EARLY STAGES OF STELLAR EVOLUTION

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A wealth of new observational data made available through the advent of modern infrared and microwave techniques, have provided astronomers with their first glimpses into the current-epoch stellar wombs - dark interstellar clouds. As a consequence, the past ten years have witnessed major advances in our understanding of the early evolution of stars and the mechanisms which trigger star formation. A future, more detached view of this period might suggest that we have achieved

1. a much more complete picture of the evolutionary status of three classes of optically observable young stellar objects (YSOs): the Herbig Ae/Be stars associated with nebulosity (HES), the T Tauri stars, and the Herbig-Haro (H-H) objects;

2. a far better understanding of the spread in times of stellar formation within cloud complexes (Strom et al. 1975a; Warner et al. 1976). In large measure, this results from our greater appreciation of the effects of circumstellar and dark-cloud environments on the observed energy distribution of YSOs.

3. an increased awareness of the interaction between YSOs and the dark-cloud material out of which they were formed. The presence of YSOs within dark-cloud complexes can

(a) heat the dust (and by collision with dust, the gas);

(b) very likely dissociate, at least locally, some molecular species;

(c) ionize hydrogen and trace elements; and

(d) by the action of stellar winds and propagating ionization fronts, alter the local velocity field and matter distribution. These interactions certainly must affect our interpretation of radio observations of cloud complexes and may, in some cases, control the subsequent evolution of the complexes.

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*Operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

T. de Jong and A. Maeder (eds.), Star Formation, 179-212.

https://doi.org/10.1017/S0074180900142317 Published online by Cambridge University Press

4. by application of new observational techniques, the discovery of a variety of unusual objects and phenomena. Some may be manifestations of extremely early evolutionary stages (Wynn-Williams and Becklin 1974); we have just begun to ask the questions which may lead to a proper understanding of the below listed newly-discovered objects in the context of a coherent stellar evolutionary scenario:

(a) OH and H_2O maser sources;

(b) compact H II regions apparently embedded within dark-cloud complexes and sometimes associated with (a);

(c) luminous infrared sources often associated with (a) and (b). Some of these objects may be extremely cool, "protostellar" objects, others appear to be luminous stars obscured by up to several hundred magnitudes of interstellar extinction;

(d) infrared sources of lower luminosity apparently embedded within cloud complexes (Grasdalen et al. 1973; Vrba et al. 1975, 1976; Strom et al. 1976a,b,c). It has been argued in some cases that these sources represent main-sequence and pre-main-sequence members of clusters still shrouded from view by the dark-cloud material out of which they were formed.

5. a primitive understanding of the mechanisms which trigger star formation:

(a) compressions of cloud material in spiral shock regions;

(b) compression behind a supernova shock;

(c) compression in the shock region which results from cloud-cloud collisions;

(d) compression behind the ionization front produced by the "turn on" of an OB-association in a dark-cloud region.

In the time allotted, I cannot begin to review all the stimulating discoveries and seminal ideas alluded to above. Rather, I will attempt a more focused summary of our current understanding of optically observable YSOs. For these objects, a combination of photometric and spectroscopic observations has been sufficient to provide the data essential to eliciting in at least a rudimentary way their physical characteristics and evolutionary status. In the hope of providing stimulation for further research, I will emphasize in this summary my own rather prejudiced beliefs concerning observations which might better elucidate the nature of these objects.

1. THE HERBIG Ae AND Be STARS ASSOCIATED WITH NEBULOSITY (HES)

A detailed discussion of the optical and infrared properties of these objects can be found in Strom et al. (1972). A summary of their characteristics is given by Strom et al. (1975b) and is quoted below:

1. Optical emission spectra ranging in complexity from those with only Hα through the rich emission spectrum of V380 Ori (Herbig 1960). In many cases the emission spectrum is reminiscent of that found in T Tauri stars; this accounts for references to some of these objects in

the older literature as "early-type" T Tauri stars. In a few cases Balmer continuum radiation has been observed as well.

