# THE EXCITING STARS OF HERBIG-HARO OBJECTS AND
# THEIR RELATIONSHIP TO T TAURI STARS

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ABSTRACT.  The properties of the stars believed to be responsible for exciting Herbig-Haro objects are discussed.  Various combinations of techniques have been used to indicate specific identifications of exciting stars yet, in very few cases, is there a visible counterpart to these objects.  Bolometric luminosities can be estimated reliably from far-infrared observations of the exciting stars but only two can be unambiguously located in the HR diagram.  However, the luminosities of all, but one, of these stars can plausibly be attributed to low-mass ($\lesssim 1 M_\odot$) protostars viewed in their very earliest phases of evolution.  Only R Mon, with its exceptionally high luminosity, is likely to be a higher mass object.

## I. INTRODUCTION

During most of the three decades since Haro(1950,1952) and Herbig(1948,1951)discovered the first Herbig-Haro (HH) objects, these nebulae were regarded as presenting enigmatic optical spectra but not as objects materially indicative of some crucial phase of star formation.  Yet, within only the past few years, their study has blossomed again.  This resurgence of interest has come on many fronts.  Observations in "new" spectral regions have led the way and the literature on HHs now spans the spectrum from X-rays to centimeter wavelengths.  But not all the startling advances have come from new techniques.  More classical investigations - astrometry and proper motion work, and polarimetry - have also been in the vanguard of research.

I should like to review briefly some of the highlights of work on the exciting stars of HHs, bringing together the different types of observation, in an attempt to relate these stars to the class of T Tau objects.  Few of the exciting stars are directly visible; one, at least, can be seen by reflection from its associated HH nebula.  Therefore, these few are crucial to our interpretation of the general class.  It is not the purpose of this paper to discuss the properties of HH objects themselves; for this, the reader is referred to the review article by Schwartz(1983).

## II. OPTICAL CRITERIA FOR EXCITING STARS

The most direct criterion that could exist would be an obvious physical involvement of a star and an HH nebulosity.  There is a significant fraction (9%) of all T Tau stars whose photographic images reveal an intimate association with tiny nebulosities and whose spectra show emission lines of [O I], not typical of chromospheres(Cohen and Kuhi 1979).  Of course, not every star involved in circumstellar material might show a resolvable nebula.  Therefore, the mere presence of the [O I] line may be taken to indicate a vigorous interaction between a star and its surroundings.  Of all the T Tau stars listed by Cohen and Kuhi(1979), 29% display [O I] emission.  The average bolometric luminosity for 31 stars in Tau-Aur that have $\lambda 6300$ emission  with infrared observations and presenting H$\alpha$ emission, is $\gtrsim 4.0 \pm 1.0$ L$_\odot$ (this is a lower limit since it includes minimal luminosi-

ties for continuum stars with unknown reddening). For a similarly constrained sample of 42 Tau-Aur stars without $\lambda 6300$ emission this average is $1.6 \pm 0.3$ $L_\odot$.

Thus we find that stars showing vigorous interaction with their surroundings tend to be the more luminous and younger stars in an association; that is, as T Tau stars age, their tendency to produce circumstellar shocks diminishes. This point was also established more generally, for emission lines of chromospheric origin, by Cohen and Kuhi (1979). Consequently, were we to seek exciting stars for HH objects among the T Tau stars, we should select only the youngest of these.

The continuum light detected in a few HH objects is found to be significantly linearly polarized, although the emission lines are not. The directions of electric vectors provide important clues as to the locations of exciting stars, whether visible directly or not. Nebular spectro-polarimetry has proved valuable for HH24 (Schmidt and Miller 1979), HH30 and HH43 (Cohen and Schmidt 1981). Most remarkable is the relatively bright continuum of HH30 in which can be seen weak but definite emission lines of FeII, multiplet 42 (Cohen and Schmidt 1981), the most prominent and most frequently observed emission lines in the spectra of T Tau stars, aside from those due to hydrogen and helium. This discovery assisted Cohen and Schmidt in identifying the visible T Tau star, HL Tau, as responsible for HH30. It also established that at least one visible T Tau star, with (sometimes) classifiable photospheric features, has produced an HH object.

