THE FREQUENCY OF YY ORIONIS OBJECTS AMONG THE T TAURI STARS*

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Summary: A list of 24 T Tauri stars belonging to the YY Orionis subclass is presented. From a statistical analysis it is estimated that at least 75% (and possibly all) UV-excess T Tauri stars are YY Orionis stars. Since about 50% of all known T Tauri stars show a strong UV-excess, the percentage of YY Orionis stars among the T Tauri stars is estimated to be 40 - 50%. This relative high percentage is in good agreement with the present theory of the formation and early evolution of low mass stars.

I. Introduction

As pointed out by Walker (1972) and others, the YY Orionis variables are very likely low mass protostars in their final hydrodynamic evolutionary phases. Thus, a study of these objects should provide valuable information on the formation and early evolution of low mass stars. For a detailed comparison with the theory high dispersion spectroscopic observations of these objects would obviously be particularly useful. Unfortunately, the YY Orionis stars in Walker's (1972) original list are all relatively faint and therefore difficult to observe spectroscopically at high dispersion. Therefore, at Heidelberg we started a search for additional (and possibly brighter) objects of this type. One of the unexpected preliminary results of this search is a strong indication that YY Orionis stars are considerably more frequent than has been assumed so far. A list of all objects of this type which are presently (September 1977) known is given in Table 1. The table also lists the mean visual magnitude, the mean U-B color and the location of stars. In addition, in the last column for each star references to the identification as a YY Orionis object are given. The total number of stars in Table 1 is 24. This is surprisingly high in view of the fact that only a small minority of the T Tauri stars has ever been observed with sufficient spectral resolution to detect the red-

*Based in part on observations collected at the European Southern Observatory, Chile and at the Observatoire de Haute Provence, France.

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Table 1: List of the known YY Orionis Stars.

Star	V	U-B	Location	References
UZ Tau f	12.88	-0.18	Tau-Aur	9
DL Tau	13.42	-0.39	Tau-Aur	9
CI Tau	13.05	-0.06	Tau-Aur	9
DM Tau	13.93	-0.34	Tau-Aur	2, 9
DR Tau	13.38	0.00	Tau-Aur	5
SU Ori	14.50	--	Orion Neb.	1
XX Ori	14.87	-0.38	Orion Neb.	1
YY Ori	13.55	-0.39	Orion Neb.	1
SY Ori	13.70	--	Orion Neb.	1
BO Ori	14.02	+0.70	Orion Neb.	1
CE Ori	14.60	--	Orion Neb.	1
NS Ori	14.20	--	Orion Neb.	1
LX Mon	14.96	-0.61	NGC 2264	1
MM Mon	14.14	-0.01	NGC 2264	1
MO Mon	13.54	-0.16	NGC 2264	1
TW Cha	13.43	-0.19	Cha T Ass.	3
VW Cha	12.64	-0.13	Cha T Ass.	3
VZ Cha	13.23	-0.48	Cha T Ass.	3
WZ Cha	15.48	-1.02	Cha T Ass.	3
LkH$_\alpha$ 450-6	13.68	-0.42	Lup T Ass.	8
CD -35^o 10525	11.62	-0.06	Lup T Ass.	7
EX Lup	13.63	0.00	Lup T Ass.	6, 8
Haro 1-1	13.34	-0.06	B 42	3
S CrA	11.49	-0.16	CrA T Ass.	4

References to Table 1:

1: Walker, M.F. 1972, Ap.J. 175, 89
2: Rydgren, A.E., Strom, S.E., Strom, K.M. 1976, Ap.J.Suppl.30, 307
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6: Herbig, G.H. 1950, Publ.A.S.P. 62, 211
7: Appenzeller, I., Mundt, R., Wolf, B. 1977 (preprint)
8 Mundt, R., Wolf, B. 1977 (private communication)
9: This paper

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ward displaced absorption components of the Balmer emission lines from which the YY Orionis stars are classified.
With one exception (BO Ori) all stars in Table 1 show a U-B color index $\langle U-B \rangle \lesssim 0.00$. Thus, as pointed out already by Walker (1972), there is obviously a strong correlation between the presence of YY Orionis line profiles and a strong UV-excess.

