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POST-T TAURI STARS IN GALACTIC CLUSTERS

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ABSTRACT. There is a number of theoretical and observational reasons to support a view of star formation and evolution as a continuous process which covers a rather long period of time. On the other hand, it can be stressed that some particular evolutionary stages are confined to relatively short lengths of time. On a purely observational basis, it seems quite evident that the typical and most "advanced" T Tauri phenomenon in a given star -and consequently its extreme spectroscopic and photometric characteristics- manifest itself during an extremely short period of time in relation to the whole evolutionary process for intermediate and late type stars. Without doubt the extreme or "advanced" features of a T Tauri object tend to diminish in periods of only -in most cases- a few million years. However, a considerably longer time is required for the process of weakening or apparent total disappearance of the most persistent T Tauri features. Nevertheless, among other problems, there emerges one of fundamental importance: can we arrive to an acceptable definition of a *bona fide* T Tauri star?

In the present work we repeat our attempt to define what can characterize an "advanced" T Tauri-type star or the minimum spectroscopic and photometric features required to classify a young star within the family that unmistakably includes all typical T Tauri objects.

At the same time, and following the trends of modern astronomy, we try to demonstrate that certain T Tauri-type stars evolve, during different periods of time and that, although they lose mass and their most conspicuous spectroscopic characteristics, they can still be described as what Herbig calls "post-T Tauri" stars, keeping some remnants of their primitive spectroscopic and photometric features.

Several years ago, we stressed that in the great majority of T Tauri stars it seems that the time required for the diminishing or even apparent disappearance of the last typical T Tauri vestiges depends on the mass or on the observable spectral type and luminosity: the earlier the spectral type, the shorter the vanishing effect. Therefore, if we look for weakened T Tauri features in stellar aggregates of various ages from which the typical and extreme T Tauri stars have already disappeared, we find that the older the aggregate, the later the spectral type in which the last prominent features are detectable.

Everything seems to suggest that it is within these possible evolved T Tauri objects that we can find the so-called post-T Tauri stars, and that a good number of flare stars detected in galactic clusters are among them. These clusters are: the Orion stellar aggregate, NGC 2264, the Pleiades, and possibly the flare stars in stellar aggregates of ages equal or superior to 10^8 years.

As I have in the past, I would like to place special emphasis on the genetic relationship between certain flare stars and their T Tauri ancestors, based not only on the very rapid outbursts of the former but also, and primarily, on the fact that these flare stars show spectroscopic characteristics reminiscent of the T Tauri original stars. In other words, the simple fact that a star presents the "flare" phenomenon does not constitute necessary and sufficient proof that it should be regarded as an evolutionary product of a T Tauri star: in addition to the flare-up the spectral types of the investigated objects must present -during maximum and minimum light- clear and reminiscent spectroscopic evidences of the original T Tauri objects; that is, spectral types as late or later than G and some emission lines, at least in H and CaII. There are some flare stars in Orion and NGC 2264 which, even during minimum light, can be classified spectroscopically as typical T Tauri stars. In the case of the Pleiades, where undoubtedly there are no T Tauri stars, many of the flare stars show spectral emission lines (H and CaII) of great intensity during maximum and of detectable intensity in slit spectrograms of not high dispersion, during minimum light. Furthermore, in the few cases in which some Pleiades flare stars have been observed on slit spectrograms of intermediate dispersion, the lithium (λ 6707) absorption line appears in the red region, indicating a superabundance with respect to the Hyades stars.

I. THE T TAURI STARS

If we want to discuss and define the post-T Tauri stars and related flare stars in clusters or associations, it seems to me quite necessary to insist in the general spectroscopic and photometric characteristics of the typical T Tauri objects.

