduction

One of the most prominent properties of young stellar objects in the optical range is the presence of emission lines, in particular the tracer of ionized gas Hα emission (6563 Å). Furthermore, the intensity of Hα emission, more precisely the equivalent width EW(Hα), is that rating, according to which it is possible to characterize an evolutionary stage of young stars (Herbig & Bell 1988). Depending on EW(Hα) values, the low-mass young stellar objects are conditionally divided into two main groups. The first group includes the classical T Tauri (CTTau) objects, in which Hα emission is mainly produced as a result of accretion activity of the circumstellar disk. The second group includes the weak T Tauri (WTTau) objects, in which Hα emission appears mainly due to chromospheric solar like flares. Supposedly, these objects have a later evolutionary stage (Class III), while CTTau objects belong to the earlier evolutionary stage (Class II). The widely used boundary value of EW(Hα) for these two groups is 10 Å. Besides, the classification proposed by White & Basri (2003) is

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also used to separate stellar objects according to their Hα activity. According to this classification, the boundary value of the EW(Hα) for WTTau and CTTau objects depends on their spectral classes (Sp) and varies from 3 Å for Sp earlier than K5 up to 40Å for Sp later than M6.

Historical overview. Already at the beginning of the last century near some dark nebulae it was discovered stars of relatively late spectral classes with bright emission lines of hydrogen and ionized calcium. But only in 1945 American astrophysics Alfred Joy (Joy, 1945) proved, that these stars are not exotic anomaly, but the new class of objects, named TTau type stars and they should be looked for the presence of a bright hydrogen emission line, which is one of their main observational features.

Progress in understanding the evolutionary status of these stars was outlined very fast. Already at the end of 40th years famous Armenian astrophysicist Victor Ambartsumyan, on the basis of stellar dynamics in associations, suggested their youth (Ambartsumian, 1949). A few years later it were also published papers, in which the basic characteristics of T Tauri stars were given, namely: 1) T Tau stars occur in groups, forming T-associations; 2) in their spectra observed continual and line emission; 3) they exhobit strong variability (Ambartsumian, 1954).

Later, the first catalogues were appeared. Most notable among those is the work by Guillermo Haro, where the list of 250 Hα emission stars observed in an area of 3.5 square degree located the brightest part of the Orion Nebula is presented (Haro, 1953).

An esential contribution to the study of this new class of stars made famous American astrophysicist George Herbig, who found many new stars of this type, and analyzed all the available observational evidences. In 1962, he published the first union catalogue containing the basic parameters of T Tauri stars, namely: 1) Sp from G to M; 2) Hα and Ca H, K emission, 3) Fe I 4063 Å and Fe I 4132 emission (Herbig, 1962). However, even earlier, G. Herbig has defined another class of young stellar objects, which are essentially intermediate analogous of T Tau stars. Later they were named after the author: Ae/Be Herbig stars. The author proposed for them the following characteristics: 1) Sp earlier than F0; 2) emission lines of the Balmer series; 3) connection with nebula. Like in the previous case, one of the main characteristics of these stars is Hα emission. Subsequently, G. Herbig and his coauthors found about 1000 stellar objects with Hα emission in following star forming regions Orion Nebula Cluster, NGC 2264, NGC 1579, NGC 7000, IC 5070, IC 348, IC 2068, Messier 8 and 20, etc. (Reipurth, 2008 and ref. therein).

The studies of stars with Hα emission have always been in the focus of Byurakan observatory. Among the most significant works should be noted the studies in Cygnus, Orion and Taurus star forming regions by E. Parsamyan and her collaborations (Kazaryan & Parsamyan, 1971; Parsamyan, 1981; Parsamyan & Chavira, 1982; Parsamyan & Hojaev, 1985). They not only revealed more than 500 emission stars in Orion Nebula, but also investigated the variability of Hα emission. The data, obtained with 40" Schmidt telescope allowed N. Melikian and A. Karapetyan to reveal and detailed study more than 200 emission stars in NGC 7000, IC 5068, IC 5070, NGC 6910, Cepheus and Cygnus star-forming regions (Melikian & Shevchenko, 1990; Melikian, 1994, Melikian & Karapetyan, 1996, 2010; Melikian et al, 2011; Melikian et al, 2014). In the low-dispersion spectroscopic plates of the First Byurakan Survey K. Gigoyan and A. Mickaelyan with collaborators detected about 1000 Late-Type Stars with Hα emission (Rossi et al., 2011; Gigoyan & Mickaelian, 2012).