This is not a trivial point. For example, although Schwartz (1974, 1975) studied in detail the HH parts of the nebulosity around T Tau itself, it is no longer clear that this star has caused these HHs. The discovery of an active radio-emitting and optically invisible component within the T Tau system (Cohen, Bieging and Schwartz 1982), coupled with infrared duplicity (Dyck, Simon and Zuckerman 1983), suggests that it is this active companion to the relatively quiescent T Tau that has triggered these HH objects.

The discovery of HH55 in the immediate vicinity of the T Tau star RU Lup (Schwartz 1977) strongly suggests that this visible star has created an HH object. Likewise, after near-infrared searches of its surroundings, Cohen and Schwartz (1983) concluded that AS353A was responsible for HH32A and B, a view strikingly supported by recent deep CCD imaging (Mundt, Stocke and Stockman 1983). However, both AS353A and RU Lup have extremely strong and rich optical emission line spectra rendering their photospheric types indeterminate, and no far-infrared data yet exist for RU Lup. Therefore, the location of these stars in the HR diagram is still not possible.

Cohen and Schwartz (1983) have found that the star associated with "R Mon" is actually displaced from the fan nebula and is invisible to us. Careful scrutiny of the visible stars believed to have produced HH nebulae leaves only the Cohen-Schwartz (1979) star, between HH1 and 2, and HL Tau as optically accessible, photospherically classifiable, definite exciting stars of T Tau type.

III. NEAR-INFRARED STUDIES

The most productive method for isolating potential exciting stars has been to map the dark clouds where the HH objects are found in the near-infrared, typically at $2\mu m$. This method has

generated a small number of very red sources, mostly invisible optically, which have been observed over the broad range 1-20 μm.  Early searches by Strom, Strom and Grasdalen(1974) were followed up by Strom, Grasdalen and Strom(1974), and the most recent survey by Cohen and Schwartz(1983) which incorporates 16 potential candidate stars.  The energy distributions of these objects sometimes reveal silicate absorptions near 10μm; their depths indicate lower limits on the optical extinctions to these sources between 3 and 20 magnitudes.  Similar numbers result if their near-infrared colors (J-H, H-K) are compared with those of normal, unreddened T Tau stars; that is, all these candidates <u>could</u> be obscured T Tau stars although there is no direct proof of this.

IV. MORPHOLOGY, PROPER MOTIONS, AND BIPOLAR FLOWS

Cohen and Schwartz(1979) singled out a faint star lying between the groups HH1 and HH2 as worthy of attention because of its infrared colors and its alignment with HH1 and HH2.  They found it to have rather weak T Tau characteristics and to be moderately obscured (by 7 mag).  Shortly thereafter, Herbig and Jones(1981) published the remarkable pattern of large proper motion vectors for individual knots of HH1 and 2.  The HHs move in opposite directions away from the Cohen-Schwartz star, vindicating the identification of this star as causing the HH nebulae.

A number of interesting alignments have been found between candidate exciting stars and their associated HH objects.  On purely morphological grounds the near-infrared source found near the unusual chain of HH objects (7-8-9-10-11) would be a likely candidate given its alignment with the chain.  The knots HH31A, B, and D are well-aligned with the potential exciting star (HH31IRS2 of Cohen and Schwartz 1983, their Fig. 5).  HH32A,B, and the recently discovered knot C are all HH objects aligned with their candidate star, AS353A(Mundt <u>et al</u>.1983)  The infrared sources associated with Haro 6-10(Elias 1978), and with R Mon and HH 17 all lie on the axes of, and close to the apices of, small fan nebulae(Cohen and Schwartz 1983).