In some respects -but only apparently- in order to define what we could accept as a *bona fide* T Tauri star, the problem can be solved according to Herbig criterion: "The unambiguous assignment of this type of stars is entirely a spectroscopic matter". Here again, we need to define within what kind of spectroscopic features we can safely accept a star as belonging to the T Tauri class. We can start with the so-called "advanced" T Tauri stars in which the spectrum is crowded with strong emission lines of low excitation and in many instances the stellar absorption lines cannot be noticed due to a strong blue continuous veiling. Therefore, in such cases the spectral types are difficult to determine. From the very beginning of the study of the T Tauri class, Professor Alfred H. Joy (1945) indicated that although the well known variable T Tauri itself is one of the brightest stars of the group and may probably be considered as the prototype, there are marked differences among the stars of the group and not two are exactly alike.

Anyway, we can repeat and try to define roughly some of the physical characteristics which are sufficiently different from other classes of variable stars, to recognize most of the stellar objects whose prototype is T Tau. According to Joy and other younger investigators, the distinctive characteristics are: 1) irregular light variations of more than one magnitude; 2) spectral types from late F to M4 or M5 with emission lines resembling the solar chromosphere; 3) medium to low luminosities; and 4) association, in most of the cases, with dark or bright nebulosity. Emission of H lines is found in all the stars of the group and also the bright CaII lines. The strongest emission lines are those of CaII, H, FeII, CaI, SrII, FeI, TiII, and some others. The general level of excitation (Herbig 1958) in the emission spectrum is never high although HeI can be present and weak HeII has been reported. According to Joy, the bright line λ4068.62 [S II] is remarkably persistent in the sample of stars with conspicuous emission spectra which he observed and published in his outstanding pioneering work in the year 1945. The change in intensity of this forbidden sulphur line does not appear to be correlated with the variation of the other bright lines, and Joy said that at times λ4068 remains practically undiminished when most of the metallic lines have disappeared. It is convenient to remember that the slit spectrograms used by Joy were taken with the 60- and 100-inch Mount Wilson telescope and the spectral dispersion were, at Hγ, from 75 Å/mm up to 220 Å/mm and only in one instance of 35 Å/mm.

Many of us have been inspired by Professor Joy and have followed his wise advices in many respects. I feel that we have the duty to pay him a recognition and enthusiastic tribute.

Many theoretical and observational works have been accomplished after Joy by different investigators, and I just would like to place a special emphasis in the detection of the red absorption lithium lines at λ6707 in T Tauri objects and the interpretation about the superabundance of lithium as an indicator of age. Apart from that, Haro and Herbig (1955), and soon afterwards Walker

(1956), found that among the T Tauri stars in the Orion Nebula and NGC 2264 are a number of stars that are extremely bright in the ultraviolet. The brightest-ultraviolet stars found originally by Haro and Herbig were: HS Ori, VY Ori, CE Ori, AU Ori, LHα No. 7 (in NGC 2264), and LHα 11, 14, 22, and 81. At that time (1955), YY Ori appeared with relatively medium or not excessive ultraviolet strong continuum and practically without conspicuous bright lines. The Lick spectrograms (430 Å/mm) showed that the distribution of energy in the continuous spectra does not resemble that of a normal star: longward of λ3800 the distribution seems much more like that of a late-type dwarf although no absorption lines could be seen. Shortward of about λ3750, however, the continuum rises, very conspicuously, with respect to that of a late-type star by an amount that was apparent even to casual inspection. It is proper to mention that the phenomenon of strong extension of the continuous spectrum into the ultraviolet has been noticed by Joy (1949) and Struve and Swings (1948) in the T Tauri star DD Tauri, although perhaps not in the extreme form that Haro and Herbig found in some of the Orion Nebula and NGC 2264 T Tauri stars.