2. An absorption-line spectrum ranging from type B1 to F8 (composite). The surface gravities derived from analysis of the wings of the hydrogen lines locate many of these objects above and to the right of the zero-age main sequence (ZAMS).

3. Direct association with dark-cloud material as indicated by the illumination of nearby reflection nebulae.

4. P Cygni profiles. With the exception of RR Tau, for which Herbig (1960) suggests the presence of an inverse P Cygni profile on occasion, the HES characteristically show P Cygni profiles in the Balmer series and in some cases in other lines as well. These observations have been interpreted in terms of an expanding gaseous envelope surrounding the HES. It is generally assumed that the observed outflow is indicative of mass loss.

5. Irregular variability. Most stars of the class have shown episodes of apparently irregular variability with amplitudes of up to 4 magnitudes. Many of them have shown long periods of remarkable stability, however.

6. Optical polarization. Breger (1974) has demonstrated that these objects have both polarizations discernibly different from those of nearby objects and rotation in position angle of the electric vector with wavelength; both characteristics provide certain identification of the observed polarization as intrinsic to the objects.

7. Infrared excesses. Gillett and Stein (1971) and Geisel (1970) first reported strong infrared excesses for these stars. Strom et al. (1972) published a more complete infrared survey of objects in this class; these results provide the basis for a more detailed analysis of HES envelope characteristics. Some stars in the group (AB Aur, LkHα 198) show evidence for the 10.2-μ "bump" often identified with emission from silicate material (Cohen 1973b; S. E. Strom, K. M. Strom, and G. L. Grasdalen's unpublished observations).

The observations in some cases of 10-μ bumps suggest the presence of dust in the circumstellar envelope. It seems more reasonable, however, that the infrared excess shortward of 10 μ results from free-free emission in the same envelope region that produces the Hα flux (see Dyck and Milkey 1972; Milkey and Dyck 1973); ion-proton, free-free radiation seems most likely.

Even in the absence of a totally satisfying description of the envelope infrared emission, it is possible to argue from their location in the H-R diagram that the majority of these objects are approaching the main sequence along equilibrium radiative tracks. From estimates of their surface gravity values based on observation of Balmer line

https://doi.org/10.1017/S0074180900142317 Published online by Cambridge University Press

wings and of their distances, Strom et al. (1972) located the HES in the H-R diagram. They appear to lie in the domain of the H-R diagram occupied by high-mass stars approaching the main sequence along equilibrium radiative tracks. This conclusion, combined with their observed close association with dark-cloud material, makes plausible their identification as pre-main-sequence objects with ages in the range 10^5 to 10^6 years.