Presently, the list of the most studied for that matter star forming regions includes ONC, Taurus-Auriga, Perseus, Cygnus, Chepheus, Monoceros, Gum Nebula, Lagoon Nebula, North America and Pelican Nebulae, Ophiuchi cloud, NGC 2264 and L1228 star-forming regions (Reipurt, 2008 and ref. therein). The search of pre-main sequence (PMS) stars with Hα emission has gone already beyond our Galaxy. Reid & Parker (2012) were able to identify about 600 emission stars in Large Magellanic Clouds combining photometric and spectroscopic observations.

Currently, the large-scale surveys serve as sources for information on the Hα activity of the young stellar population are. The most prominent photometric surveys for search the Hα emission stars are both the IPHAS (Drew et al., 2005) and its southern counterpart VPHAS (Groot et al., 2009). These surveys cover about 10° × 360° square view of the entire Galactic Plane at roughly one arcsec spatial resolution. In total, the present catalogue contains 4853 point sources that exhibit strong photometric evidence for Hα emission. Undoubtedly, a significant contribution to the study of Hα activity of PMS stars has already been invested and will be invested more by the data obtained by Gaia mission. Already by using the sample of 22035 spectra 3765 stars with intrinsic Hα emission have been found and classified by their profile of emission line (Traven et al, 2015).

2. The search of PMS stars with Hα emission by slit-less method

For detection the stellar objects with Hα emission are used both photometric and spectral selections. In the latter case, the most widely have been used an objective prism or slit-less methods.

For our study we used the slit-less method, which has some advantages over the photometry and objective prism, as will be discussed below. It is the combining of the grism working in the 5500-7500 Å range with a dispersion of 1 - 2 Å/pixel with a narrow-band Hα interference filter. In the prime focus of the 2.6-m telescope of BAO with 1800 sec exposure it is possible with high certainty to find emission for the stars with $m_R \leq 21.0$. The limiting of the measuring of EW(Hα) is about 2 Å. For objects with R < 17.0 the measurement errors of EW(Hα) are not more than 30%, for weaker objects errors increase up to 40% of the EW(Hα). On the Fig.1 the example of the image was obtained by slit-less observation in IC 348 young stellar cluster is presented.

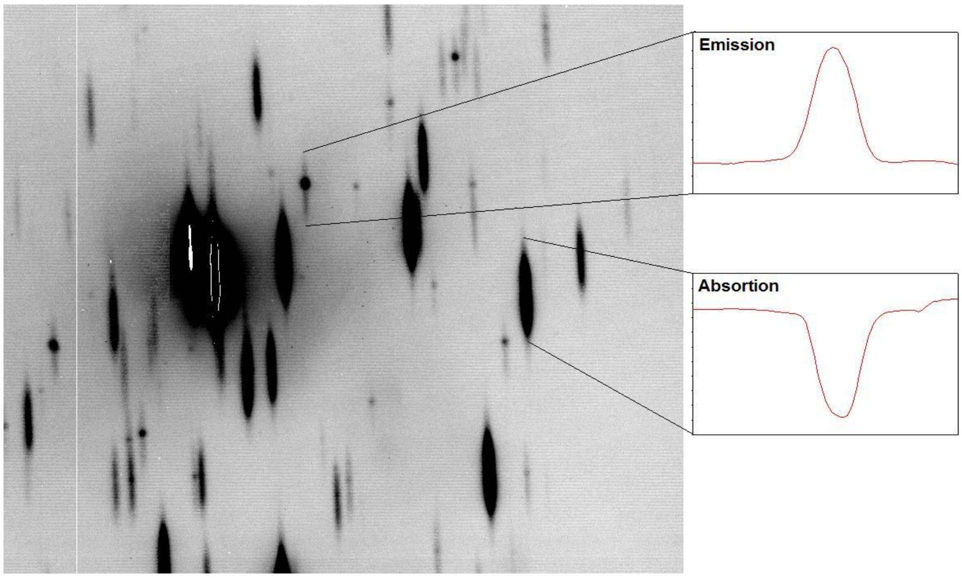

Figure 1. The image was obtained by the slit-less method for IC 348 cluster.