Proper motion vectors indicate that the following HH objects are moving away from their exciting stars: HH11 from SSV13(Jones 1982, Priv. Comm.); HH28 and 29 from L1551IRS5(Cudworth and Herbig 1979); HH39 from R Mon(Jones and Herbig 1982); HH43 from IRS1 of Cohen and Schwartz(Jones 1982, priv. comm.), along the line to HH38; HH47 and 47C from an infrared object hidden between HH46 and 47(Dopita, Schwartz and Evans 1983).  Ejection of HHs by their stars seems a strong possibility.  However, the often high velocities even far from the parent stars make it plausible that the HH objects are parts of the walls, that confine these stellar jets, which have become entrained in the flows, but not necessarily in the immediate stellar vicinity(Königl 1982; Mundt <u>et al</u>.1983).

All these alignments indicate anisotropic mass loss from the candidate stars (e.g. Cohen 1982), probably well-collimated.  The phenomenon of CO bipolar flows has elucidated this situation for deeply embedded sources.  If ejection were to occur in two opposite directions from a heavily obscured star,only where the products of this ejection broke free of the dark cloud material would we see visible evidence of this ejection.  However, the oppositely-directed flows would sweep up interstellar material,creating two, much more slowly-moving, masses of gas.  CO emission maps have revealed this bipolarity for L1551IRS5(Snell,Loren and Plambeck 1980), HH7-11(Snell and Edwards 1981),

R Mon(Cantó et al. 1981), and the regions around HH25 and 26(Snell and Edwards 1982). Visible evidence for bipolarity occurs only for flows within the plane of the sky or for stars with relatively little obscuration (e.g., AS353A; Cohen-Schwartz star).

It is clearly important to investigate the possible occurrence of bipolar CO flows around visible T Tau stars. Whilst evidence is found for high-velocity wings(Edwards and Snell 1982; Calvet, Cantó and Rodríguez 1983), no clearly defined bipolar molecular flows have yet been recognized. Of course, one might argue that the well-beamed phase of mass loss occurs only at the earliest stages of evolution for T Tau stars and dies away in the later, visible stages.

V. IONIZED GAS FLOWS

Cohen, Bieging and Schwartz(1982) searched with the VLA for 6 cm continuum radiation from a sample of T Tau stars. Among their six detections, only T Tau, V410 Tau, and DG Tau are strictly T Tau stars. They also detected and mapped ionized gas around L1551IRS5, obtaining the first accurate position for this source. Subsequent careful astrometry by Cohen and Schwartz(1983) has established that the infrared and radio sources are coincident with a small elliptical condensation at the eastern end of a small photographic "jet" of nebulosity. At the west end of this jet, the flow "flares out" in photographs, strongly supporting Königl's(1982) proposal that deLaval nozzles are operating above the exciting stars.

This VLA survey was also important in finding that the bright radio object in the field of T Tau is actually displaced to the south by 0.6 arcsec from the accepted optical position of the star. A reinvestigation of the astrometry for T Tau itself(Jones 1982, Priv. Comm.) has borne out this displacement and a new 6 cm map of the T Tau field by Simon and Schwartz(Schwartz 1983, priv. comm.) leaves no doubt that the weak protuberance north of the VLA source (Cohen et al. 1982) is in fact T Tau itself. These studies, combined with infrared speckle work(Dyck et al. 1983), have contributed much to our recognition that the prototypical T Tau star may be a very poor prototype!

In a new VLA study, Cohen, Bieging and Schwartz(1983)have undertaken an unbiased 6 cm survey of all T Tau stars above bolometric luminosity Log L=0.2 in Tau-Aur and tabulated by Cohen and Kuhi(1979). Only a single new detection of a T Tau star resulted. However, their parallel study of several potential exciting stars for HH objects yielded three new detections among these stars. It seems singularly appropriate at this symposium to be able to report the detection of Haro 6-10 at 6 cm (Fig.1). These statistics suffice to suggest that, if the exciting stars are indeed related to T Tau stars, their phase of most active mass loss is already completed by the time that they have become visible stars.

VI. CIRCUMSTELLAR DISKS

The discovery of radio continuum emission from L1551IRS5 shows that the alignment mechanism operates from the immediate stellar vicinity across distances of order 0.5pc. An important question relates to the precise origin of the high degree of collimation. Does this take place at the stellar surface, for example through coronal holes, or is beaming imposed upon a more isotropic flow at some

distance from the star?