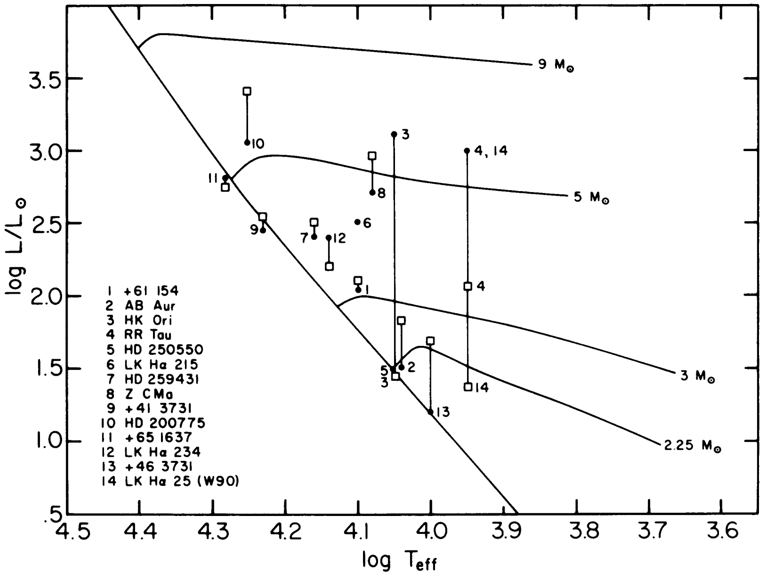

Fig. 1. - The location of the Ae and Be stars in the L-T_{eff} plane. The spectroscopic luminosity determinations are plotted as solid dots; bolometric luminosities are plotted as open squares. Permission for republication granted by Annual Reviews Inc. (*Ann. Rev. Astron. Astrophys.* 13, 187).

The line and continuum emission characteristics of the class seem best explained by proposing that these stars are surrounded by a hot ($T \sim 2 \times 10^4$ K), expanding, ionized region. In this model, the Balmer lines, Balmer continuum, and infrared excess radiation are produced by bound-bound and bound-free radiation in this hot region. Optical variability is produced either by intrinsic variations or, more likely, by variations in the emission measure of the envelope material. If the envelope is somewhat inhomogeneous, the optical polarization can be explained plausibly by electron scattering (in the envelope region) of photospheric radiation. The 10.2-μ bump results from emission by "ambient" dust (either circumstellar or dark cloud) containing silicate material. It is also possible that the dust may be formed in the cooler regions of the expanding envelope.

Important observations which might provide more quantitative physical descriptions were recently outlined by Strom (1976) and are quoted below:

1. No detailed, self-consistent model of the emitting region has yet been made. Such a model would attempt a simultaneous explanation of all the emission processes. Observationally, the input required for such a model should include a detailed spectral-energy distribution for the "excess" radiation; calibrated spectrophotometry of the P Cygni profiles, with special attention to deriving accurate measures of the Balmer decrement; and spectrophotometry of Paschen and Brackett emission lines, which would provide important checks on the consistency of the model because some of these lines are likely to be optically thin, while the Balmer lines are probably optically thick.

2. As a corollary to problem 1, it is important to establish the mass-loss rate characteristic of these objects. This involves detailed modeling of the P Cygni lines possibly in the spirit of the recent analysis of O-type stars by Kuan and Kuhi (1975). C. Anderson at the University of Wisconsin has recently obtained echelle spectrograms of a number of HES; these data may provide a basis for further discussion of this problem. In addition, the relationship between these winds and stellar rotation may give some further clues to the origin of mass outflows in these stars. A larger sample of such stars will be needed before such an analysis can bear fruit.

3. Infrared spectroscopy of these stars, with particular attention to measuring characteristic emission-line strengths, may be of critical importance in attempts to classify similar, more heavily obscured objects not accessible to optical observations. Grasdalen at Kitt Peak National Observatory and R. Thompson at Steward Observatory have already made considerable progress in this area.

4. The relative behavior of the various emission features has not been firmly established for this class of object. Simultaneous infrared and optical observations of these features will be essential in confirming the working hypotheses concerning the origin of optical variability and the sources of excess radiation.

5. Ultraviolet (λ < 3000 Å) observations of a few of the brighter stars of this class (e.g., AB Aur) would provide further insight into the details of the emission processes. In particular, I would imagine that "veiling" analogous to the blue continuum superposed on the photospheric absorption spectra of T Tauri stars would be observed for the HES if Balmer continuum emission from the envelope contributes a significant fraction of the radiation from these objects.

2. THE T TAURI STARS

Objects of this class (as summarized by Strom et al. 1975b) are characterized by:

1. Balmer line emission.

2. Emission in the H and K lines of Ca II as well as Fe I, Fe II, Ti II, and [S II] in varying degrees.

3. Underlying spectral types between late F and middle M; often the photospheric lines are broad. The broadening of the lines has usually been interpreted as arising from rotation (Herbig 1957).