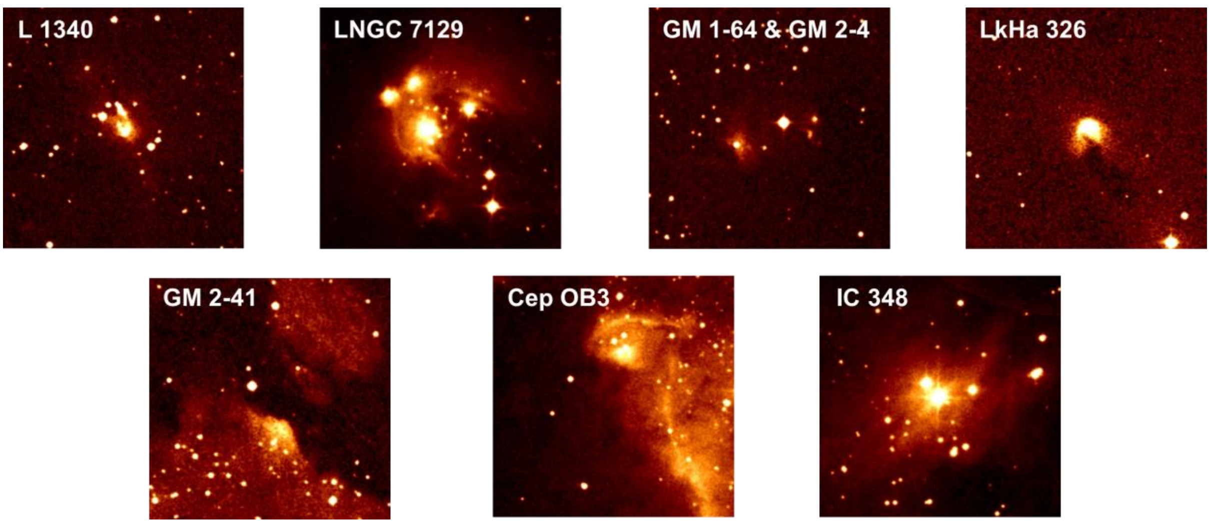

Figure 2. The star formation regions in which young stellar objects with Hα emission were studied.

During the period from 2002 up to 2015 our group published number of papers, presenting the results of the search and study of stars with Hα emissions in several star-forming regions, namely in L 1340 (Magakian et al., 2003), NGC 7129 (Magakian et al., 2004), LkHa 326 (Movsessian et al., 2008), GM 1-64 & GM 2-4 (Nikogossian et al., 2009), GM 2-41 (Nikoghosyan et al., 2012), Cep OB3 (Nikoghosyan, 2013) and IC 348 (Nikoghosyan et al., 2015). Figure 2 shows the images of these star-forming regions. Totally, we revealed about 250 emission stars and 200 of them are new discovered (see Table 1).

Table 1. *The number of revealed stars with Hα emission*

Region	N of revealed objects	N of new discovered
L 1340	14	11
NGC 7129	22	16
LkHα 326	6	5
GM1-64 & GM 2-4	12	12
GM 2-41	43	30
Cep OB3	150	123
IC 348	196	5

As it was mentioned at the beginning, the slit-less method has some advantages. For example, by using objective prism in L 1340 and NGC 7129 on the images with same photometric limit, only 3 (Kun et a.l, 1994) and 4 (Hartigan&Lada, 1985) emission stars were obtained, respectively. In GM 2-41 region by photometric selection were revealed only 14 objects (Vink et al., 2008).