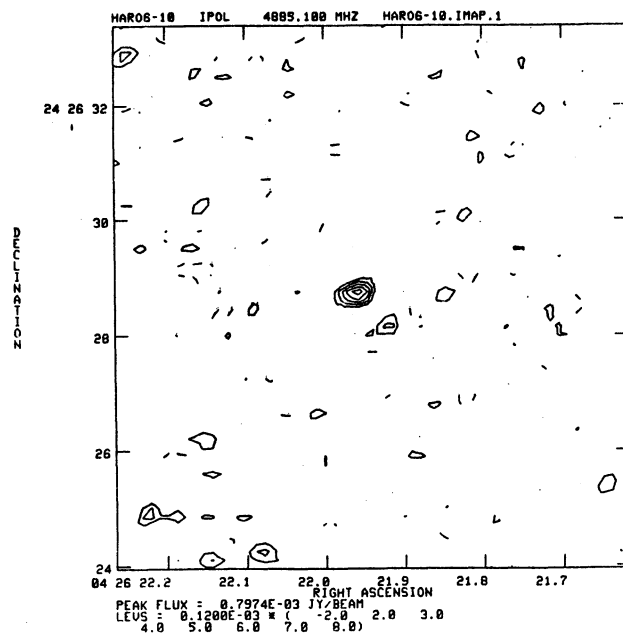HAR06-10   IPOL   4885.100 MHZ   HAR06-10.IMAP.1

Fig. 1. 6cm VLA map of Haro 6-10 (from Cohen, Bieging and Schwartz 1983).

Königl(1982) would beam the flow at the nozzles, displaced from the star, but aligned normal to the plane of an equatorial disk. Hartmann and MacGregor(1982) would construct a disk directly with their anisotropic flow, while Canto et al.(1981) have sought to focus an isotropic flow using a toroid that surrounds the star. The common ingredient of all these models is the presence of some kind of circumstellar disk. What direct evidence exists for disks around exciting stars, and around T Tau stars?

The morphology of fan-shaped nebulae can be persuasive of the presence of disks(Cohen 1974). The growth of near-infrared flux with aperture size for L1551IRS5 may be indicative of an edge-on dust disk although its orientation cannot be defined from the near-infrared data(Cohen and Schwartz 1983). But only for HL Tau can we be certain that a disk is present, for we see this star through the plane of its disk(Cohen 1983a). This disk must be thin to account for the simultaneous presence of a unique ice absorption, a unique silicate absorption, and a uniquely high level of optical linear polarization in only this star among all the other T Tau stars studied for these phenomena. It may be more fruitful to look for face-on end inclined disks that to seek the elusive edge-on disks around T Tau stars, an approach recently taken by Cohen and Witteborn(1983) in a sensitive ten-micron spectrophotometric survey.

Since the phenomenon of beamed mass loss must also clean out the circumstellar environment it is likely that only vestigial disks remain among the visible T Tau population. Recently, Torrelles et al.(1983) have sought direct evidence for more substantial toroids in an ammonia survey

of embedded sources known to exhibit bipolar molecular outflows.  They conclude that focussing by
high-density toroids is a viable producer of bipolarity although they note that for L1551IRS5 the
orientation of this ammonia cloud is along the CO axis, not perpendicular to it.  Clearly, more work
remains to be carried out on the embedded exciting stars of HH objects.