4. P Cygni profiles. With the exception of the class of "YY Ori" stars discussed by Walker (1972), the T Tauri stars exhibit P Cygni profiles in the Balmer line and in the H and K lines of Ca II. The YY Ori stars, at times, exhibit "inverse" P Cygni profiles (redward displaced absorption features).

5. An "ultraviolet excess" and in some cases a "blue continuum." At visual wavelengths, many T Tauri stars are observed to exhibit a steep rise toward the blue (as compared with normal stars of the same spectral type) in their spectral energy distributions. This is often accompanied by the apparent weakening or disappearance of photospheric lines; the washed-out spectral appearance is described as "veiling." In some cases, the veiling phenomenon extends to the red.

6. Optical polarization. Hunger and Kron (1957) first reported optical polarization for T Tauri. Since then, little work had been done on this question until Serkowski (1969a,b) and Breger (1974) surveyed a few objects of this class. The polarization appears to be variable with time, and from some of our own unpublished data can achieve values as high as 12 percent (HL Tau). The observation of variable polarization indicates an intrinsic origin.

7. Infrared excesses. Mendoza V (1966, 1968) was the first to report the unusual infrared characteristics of the T Tauri stars. Some, though not the majority, of these stars appear to show evidence of a 10-μ emission bump (Rydgren et al. 1976) and a sharp rise at 20 μ (Cohen 1973a,b; K. M. Strom and S. E. Strom's unpublished observations).

8. Irregular variability at optical wavelengths. Some stars have amplitudes as large as 5 magnitudes; more typically, ranges of 1 to 2 magnitudes are observed. No evidence for periodicity has been found (Plagemann 1970). In one case (V1057 Cyg), a 6-magnitude rise in a time $\lesssim$100 days has been observed. This rapid rise in luminosity is similar to that observed for FU Ori (Herbig 1966), a previously discovered star presumably analogous to V1057 Cyg.

A detailed study of these objects has recently been published by Rydgren et al. (1976). Their basic conclusions can be summarized as follows (Strom 1976):

1. The emission features (Balmer continuum, Paschen continuum, infrared excess, Balmer lines) arise in a hot ($T \sim 2 \times 10^4$), dense ($n \sim 10^9$-10^{12} atoms cm^{-3}), circumstellar envelope.

2. The optical variability stems from changes in the envelope emission measure, indicating changes in the density or physical size of the envelope.

3. Mass outflows or stellar winds characterize most, if not all, of these objects; Kuan (1975) has related the mass-outflow rates to the strengths of emission lines and continua.

4. Polarization results from electron scattering of photospheric radiation in the inhomogeneous envelope region.

5. The largest rates of mass outflow and strongest emission features are found in the youngest T Tauri stars, which are still confined within a dark cloud or within the condensation of gas and dust (the "placental cloud") out of which the individual stars are presumably formed. The mass-outflow rates decrease as the stars approach the main sequence.

6. The large majority of T Tauri stars have relatively low mass ($M \lesssim 2\ M_{\odot}$) and are approaching the main sequence along quasi-static equilibrium tracks.

7. The mass outflows, coupled to the photospheric layers by strong magnetic fields, may represent the mechanism by which stars of near-solar mass slow their rotation to values consistent with the low rotational velocities characteristic of main-sequence stars of this type.

A number of alternative proposals have been made to explain separately either the infrared excess radiation or the optical emission features characteristic of the T Tauri class. While none of these proposals attempts the rather broad synthesis of the Rydgren et al. model, they may, individually, provide important insights into the T Tauri phenomenon.

Cohen (1973a,b) and Gahm et al. (1974) interpret the excess infrared radiation in terms of emission from heated ($T \lesssim 2000$ K) dust. The light variations are presumed to arise from periodic obscuration of the stars by dust clouds comparable in dimension to the stellar radius. This picture runs into some difficulties in explaining the optical variability in total light and color: if dust clouds obscuring the star are responsible for decreases in brightness, one would expect that T Tauri stars would always be redder when fainter. However, T Tauri stars showing the largest amplitude exhibit approximately constant colors over a wide range in brightness. Furthermore, the sketchy data available to date (Rydgren et al. 1976) suggest that the optical and infrared brightness vary in lockstep rather than inversely, as suggested by the dust envelope models.