3. Main results

The numerical relationship between CTTau and WTTau objects. As noted above, with respect to EW(Hα) the low-mass young stellar objects are conditionally divided into two main groups at different evolutionary stages: CTTau and WTTau objects, in which Hα is mainly produced as a result of accretion activity and chromospheric solar like flares, respectively. In Table 2 are presented the numerical ration of CTTau and WTTau objects obtained for four star-forming regions, as well as the ages and the distance modules plus interstellar absorption of their parent stellar clusters. For comparison, in the Table 2 the same data of other star-forming regions in which the search of Hα emission stars are carried out with about the same limit by means of both photometry and spectroscopy are given.

We can see, that there is no noticeable dependence between relative number of C and W TTau objects and distance module. This fact indicates a lack of samples selectivity. Therefore, the lack of a correlation between the percentage of objects with different evolution classes and clusters' age reflects the real situation that somewhat unexpectedly.

Moreover, the data analysis of two rich clusters Cep OB3 and IC 348 shows, that there is no noticeable difference between the special distribution of CTTau and WTTau stars according the direction of the star forming wave.

Table 2. *CTTau/WTTau ratio, age and distance module*

Region	CTTau : WTTau	Age (years)	Dist. mod. + A_R
NGC 7129	67% : 33%	$3.0 \cdot 10^6$	11.8
Cyg OB2	83% : 17%	$1.0 \cdot 10^6$	12.8
Cep OB3	34% : 66%	$7.4 \cdot 10^5$	11.0
IC 348	34% : 66%	$2.0 \cdot 10^6$	11.4
For comparison			
L 988 (Herbig & Dahm, 2006)	60% : 40%	$6.0 \cdot 10^5$	10.9
LkHα 101 (Herbig et al., 2004)	60% : 40%	$5.0 \cdot 10^5$	17.2
NGC 2264 (Dahm, 2008)	50% : 50%	$1.1 \cdot 10^6$	11.1
IC 5146 (Herbig & Dahm, 2002)	31% : 69%	$1.0 \cdot 10^6$	12.8

The correlation between Hα emission and other signs of activity. The existence of stellar envelope and disk, stellar wind and bipolar outflow determines the observational evidences of young stellar objects, which cover the wide wavelength range from X-ray to radio. These evidences distinguish young stellar objects from other stellar population. The quantitative ratio of these features changes during the evolution from very young protostars to PMS stars with later Class III evolution stage.

Table 3. *Hα emission and other sings of activity*

Objects	N	X-ray	$\alpha>-1.8$	$-2.56<\alpha<-1.8$	$\alpha<-2.56$	Age (years)
Cep OB3						
CTTau	39	25 (64%)	39 (100%)	-	-	$4.6 \cdot 10^5$
WTTau	75	69 (92%)	24 (32%)	9 (12%)	42 (56%)	$7.1 \cdot 10^5$
Faint cont.	34	12 (38%)	23 (68%)	6 (18%)	5 (14%)	$4.8 \cdot 10^5$
Absorption	57	54 (95%)	5 (9%)	7 (12%)	45 (79%)	$1.6 \cdot 10^6$
IC 348						
CTTau	77	25 (32%)	65 (84%)	8 (10%)	-	$2 \cdot 10^6$
WTTau	138	89 (64%)	29 (21%)	102 (74%)	-	$2 \cdot 10^6$
no em. ($M_\odot<1$)						$2 \cdot 10^6$
no em. ($M_\odot>1$)						$7 \cdot 10^6$

The data in the Table 3 show the quantitative estimation of CTTau and WTTau objects in relation to the other signs of activity of young stars in Cep OB3 and IC 348 clusters. One of these signs is the infrared excess characterized by the slope of the spectral energy distribution (α) in the mid-infrared range, which strongly depends on the evolutionary stage (Lada et al., 2006). The spectral energy distribution (SED), is defined as $\lambda F_\lambda \propto \lambda^\alpha$. The values of α slope, measured over the 3-8 μm IRAC bands range from α < -2.56 for purely photospheric emission (Class III), -2.56 < α < -1.8 for evolved disks (Class II/III), and -1.8 < α < 0 for full disks (Class II). According to the data presented in Table 3, one can see, that there is the correlation between the α slope or infrared excess and Hα activity. The majority of the objects with strong Hα emission, as well as most of the stars of Cep BO3 for which EW(Hα) were not measured because of the weakness of the continuum. These objects have a gently sloping spectral energy distribution in the infrared range, scilicet a high infrared excess, which can be explained by the presence of an optically thick disk and envelope. On the contrary, most of the stars with faint emission or absorption in Cep OB3 region belong to later disk-less evolutionary classes.