II. The Frequency of YY Orionis Stars among the UV-Excess T Tau Stars

A rough quantitative estimate of the strength of the correlation between the UV-excess and the presence of YY Orionis line profiles in the spectra of T Tauri stars can be derived from the following observational results: Up till now we studied at Heidelberg the spectra of 23 strong UV-excess (U-B $\lesssim$0.00) T Tauri stars. Of these 23 objects 14 stars (or 61%) showed (on at least one spectrogram) definitely the inverse P Cygni profiles characteristic of the YY Orionis stars. In six cases (26%) we did not find conspicuous redward displaced absorption components but other evidence for the YY Orionis character of the spectra (like asymmetric emission lines with blue shifted peaks which are sometimes observed in known YY Orionis stars when the redward displaced absorption components are weak or unresolved). Thus, these six stars should also be regarded as possible or likely members of the YY Orionis class. Only in three cases (13%) we found definitely no evidence for YY Orionis profiles.

If we add the six stars which we regard as "possible or likely" members of the YY Orionis class with half weight to the percentage of the identified YY Orionis stars, we find that about 75% of our small sample of UV-excess T Tauri stars should be classified as YY Orionis stars from the available spectrograms. However, since (as noted already by Walker) the redward displaced absorption components are variable and not always visible, we can not rule out that those stars in our sample for which we found no evidence for inverse P Cygni profiles will turn out to be YY Orionis stars as well if further spectrograms are obtained. Thus, the 75% derived above are probably only a lower limit of the percentage of the YY Orionis stars among the (strong) UV-excess T Tauri stars.

In principle a correction to the percentage derived above could be applied if the probability to observe the inverse P Cygni profile of a known YY Orionis star on a randomly selected night would be

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known. Unfortunately our data are not complete enough to estimate this probability. However, it seems rather clear from our results, that this probability depends on the individual star and is highly different for different YY Orionis objects. In the case of the bright YY Orionis star S CrA we found e.g. that on spectrograms (of sufficient quality) taken on 25 nights between 1942 and 1977 inverse P Cygni profiles were clearly visible on 23 nights (or 92%) and absent on only two nights. On the other hand, in the case of the UV-excess T Tau star AS 209 we found from observations on 9 different nights (all in Spring and Summer 1977) only on two nights (22%) weak evidence for inverse P Cygni profiles. (None of these spectrograms was conclusive enough to include AS 209 in Table 1).

III. The Percentage of UV-excess T Tauri Stars.

Herbig and Rao (1972) list in their catalogue (among other Orion poulation objects) 161 T Tauri stars. For 65 of these objects UBV data are available. Of these 65 T Tauri stars with known UBV data 34 (or 52%) have a mean U-B color index $\langle U-B \rangle > 0.00$, 31 stars (or 48%) have $\langle U-B \rangle \leq 0.00$. Thus, (assuming that there is no selection effect in these data) the values listed in the Herbig and Rao catalogue indicate that roughly 50% of the T Tauri stars are strong UV-excess ($U-B \leq 0.00$) objects. If we combine this result with the percentage of YY Orionis stars among the sample of UV-excess T Tauri stars described in Section II of this paper, we find that probably <u>about 40 - 50% of all T Tauri stars belong to the YY Orionis subclass</u>.