VII.  FAR-INFRARED EMISSION

         Since the initial detection of far-infrared emission from L1551IRS5(Fridlund et al.1980)
much work has been carried out on HH objects using the Kuiper Airborne Observatory (KAO).  The results
of this study from the KAO(Cohen, Harvey, Schwartz and Wilking 1983) are several.  Complex, exten-
ded 100μm emission has been detected and mapped around HH1/2, HH25/26, and HH34.  While the exciting
stars for these HHs do emit at far-infrared wavelengths, they are not the most prominent locations
in the 100μm maps.  Both HH1 and 25 are themselves bright far-infrared sources, and the map for HH
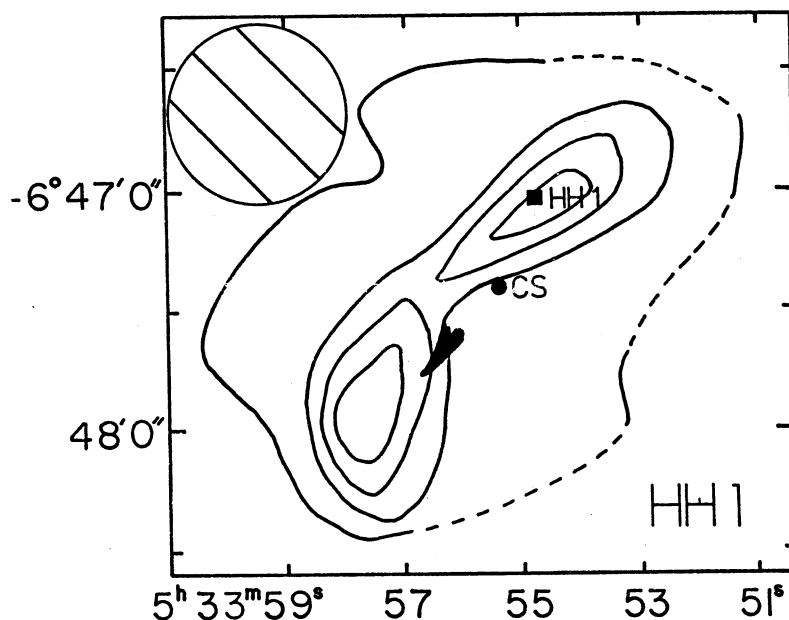1 and 2 reveals an intriguing bipolar distribution of emission (Fig. 2).



Fig. 2.Bipolar structure of 100μm emission from HH1/2 region
(from Cohen, Harvey, Schwartz and Wilking 1983).

         What the far-infrared observations also offer are accurate estimates of the bolometric lu-
minosities of the exciting stars.  The importance of having data beyond 20μm can be recognized from
Figs. 3 and 4 which present the entire energy distributions for exciting stars in the range 1.2 and
160μm.  Fig. 3 includes all the objects that are either visible directly, or indirectly from the
optical continuum in a reflection nebulosity.  Fig. 4 incorporates the deeply embedded sources.