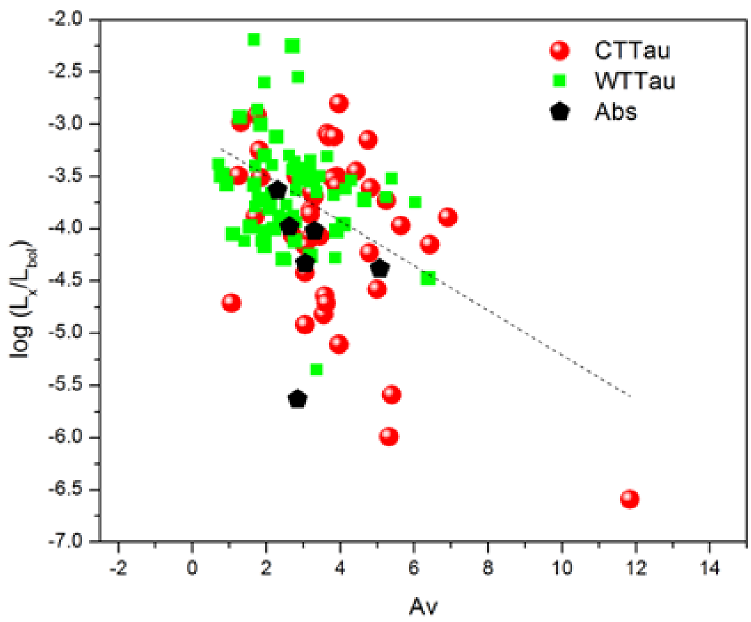

Figure 3. Log(Lx/Lbol) vs. extinction (Av).

The data in Table 3 also show that the percentage of X-ray sources among the WTTau stars is considerably higher than among the CTTau stars. A similar pattern has been observed in other young stellar clusters (Feigelson et al, 2006). One explanation for this relationship the following: X-ray emission in "older" WTTau objects is mainly produced by chromospheric activity, while in CTTau stars it is caused by accretion activity, which assumes the existence of a massive disk. On the other hand, a massive disk can absorb a significant fraction of X-rays. This, rather than an absence of X-ray activity, is probably the reason, why the X-ray emission in a large number of the CTTau stars is below the detection threshold. To test this assumption, the dependence of X-ray luminosity on extinction (Av) for members of IC 348 stellar cluster have been considered. The values of X-ray luminosity were borrowed from Preibisch & Zinnecker (2002) and Stelzer et al. (2012) and the values of Av from Luhman et al. (2003). The diagram Log(Lx/Lbol) versus extinction (Av) (see Fig. 3) clearly shows that there is a well-defined inverse relationship between these two parameters.

The evolutionary age of stellar objects in both regions has been defined by two different ways. First, it was used the isochron model proposed in D'Antona & Mazzitelli (1994) and Baraffe et al. (1998). The evolutionary ages for the Hα emitters were also determined by using the SED fitting tool of Robitaille et al. (2007). In both cases, the estimate of the evolutionary age was only slightly different. However, there is a certain difference between the data obtained for clusters. The median values of the evolutionary ages for different sample of Cep OB3 and IC 348 clusters are presented in Table 3. We can see that in Cep OB3 cluster the evolutionary ages of samples are different. It is increasing with decreasing Hα activity. In IC 348 cluster, on the contrary, the age estimations for CTTau, WTTau and objects with Hα absorption are practically the same.

IC 348. On the example of IC 348 cluster we try to estimate the total percentage of objects with Hα emission in respect to their luminosity. On the Fig. 4 the R luminosity functions for the stellar objects with Hα emission are presented (Nikoghosyan et al., 2015). For the histogram on left panel the visible R magnitudes are used, while on the right panel - corrected for the absorption.