IV. Discussion

The observed relatively high percentage of YY Orionis stars (i.e. protostars in their final stages of their hydrodynamic collapse) is not unexpected since (as pointed out by various authors) the YY Orionis stage of protostellar evolution is relatively slow, the protostars are relatively bright (bolometrically) at this stage, and the probability to detect a star (or rather a protostar) at this evolutionary stage is therefore fairly high (c.f. Figure 1). (As shown e.g. by Fig. 1, the protostar theory and the observed properties of YY Orionis stars are generally in very good agreement). According to Walker (1972) most non-UV-excess T Tauri stars

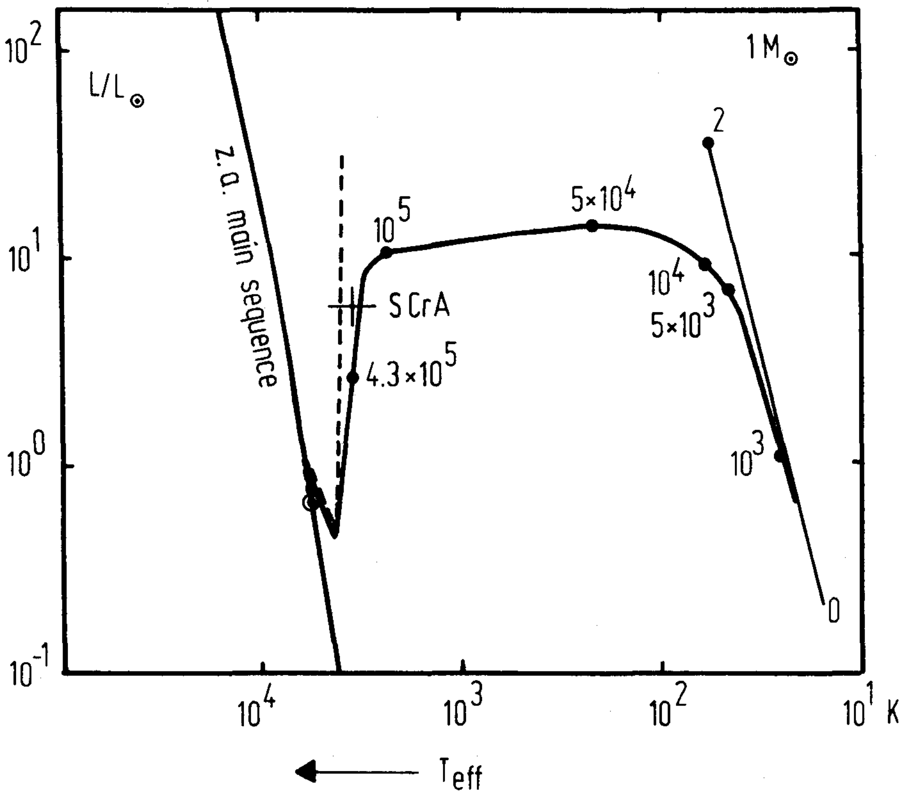

Fig. 1: The location of the YY Orionis star S CrA in the HR diagram. For comparison the evolutionary track of a 1 $M_⊙$ protostar (Appenzeller and Tscharnuter 1975), the zero age main sequence, and the (hypothetical) 1 $M_⊙$ purely hydrostatic evolutionary track (broken line) are also included. The numbers on the evolutionary track indicate the evolutionary age (i.e. the time since the formation of the hydrostatic core) of the protostar. Note that S CrA is slightly more massive (~ 1.7 $M_⊙$) and therefore above the 1 $M_⊙$ track. The values of L and T_e of S CrA have been taken from the analysis of Appenzeller and Wolf (1977) and Wolf et al. (1977) where T_e was determined from the surface radius as derived from the maximum infall velocity observed in the line profiles. (In the absence of model computations for the complex atmospheres of protostars T_e can and should not be determined directly from the observed line spectrum).

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are probably "old" protostars (or pre-main-sequence stars) where the mass accretion has become negligible or has been reversed by radiation pressure effects (c.f. Wolf et al. 1977) or stellar winds. In the HR-diagram (Fig. 1) these older objects should be found in the low luminosity part of the evolutionary track where the hydrodynamic and hydrostatic tracks merge. Unfortunately, for most T Tau stars neither the bolometric luminosity nor T_e is well enough known for a quantitative comparison.