In Walker's study of extremely young clusters (1972), he described some of the ultraviolet excess stars in the Orion Nebula aggregate and in NGC 2264. He postulated that the T Tauri stars have 0.2 - 0.5 $M_\odot$ and radii of 2 - 6 $R_\odot$, and indicated that infall of material is occurring: the rate of infall is variable and amounts to $\lesssim 10^{-6}$ $M_\odot$ per year. He presented YY Ori as a prototype of this kind of T Tauri stars and pointed out the absence of forbidden lines from the 25 ultraviolet-excess stars in Orion and in NGC 2264 which he observed. He obtained spectrograms of 48 Å per millimeter. (It can be pertinent to mention that Bertout, Carrasco, Mundt and Wolf (1982) observed two of the so-called YY Orionis stars: S Cr A and CoD - 35°10525 and with spectral dispersion of 20 Å/mm, and they detected a quite weak emission [S II] at λ4068 and found rapid variations in the ultraviolet part of the spectrum correlated with changes in the appearance of the line spectrum).

It is important to stress that Walker (1972) introduced the YY Orionis star as a subclass of the T Tauri group, based not only on the variable ultraviolet-excess but in the redward displaced absorption component at the edge of the Balmer emission lines (the inverse P Cygni shift).

If we talk about "advanced" T Tauri stars, we are suggesting implicitly and explicitly that there are T Tauri stars which are "not advanced". An obvious question arises: What would be the "intermediate" and "minimum" spectroscopic and photometric properties of a star so that it might be accepted unanimously as belonging to the T Tauri class? Here is where the problem starts being complicated. I would dare to propose that the "intermediate" and "minimum" characteristics would need to be determined quite empirically: for instance the stars which would show diminished intensity in the most prominent T Tauri features, if they are observed, let us say, with slit spectrograms with a dispersion of 430 Å/mm.

For the faint or very faint (Orion and NGC 2264 stars), it would be safe to say that the stars showing in an objective prism a strong Hα emission line, a moderate to very strong ultraviolet color, being U-B and U-V negative, and are variable stars, can be accepted as "advanced" T Tauri stars provided that they are of spectral types corresponding to late F or as late as M's

(Haro 1976).

From the well accepted T Tauri stars, it seems observationally inevitable to point out that there could be several T Tauri sub-classes. For instance:

1) T Tauri stars in which the hydrogen and calcium emission lines are strong and some of the iron lines and HeI are in emission together with the presence of bright [S II] and [O I] lines. In many cases a blue continuous veiling masks the absorption lines. In this type of "advanced" T Tauri stars, although there might exist ultraviolet excess, the $U-B$ and $U-V$ colors are always positive. Good examples of this type of stars are: XZ Tau, T Tau itself, HL Tau, CW Tau, etc.

2) The emission spectrum is characteristic although the presence of forbidden lines is not always certain. In this second type of "advanced" T Tauri objects, the main difference in relation to the first type is the very strong excess, the $U-B$ color is highly negative and in some extreme instances the $U-V$ color is also negative. Good examples of this second type of "advanced" T Tauri stars are: FM Tau, HS Ori, VY Ori, NX Mon, AU Ori, CE Ori, etc. In some instances we could include YY Ori (Haro 1976).

With respect to what I have called the first sub-type of "advanced" T Tauri stars, in some instances the star is associated with Herbig-Haro emission nebulae (T Tau, HL Tau, XZ Tau). It seems that none of the stars related to the Herbig-Haro nebulae have negative $U-B$ color or not, of course, the extreme negative $U-V$.

It is of special interest to stress the fact that neither Rydgren *et al.* (1975) nor Walker (1972) detected the [S II] and [O I] emission lines in the stars with "very strong" blue veiling or ultraviolet color.

For me it is not easy to understand why Walker, considering the occurrence of the inverse P Cygni effect observed by him in the so-called YY Ori-type stars, reached the conclusion that these particular stars are younger than the other "advanced" T Tauri objects just because he believes that in the YY Ori-type stars accretion of the remains of a pre-stellar cloud still occurs in contrast with the T Tauri stars in which ejection of material is observed. I believe that from the observational point of view it might be easier to accept that ejection of stellar material characterizes the most "advanced" and possible youngest T Tauri stars, even if the results of the observations do not fit well within the gravitational contraction models of star formation.