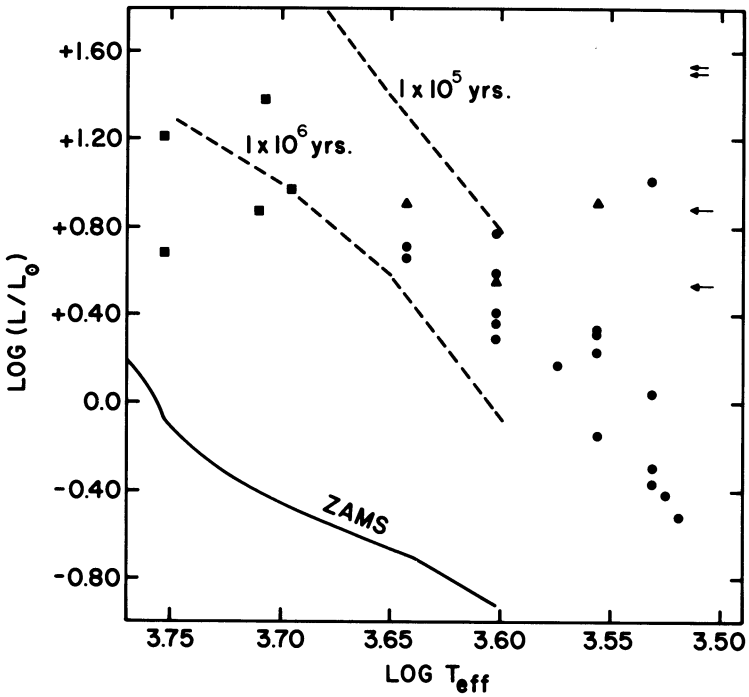

Fig. 2. - H-R diagram for T Tauri stars in the Taurus cloud. The ZAMS is indicated by a solid line and isochrones for 1 x 10^5 and 1 x 10^6 years (Iben and Talbot 1966) are shown as broken lines. ■ = G- or early K-type T Tauri star; ▲ = strong-emission star; ● = other T Tauri star. Stars with unknown photospheric spectral types are indicated by arrows at the appropriate luminosity. Permission for republication granted by The University of Chicago Press for the AAS (*Astrophys. J. Suppl.* 30, 307).

Dumont et al. (1973), Scharmer (1976), and Herbig (1969) have suggested that the optical emission features, and perhaps the infrared excess radiation, can be explained by a strong stellar chromosphere. Mechanical heating is presumed to create a temperature rise at optical depths $\tau \gtrsim 0.3$ to 0.1 as opposed to $\tau \sim 10^{-3} \rightarrow 10^{-4}$ (the value at which the solar temperature rise begins). This "premature" chromospheric temperature rise can, in principle, explain the strong emission observed at H and K and in the Balmer lines and the Balmer continuum, and might also offer an explanation of the infrared excess. A self-consistent description of the stronger line emission features and the Balmer continuum appears possible with these models (Dumont et al. 1973). However, this model seems inconsistent with the characteristics of "veiling" phenomenon. Observations by Rydgren et al. (1976) and by Kuhi (unpublished) suggest that as the strength of the emission lines and of the

Balmer continuum emission increases the veiling begins to extend from shorter wavelengths ($\lambda \sim 4000$) to longer wavelengths. The chromospheric models demand higher temperatures at deeper τ values in order to increase the strength of the emission features. By increasing the temperature at $\tau \sim 0.1$, emission will be observed first at *long* wavelengths (near the Paschen limit) rather than in the transparent regions near $\lambda \sim 4000$ Å. This follows from the relative opacities at $\lambda \sim 8000$ Å compared to $\lambda \sim 4000$ Å; near 4000 Å, one typically samples atmospheric regions near $\tau \sim 1$, while at 8000 Å, one is looking near $\tau \sim 0.3$, near the region where the temperature rise is presumed to begin. The expected sense of the observed correlation between veiling and emission-line strength therefore appears to run counter to the chromospheric models.