VIII.  SUMMARY OF OBJECTS BELIEVED TO BE EXCITING STARS

         In Table 1 are assembled a list of candidates for the exciting stars of HH objects.  These
are drawn principally from Cohen and Schwartz(1983), with supplementary far-infrared data from
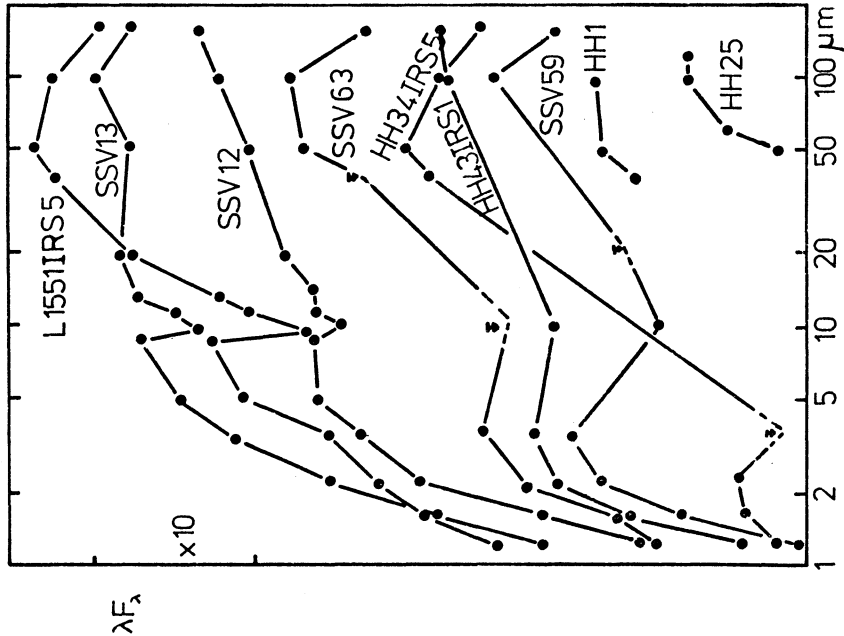
Fig. 4. Energy distributions for exciting stars which are optically invisible (ref. as in Fig. 2).
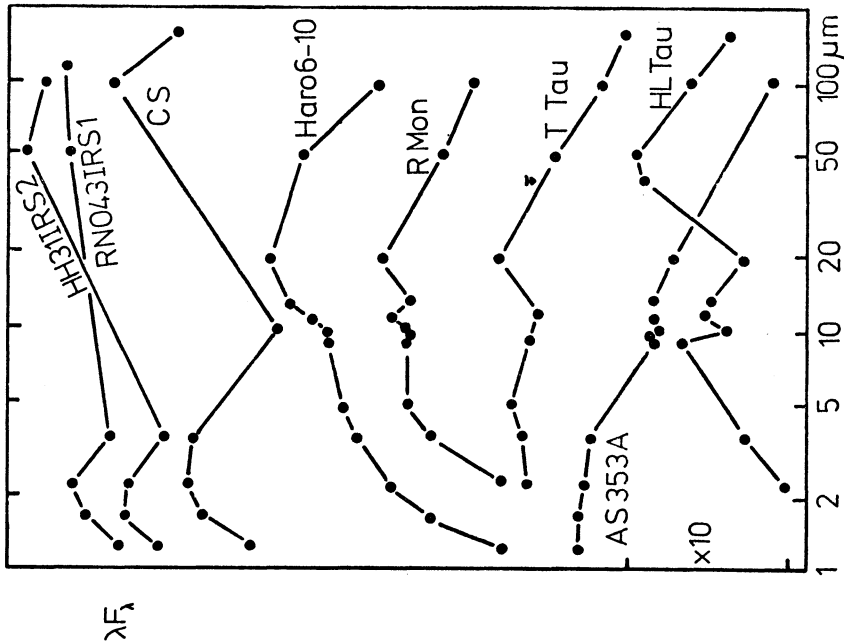


Fig. 3. Energy distributions for exciting stars with visible counterparts (ref. as in Fig. 2).

Cohen, Harvey, Schwartz and Wilking(1983), and radio information from Cohen, Bieging and Schwartz (1983). A bolometric luminosity is only tabulated based upon the far-infrared and ground-based observations.

TABLE 1. Data on Probable Exciting Stars

| HH(s) | Star/IRS | Vis? | VLA? | Far-IR? | Sp'pol? | μ? | Morph? | $L_{bol}$ |
|-------|----------|------|------|---------|---------|------|--------|------|
| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
| 12 | SSV12 | √n | x | √ | | ? | x | 23 |
| 7-11 | SSV13 | x | x | √ | | √ | √ | 58 |
| nr.T Tau | T Tau | √? | √ | √ | | | ? | 37 |
| 31A,B,D | IRS2 | √n | | √ | | | √ | 0.7 |
| Haro6-10 | same | √n | √ | √ | | | √ | 6.5 |
| 28,29 | L1551IRS5 | √n | √ | √ | ? | √ | √ | 32 |
| 30 | HL Tau | √ | x | √ | √ | x | ? | 7.2 |
| RNO43 | IRS1 | √ | | √ | | | √ | 18 |
| 34 | IRS5 | √n | | √ | | | x | 23 |
| 1,2,3 | CS star | √ | x | √ | ? | √ | √ | 27 |
| 38,43 | IRS1 | x | x | √ | √ | √ | √ | 5.3 |
| 24 | SSV63 | x | √ | √ | √ | ? | √ | 25 |
| 25,26 | SSV59 | √n | x | √ | | | √ | 15 |
| 39 | R Mon | √n | x | √ | √ | √ | √ | 1360 |
| 32A,B,C | AS353A | √ | x | √ | ? | | √ | 18 |