I clearly realize that when proposing the possible existence of different sub-classes of "advanced" T Tauri-type stars, I am presenting an oversimplified classification, that in practice does not correspond to the very complex different types of "advanced" or "non advanced" T Tauri stars. In some instances it would be rather difficult to assign a given T Tauri star to a single sequence-type because it could happen that, at times, spectroscopically and photometrically it represents a mixture of two or more different sub-types which I have tried to define. We need to recognize that our knowledge of the real nature of T Tauri stars is very limited and that we are not even certain within which ranges of masses the T Tauri stars are comprised.

II. FLARE STARS AND THE PTTS

Among the flare stars found in the Orion aggregate (several hundreds) a certain percentage, about 30%, can be classified at the same time as belonging to the T Tauri type, representing some kind of a real parallel continuum, and forcing us to establish a genetical relation between the *bona fide* T Tauri stars and the Orion flare stars in general. The spectral types of these Orion flare stars go from Ge (Herbig 1962) up to M2-3 (Blanco 1963). Good examples of the Orion T Tauri stars, which at the same time are flare stars, are among others: YY Ori, NS Ori, SU Ori, IZ Ori, YZ Ori, BW Ori, SW Ori, etc., etc.

Apart from the Orion flare stars that at the same time can be classified as typical T Tauri stars there are the majority of the other flare stars that obviously do not fall within our T Tauri spectroscopic classification. Now the problem would be to decide if the late type irregular variables in Orion are just coinciding in the same volume of space with the Orion typical T Tauri stars or are genetically related and represent a more evolved stage. If this is so, it is not difficult to predict that obtaining slit spectrograms of dispersion as high or higher than 200 Å/mm, in most cases, we would be able to detect some of the spectroscopic emission lines remnants of the T Tauri origin. At the same time it seems that the infrared photometry (see for instance Mendoza 1966, 1968), would help to establish some additional evidences.

In NGC 2264 we found a similar situation to that of the Orion Nebula region. The concentration of the flare stars found in a small area and the fact that two of the flare stars (LHα 67 and 69) were previously classified by Herbig (1954) as T Tauri stars indicate that they belong to the same stellar aggregate. The earliest spectra type among these flare stars, according to Herbig (1959) is K0.

Regarding the Pleiades flare stars, it is not possible to draw a direct connection between the T Tauri stars and the flare stars as is the case in Orion and NGC 2264 associations. But here we have important and very significant information:

1) Undoubtedly the Pleiades cluster is older than the Orion and NGC 2264 aggregates in such a scale that we cannot expect to find T Tauri stars.

2) Anyway, in the Pleiades there exist clouds of interstellar matter easily detected as reflection nebulae and some of the flare stars members of the group show emission lines of H and CaII if observed with dispersions as high or higher than 300 Å/mm (Kraft and Greenstein 1969; McCarthy 1969).

3) The flare stars observed in the infrared (Iriarte 1969; Zappala 1974) show excesses that are not due to simple reddening.

4) Stauffer (1980) on his photometric results on the *BVRI* shows a pre-main sequence at about $M_V = +9\overset{m}{.}4$ (nuclear age of the Pleiades derived from high-mass

stars in the cluster, TN = 7×10^7 years. The so-called contraction age of the cluster TK = 2.2×10^8 years).

Most of the stars observed by Stauffer are flare stars and the spectral types go from dM0 up to dM3 (distance modulus m-M = $5^m.54$). Later on (1982), Stauffer states that the supposed pre-main sequence in the Pleiades appears likely to be composed of binaries rather than of pre-main sequence stars. Stauffer has also detected Hα emission in many of the Pleiades flare stars observed by him and he indicates that the bright Hα is found to increase in strength with increasing spectral types.