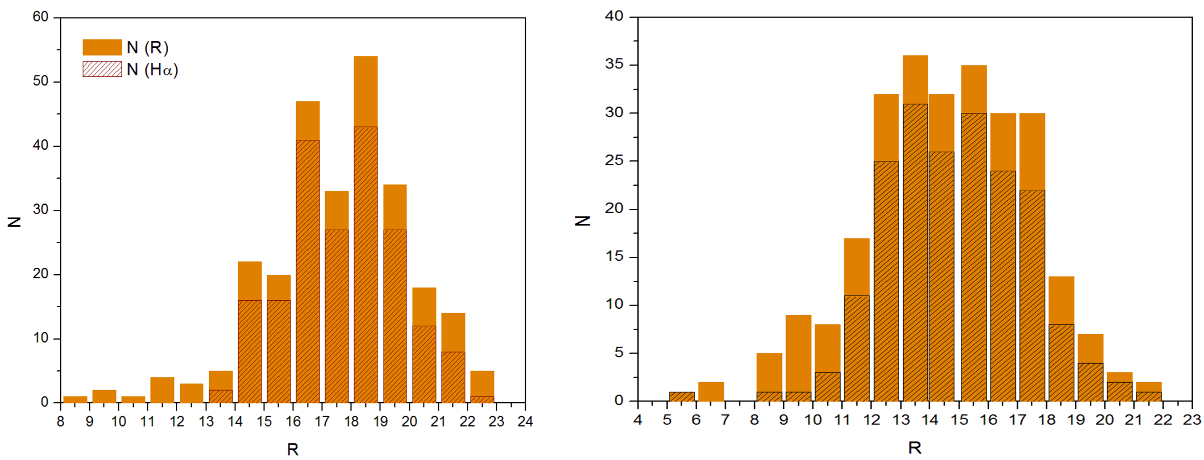

Figure 4. R band luminosity function of IC 348 stellar cluster for visible magnitudes (left panel) and corrected for the absorption (right panel).

The histograms clearly show that the percentage of stars with Hα emission varies, depending on the brightness. On the left panel we can see, that the proportion of emission stars in the range $14.0 \leq R \leq 20.0$ reaches ~80% and remains practically unchanged. Among the bright stars with $R \leq 13.0$ no objects with Hα emission shows up and among faint stars ($R \geq 20.0$) the percentage of emission stars is significant lower. The absorption correction does not significantly change the situation. The range with a relatively constant fraction of emission stars only shifted to the left by one magnitude. In this case, it corresponds to the range of $13.0 \leq R \leq 19.0$.

Apparently, 80% are below of the lower limit of the estimation of the relative number of stars with Hα activity. One possible reason for the lack of Hα emission in the remaining 20% - a variability between low emission and absorption. Taking into account these factors, the percentage of emission stars certainly should raise and approach to 100%. The lower percentage of the emission stars among brighter objects likely reflects the reality. The decrease in the percentage of the emission objects among the fainter stars in the first, of course, can be explained by the incompleteness of the observational data.

Really, the detailed study of the stellar population in IC 348 reveals the significant number of the stellar objects with variable EW(Hα). In total. on the bases of photometric and slit-less multi-epochs observations, was found that 90 out of 127 examined stellar objects show a significant variability of EW(Hα). We also identified 20 stars, which show not only a significant variability of the equivalent width, but also change the evolutionary stage (CTTau ⇔ WTTau). For 6 stars the Hα line was observed both in emission and in absorption. It should also be noted that our studies have also shown that the masses of CTTau and WTTau variable objects are significantly higher than of non-variable ones. Moreover CTTau variables have the higher mass accretion than the non-variable ones.

4. Summary

As a conclusion, we want to mention some unclear issues. If value of Hα activity, i.e. EW(Hα), represent the evolution stage of PMS objects, why:

- There is no noticeable dependence between the relative content of CTTau and WTTau stars and cluster's age.
- They are distributed evenly in cluster relative to the direction of the star formation wave.
- There is no distinct difference in location of CTTau and WTTau stars according the evolution tracks.

Undoubtedly, future research will help clarify these issues, which, in turn, are closely related to the formation and evolution of young star clusters in general.

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