A chromospheric origin for the infrared excess seems unlikely because the magnitude of the temperature rise required to explain the excess radiation is so large that one expects to observe coronal emission-line features; these features have not yet been observed in stars of the T Tauri class.

The chromospheric model seems difficult to defend on empirical grounds as well, at least if one postulates a smooth transition between "normal" chromospheres surrounding young main-sequence and non-emission pre-main-sequence stars and the T Tauri stars. Kuhi (unpublished) has extended observations of the Ca II K-emission strength-age correlation (Kraft 1967) to include the non-emission pre-main-sequence stars in NGC 2264; however, as opposed to that group, the T Tauri stars have K-emission strengths well in excess of those expected for their age. Moreover, the widths of the K-emission features appear to be entirely inconsistent with the Wilson-Bappu relationship, allowing even the most liberal errors in the estimates of the intrinsic visual luminosities of stars of this type. Hence, it appears to me that chromospheric models run into significant difficulty in explaining the basic emission characteristics of T Tauri stars. Nevertheless, it seems likely, given the extraordinary strength of the stellar winds in these objects, that *some* mechanical energy is deposited *somewhere* in the photosphere and therefore that *some* effects on the photospheric temperature distribution may be expected.

The interpretation of the P Cygni-type profiles in terms of a mass outflow has also come under attack recently (Roger Ulrich, unpublished). He argues that under somewhat special but plausible geometric conditions, these profiles can be explained in the context of a mass-inflow model. Ulrich suggests that such a model provides a ready explanation for the observed emission-line strengths, Balmer and Paschen continuum excess, and possibly the infrared excess. Moreover, he believes that the large amount of energy (comparable in some cases to the total photospheric radiation) emitted by the "envelope" most plausibly arises from shock heating at the envelope-photosphere interface as matter flows inward from an extended envelope region (as opposed to the deposition in an envelope region of mechanical energy generated from within the star, the presumed mechanism for "chromospheric-type" models). These models, when published, deserve the most careful scrutiny because they bear so fundamentally on the character of the envelope regions of T Tauri stars and on possible effects of these envelopes on the dark-cloud environment.

A number of outstanding problems need further study:

1. Photosphere-envelope models should be constructed and compared in detail with observations. This would involve deriving quantitative estimates of the relative contribution of the envelope continuum-emission by, for example, measuring and comparing the line-center intensity in the photospheric absorption spectrum in T Tauri stars and normal stars in the same spectral-type range. Thus, the contribution from the envelope can be isolated and compared more accurately with model computations.

2. Critical to the above is the simultaneous measurement of emission lines, Balmer continuum, "blue veiling," and infrared excess over a period of several months for a selection of stars exhibiting a range of emission characteristics. Such data should permit estimates of the relative contribution of constant (presumably photospheric) and variable (presumably envelope) components. Furthermore, the data should permit critical tests of the competing (dust versus free-free emission) models for infrared emission. R. Schwarz and M. Cohen have begun such a program during the past year.

3. The nature of the variability in T Tauri stars should be further explained. Although no periodicities have yet been detected, the data base is not well suited for such studies in most cases; photoelectric observations using a small reflector (24-36 inches) of a small sample of T Tauri stars over a period of years would prove valuable. These observations are of particular importance to models which suppose that the variability is produced by periodic occultation of the stars by opaque dust clouds. Also of value would be observations of the short-period ($1 \lesssim \tau \lesssim 1000$ sec) variations for T Tauri stars having different emission characteristics. Kuan (1976) has reported the results of a power spectrum analysis of the short-term variations in four T Tauri stars. He concludes that the power increases toward lower frequencies and proposes a model in which fluctuating hot regions on the stellar surface are responsible for the variability of the Paschen, Balmer, and infrared continua of these stars.