Column (1) indicates the relevant HH objects; column (2) the designations of exciting stars or near-infrared sources; columns (3)-(8) indicate the existence of a visible counterpart (star or nebula with the symbol "n" denoting a nebulosity rather than a visible star), of a VLA radio continuum detection, of a far-infrared detection, of HH nebular spectropolarimetry, or proper motion vectors or alignments of stars with HHs, that assist the identification of the exciting stars, respectively. The notation used in columns (3)-(8) is: √=yes; x=no; blank=no observations of this type yet available; ?=observations exist but do not clearly vindicate the choice of exciting star. In column (9) are bolometric luminosities in units of $L_\odot$.

Less certain, but still possible, exciting stars are: the infrared object (IRS1) associated with the apex of the fan nebula HH17 (but no far-infrared detection has so far been made, only an upper limit at 50 and 100μm); NGC7129 IRS1, the intriguing T Tau star that has brightened since 1955 (Gyulbudaghian, Glushkov and Denisyuk 1978), is probably of late spectral type (Cohen, unpublished spectra), and is well-aligned with the nebulae GGD33a,b (yet on six separate spectra no emission lines have been detected from these objects rendering their status uncertain (Cohen 1983b)); and of course RU Lup which lies extremely close to HH55.

IX. CONCLUSIONS

There are some new observations that clearly need to be made. For example, if RNO43 were really excited by the faint star IRS1 (Cohen and Schwartz 1983) then its optical spectrum is of great interest. If the HH objects near T Tau were caused by the infrared/radio companion, then perhaps an optical spectrum of this star could be gleaned by reflection from Burnham's Nebula. AS 353A should be monitored spectroscopically for the strong-line T Tau stars sometimes lose their emission character almost entirely, revealing their photospheres briefly. Aside from these possibilities we have only HL Tau and the Cohen-Schwartz star that can be plotted in the HR diagram. From their locations we learn that HL Tau is a T Tau star of 1 $M_\odot$ at age $10^5$ yr (Cohen 1983a), and the Cohen-Schwartz star is an object of ~2.5 $M_\odot$ at age a few x $10^5$ yr. Of course, given the dynamical time-scales for various HH objects to have moved to their present locations, it is not required that exciting stars are currently active, merely that they once were. Indeed, eruptive events have been proposed for the production of HHs (e.g., Mundt and Hartmann 1982).

A number of exciting stars are still active, as indicated by the detection of radio continuum emission, probably from stellar winds. However, for these objects we usually know only the luminosity, and no estimate of effective temperature is available. These luminosities suffice to exclude the possibility that we are dealing with O or early B stars (with the sole exception of the luminous R Mon), and this fact in turn eliminates normal Stromgren zones for the origin of the radio emission (Cohen et al. 1982). If these exciting stars were main sequence objects then they would have spectral types from B5 to F5. There is not the slightest evidence that such normal stars as these might be capable of extraordinary phenomena, like the ejection of HH objects, or collimated flows, even if they happened to lie in an unusual environment such as a dense cloud. Therefore, we are most likely to have found a pre-main-sequence population.

With the clue (deduced in sections II and V) that the phase of ejection of HHs and of highly anisotropic mass loss is a very early one, we may be tempted to see, in our population of exciting stars, evidence for the elusive low-mass "protostars", that is, stars still undergoing accretion.

The model calculations for protostellar collapse of Stahler, Shu and Taam (1980) shows that these objects are purely infrared emitters in the accretion phase. Further, their "dust photosphere" track for the construction of stars of up to 1 $M_\odot$ grows in luminosity from 0.6 to 63 $L_\odot$, a range conspicuously like that in Table 1 (R Mon would have to be of somewhat higher mass - perhaps ~5 $M_\odot$).

This is not regarded as proof, but it is my belief that strong plausibility arguments can be made that link the embedded exciting stars with the very earliest ($< 10^5$ yr) phases of evolution of low-mass protostars, stars that will one day become visible as T Tau stars.