5) Apart from the emission corresponding to the Balmer series and the CaII lines, H and K, none of the emission lines found in the typical T Tauri stars has been observed in the Pleiades stars (Cohen and Kuhi 1979).

6) According to Mundt and Bastian (1981), using medium resolution blue and red spectrograms (30 Å/mm in the blue and 60 Å/mm in the red), the Pleiades flare stars H II 134, 1173 and 1321 show the Balmer lines and the Ca II H and K lines in emission and they emphasize that the broad emission lines observed for H II 134 may be a relic of its T Tauri phase. They also indicate a conservative apparent limit for Li I λ6707 abundance:

TABLE 1. Number of Observed Flare-ups

H II 134	9	from Δm 0.8 up to 4.0 magnitudes
H II 1173	5	from Δm 0.7U up to 2.7U
H II 1321	8	from Δm 1.0U up to 2.2U

7) Zappala (1972) reports that the Pleiades G and K stars appear to be genuinely overabundant in lithium λ6707 with respect to the Hyades, and he includes in his list the flare star H II 1100, spectral type K3, which has shown two different flare-ups observed with ΔmU = 0.7 to 1.3.

Herbig (1978) proposed that the PTTS can be identified by the possession of an appropriate intermediate value of the following characteristics (arranged approximately in order of lengthening decay time):

a) Hα emission
b) Irregular variability
c) Infrared excess
d) CaII emission
e) Surface lithium abundance.

I believe that some of the data presented satisfy Dr. Herbig's claims, but I want to stress that some of his spectroscopic evidences can only be obtained using medium or high resolution in blue and red spectrograms and not through an objective-prism survey. I really believe that most proper and natural areas for looking for the PTTS are not, in general, the regions of heavy obscuration but in the regions which are characterized by the existence of T Tauri associations or in clusters as the Pleiades or perhaps in much older groups such as the Hyades, Praesepe, etc., or even in some of the individual dMe flare stars. It seems that in the great majority of the post-T Tauri stars the time required for the diminishing or disappearance of the typical T Tauri vestiges depends on the mass and luminosity of the original object or on the observable spectral type: the earlier the spectral type and/or the greater the mass, the more rapid the vanishing effect; the later the spectral type and the smaller the mass, the longer the lapse during which the T Tauri spectroscopic remnants will perdure and at the same time the flare phenomenon, apparently, will tend to increase. Therefore, if we look for weakened T Tauri features in aggregates of different ages but in which the post-T Tauri characteristics still can be observed, we will find that the older the aggregate, the later the spectral type in which we would detect the last T Tauri relics (Haro 1976).