At least some YY Orionis stars (like at least some normal T Tauri stars) lose mass from the outermost layers of their envelopes (see again Wolf et al. 1977). As pointed out elsewhere, the simultaneous mass loss (from the outermost layers) and mass accretion (from the inner envelope layers) seems to be a natural consequence of realistic protostar models. On the other hand, there are objects which have been classified as T Tauri stars and which show conclusive evidence for strong mass loss from the inner envelope layers. At present, two objects of this type seem to be known (AS 353 and V 1331 Cyg = Lk H_α 120), although (as I learned during this meeting) one of them (Lk H_α 120) may not be a T Tauri star but should rather be classified as a Herbig Ae object (c.f. Andrillat and Swings, 1977). In any case, these high mass loss T Tauri stars seem to be relatively rare ($<$ 2% of all T Tauri stars), much more luminous, and certainly more massive objects than the ordinary T Tauri stars. A comparison with published model computations of massive protostars suggests that these objects (and the probably related Herbig Ae and Be stars) have hydrogen burning cores and are presently ejecting their envelopes by radiation pressure as predicted by the theory (Larson and Starrfield 1971, Appenzeller and Tscharnuter 1974, Yorke and Krügel, 1977).

In conclusion I would like to emphasize once more that, provided the observed objects are identified properly, all available observations of YY Orionis and T Tauri stars are in good agreement with the present theory of the formation and early evolution of low mass stars as outlined e.g. by Larson (1969).

Acknowledgements:

Part of the spectrograms unsed for this paper were obtained at the European Southern Observatory and at the Observatoire de Haute Provence. I wish to thank both institutions for observing time. Some of the YY Orionis stars listed in Table 1 were identified or reidentified from plates taken by A.H. Joy between 1941 and 1946 at the Mt.Wilson Observatory. I wish to thank Professor Guido Münch from the Hale Observatories for allowing me to inspect these valuable historic spectrograms. This work was supported by the Deutsche Forschungsgemeinschaft (SFB 132).

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D I S C U S S I O N of the paper by APPENZELLER:

WALKER: It is interesting and for me, very gratifying, that following a long period when it has been the opinion that the YY Ori phenomenon was a very rare and unimportant one, there is currently the great interest in those objects which we see here today. Dr. Appenzeller has been able to show that these objects are much more numerous than has been supposed and represent a major effect in the early stages of stellar evolution.

It is important to emphasize that the YY Ori phenomenon appears to occur only among the UV excess stars. The original study (Walker 1972) was restricted to bright UV stars in the Orion nebula cluster and NGC 2264. Subsequently, I have observed a sample of about 50 stars selected at random from the fainter portions of the color magnitude diagrams of three clusters and have found only one additional YY Ori star.

Did the list of YY Ori stars which you presented, include those which you selected because of asymmetry of the H line profile in the absence of detectable inverse P Cygni absorption? It would appear that these objects could represent a different subgroup from the classical YY Ori stars since in YY Ori itself, when the inverse P Cygni absorptions are not present, the profiles are symmetric; one cannot thus be sure of detecting all YY Ori stars from the emission line shape in the absence of visible redward displaced absorption.

APPENZELLER: For those stars included in my list, we have seen the red-ward displaced absorption components at at least 3 different Balmer lines.

GRASDALEN: In regard to your proposed evolutionary sequence, are the YY Orionis stars systematically brighter than the "normal" T Tauri stars in the Orion nebular cluster?

APPENZELLER: They should be brighter bolometrically. Since a significant part or most of the radiation is emitted in the infrared, the bolometric luminosity can be determined only if complete infrared data are available. Since no infrared data are available for most of these stars, your question cannot be answered on the basis of the existing data.

WALKER: The YY Ori stars do tend to be among the brightest of the "T Tau" or "late-type Orion" variables in the Orion nebula cluster and NGC 2264.