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## DISCUSSION

*Graham:* Are there some HH-objects for which you have not been able to find the source? What is your success rate?

*Cohen:* Yes, we have failed to locate a few exciting stars at 2 or 10 μm, but our far-infrared success rate is higher (7/9 sources observed). February 15, 1983, *Ap. J.*, gives the details of our near-infrared success rate; it is about 70% successful. Near-infrared failures could represent even more deeply embedded stars.

*Pişmiş:* (*Comment*) On the VLA map of L1551 the contours showed a displacement of the apparent "major axis" of the image gradually displaced. This can be explained in a simple manner from geometrical consideration. For a bipolar ejection from a rotating source the locus of the ejected matter will be of spiral shape, if the shape of the spiral (say its equation) of the ejected matter shows a variation. The "major axes" of the projected image will show the gradual variation observed. The problem is very similar to the variation of the apparent major axes of an inclined spiral galaxies as you go outwards from the center. This problem is treated analytically in a paper published by myself in Modern Astrophysics, a memorial to Otto Struve (ed. M. Hack, *Gauthiers Villars,* 319).

*Cohen:* I think its remarkably exciting that such small systems as T Tau stars can mimic the highly energetic processes that occur on galactic scales.

*Calvet:* (*Comment*) Cantó, Rodríguez and I have mapped the CO around HL Tau and found that the CO outflow does not get as far as HH 30. This suggests that even though HH 30 is reflecting light from HL Tau there may be no physical connection between the two objects.

*Cohen:* CCD pictures show two independent stars each with its own HH nebulae: HH 30 and its star; HL Tau and its HH-objects. It is perverse of

nature to have arranged the electric vector in HH 30 to suggest that HL Tauri was the exciting star of HH 30.

S. *Strom*: For HL Tau: if you assume "standard" dust emissivity L(100μ) should allow an estimate of τ(dust). With that, you predict τ(visible) it almost certainly is large. Hence, the disk you propose must be slightly inclined with respect to exactly edge-on. Nevertheless, the 100μ results surely suggest a non-spherical distribution of dust around the star.

*Cohen*: This technique only works if the far-infrared emission fills the beam; for HL Tau this almost certainly is not the case.

*Krautter*: Does Haro 6-10 look stellar-like on the photograph you showed?

*Cohen*: No. It has the appearance of a small, parabolic, nebulous fan, apex to the north.

*Fridlund*: Did you investigate the far infrared properties of HH 28 and HH 29?

*Cohen*: Not yet; but next year we shall be using the Kuiper Airborne Observatory to map the blue CO lobe of L1551 all the way from IRS5 to HH 28 and 29.

*Appenzeller*: I found your arguments for a very young (pre-T Tauri) nature of the exciting stars of HH-objects very convincing. But then I do not understand why the Cohen-Schwartz star appears to be such a normal T Tauri star. Could you comment on that?

*Cohen*: The Cohen-Schwartz star is not currently active in the radio or the optical but one requires only that these stars were *once* active, in the past, not that they are either continuously active nor presently active.

*Bashi*: Can you give us your expert opinion on the observational evidence for disks in T Tauri stars other than HL Tau?

*Cohen*: I think it may now be easier to seek evidence for inclined and face-on disks than edge-on disks. Fred Witteborn and I now have about 50 spectra ($\Delta\lambda/\lambda \sim 2\%$) of T Tauri stars between 8 and 13μm. We are seeking a correlation between optical linear polarization and the strength of the commonly-found 10μm silicate emission features. If such correlations do exist, they could indicate the presence of inclined dust disks.

*Rodríguez*: (*Comment*) To illustrate how complicated this alignment game can be, I would like to mention that we have mapped L1551 in ammonia both with Haystack (single dish) and with the VLA. With Haystack we found an elongated clump (5'×3') aligned *parallel* to the outflow axis, while with the VLA we resolve this large structure out and detect a small condensation (30"×15") aligned *perpendicular* to the outflow. We are still trying to make some sense out of this.

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