REFERENCES

Bertout, C., Carrasco, L., Mundt, R., and Wolf, B. 1982, *Astr. and Ap. Suppl.*, 47, 419.
Blanco, V. 1963, *Ap. J.*, 137, 513.
Cohen, M. and Kuhi, L.V. 1979, *Ap. J. Suppl.*, 41, 743.
Haro, G. 1976, *Bol. Inst. Tonantzintla*, 2, No. 1, pag. 3.
Haro, G. and Herbig, G.H. 1955, *Bol. Obs. Tonantzintla y Tacubaya*, Vol.2, No. 12, 33.
Herbig, G.H. 1954, *Ap. J.*, 119, 483.
Herbig, G.H. 1958, *Etoiles A Raies D'Emission Extrait des Memoires in 8°de la Societe Royal des Sciences de Liège, TOME XX*, (Belgique: Institut D'Astrophysique Cointe-Sclessin), p. 251.
Herbig, G.H. 1959, private communication.
Herbig, G.H. 1962, *Advances in Astronomy and Astrophysics*, ed. Z. Kopal (Academic Press), 1, 47.
Herbig, G.H. 1978, *Problems of Physics and Evolution of the Universe*, ed. L.V. Mirzoyan (Yerevan: Publishing House of the Armenian Academy of Sciences).
Iriarte, B. 1969, *Bol. Obs. Tonantzintla y Tacubaya*, Vol. 5, No. 32, 89.
Joy, A.H. 1945, *Ap. J.*, 102, 168.
Joy, A.H. 1949, *Ap. J.*, 110, 424.
Kraft, R.P. and Greenstein, J.L. 1969, *Low-luminosity Stars*, ed. Shiv. S. Kumar (Gordon and Breach Science Publishers), p. 65.
McCarthy, M.F. 1969, *Low-luminosity Stars*, ed. Shiv. S. Kumar (Gordon and Breach Science Publishers), p. 83.
Mendoza, E.E. 1966, *Ap. J.*, 143, 1010.
Mendoza, E.E. 1968, *Ap. J.*, 151, 977.
Mundt, R. and Bastian, U. 1981, *Pub. A.S.P.*, 93, No. 555, p. 601.
Rydgren, A.E., Strom, S.E., and Strom, K.M. 1975, *Ap. J. Suppl. Ser.*, 30, 307.
Stauffer, J.R. 1980, *A.J.*, 85, 1341.
Stauffer, J.R. 1982, *A.J.*, 87, 1507.
Struve, O. and Swings, P. 1948, *Pub. A.S.P.*, 60, 61.
Walker, M.F. 1956, *Ap. J. Suppl.*, 2, 365.
Walker, M.F. 1972, *Ap. J.*, 175, 89.
Zappala, R.R. 1972, *Ap. J.*, 172,57.
Zappala, R.R. 1974, (pre-print), *Annual Report of the Director*, Hale Observatories 1972-1973, p. 110.

DISCUSSION

Ambartsumian: Pleiades are not pre-main-sequence stars, in my opinion. The problem is, how far they deviate from the main-sequence band in the color-magnitude HR diagram.

Stauffer: *(Comment)* In response to Dr. Ambartsumian's comment relative to the location of Pleiades stars in the HR diagram, the simplest statement is that there are Pleiades stars within 0.2 mag. of the main-sequence to V = 17.5 mag which differs greatly from any of the theoretical predictions for an age corresponding to the nuclear age at a cluster.

Jones: *(Comment)* Li abundance determinations of stars in the Pleiades show an increasing dispersion as one goes to later types. Naively interpreted this implies an age spread of 3×10^8 years.

Giampapa: *(Comment)* I have a comment concerning ages based on Li 6707 A line strength. I have observed significant changes in 6707 strength in various active regions (plage and spots) on the Sun. Given the thermal inhomogeneities that exist on the surfaces of other chromospherically active stars, one must be very careful when attempting to infer ages from this temperature sensitive line.

S. Strom: Can anybody comment in detail on decay emission problems in T Tauri stars?

Herbig: (*Comment*) With respect to the question whether observational evidence exists for decay of T Tauri characteristics with time: if T Tauri emission lines fluxes are to be connected with those for the same lines in main sequence stars, then one notes the following: a) Hα line emission is almost unknown in single main sequence stars of any age and b) CaII emission is much weaker in main sequence stars than in T Tauris, and on the main sequence seems to decay with age (a la Skumanich). These are the reasons for believing that old pre-main sequence stars should be identifiable by having weaks or indetectable Hα, but still strong H and K CaII emission. Do such stars exist? Feigelson and Kriss, and Walter and Kuhi have found 5 stars in the Taurus clouds, detected from their X-ray emission, which look just like this specification.

Herbig: Are there many other such stars in Taurus? Last month, I conducted a survey (at Kitt Peak with the Burrell Schmidt and an interference filter that isolated the λ3950 region) for stars that were missed in the Hα surveys of the Taurus clouds, yet have strong CaII emission. About 50 of the already-known T Tauris were discovered, but in addition about 20 other stars having H, K bright. Also detected were 3 of the 4 X-rays stars. So such stars do exist. To the limit of this survey, there are about half as many of them as there are T Tauri stars. Detailed study of these stars will begin in the next observing season.

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