4. The duplicity of these stars merits further study. In a moment of pessimism, Strom et al. (1975b) entertained some plausibility arguments in support of the view that stars of the T Tauri class might represent unrecognized pre-main-sequence spectroscopic binaries in which the emission-line features are produced in an envelope common to the two stars. What little reliable radial velocity work was available until recently tended to contradict this unsettling hypothesis; four well-observed T Tauri stars (T Tau, RY Tau, UX Tau, and SU Aur) have mean radial velocities relatively close to the Taurus dark-cloud velocities determined from molecular-line studies (Herbig 1962; S. E. Strom and K. M. Strom's unpublished observations). The radial velocity data are few. Moreover, their reliability is questionable because of the complexities of measurement introduced by the inherent line width and the

overlying emission. More work at higher spectral resolution is clearly necessary. The binary origin hypothesis for T Tauri stars cannot be ignored, despite its unpleasant consequence, because we have not yet identified pre-main-sequence binaries. Furthermore, we expect 30-50 percent of stars in the mass range 0.5-1.5 $M_{\odot}$ to be binaries; this figure is hauntingly close to the observed fraction of T Tauri stars relative to the total number of pre-main-sequence objects occupying the same region of the H-R diagram. A program currently in progress at Lick Observatory by Herbig should provide further insight into this possibility.

5. Quantitative estimates should be made of the interaction between specific angular momentum and the rate of mass outflow. If accurate projected rotational velocities and estimates of mass outflow can be obtained from the analysis of high-resolution spectra, this would represent an important step towards providing an empirical basis for discussion of "spin-down" problems.

6. Further study of the YY Ori phenomenon seems warranted. Rydgren et al. (1976) suggest that while Hα may exhibit an inverse P Cygni profile in some stars, the upper Balmer lines often exhibit normal P Cygni profiles. Whether these observations can be reconciled with a mass infall picture seems doubtful but deserving of additional thought and observation. It should be noted that the YY Ori stars in NGC 2264 do not appear to exhibit infrared emission characteristics which distinguish them from more normal T Tauri stars (Warner et al. 1976). Additional, high-resolution spectra, with particular attention to accurate photometry and velocity studies of a number of strong emission lines, might offer more definitive interpretation of the YY Ori class.

7. Estimates of magnetic field strengths would be extremely valuable. Accurate high-dispersion studies of absorption lines sensitive to Zeeman splitting will be difficult to make, primarily because of the intrinsic broadening due to stellar rotation. However, even a few such measurements would yield important information concerning the behavior of the field as a function of time and of rotational velocity.

8. Indirect study of the circumstellar environment of the T Tauri stars is needed. These objects are among the most likely to be surrounded by protoplanetary material. Observation of such material would clearly be of great importance to understanding the development of the early solar system. Several T Tauri stars illuminate reflection nebulae (R CrA, T Tau, and the unusual object R Mon). These systems may make possible the optical detection of thick clouds of orbiting circumstellar material. Synoptic studies of reflection nebulae might lead to the detection of T Tauri stars, by the discovery of periodic changes in light and brightness across the face of the nebulae, which take place on a time scale faster than the apparent light-travel time between the variable regions.

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9. Studies should be made of temperature structures in the upper photosphere. The combination of higher rotation and possibly greater magnetic-field strengths may produce greater heating in the chromosphere and upper photosphere. Such effects might be detected by comparing, in T Tauri stars and "normal" stars, the temperature-sensitive lines formed near the stellar boundary. High-resolution spectrograms at $\lambda \gtrsim 5000$ Å should provide a basis for such a study. Again, such studies might increase our understanding of the basic heating mechanisms that give rise to stellar chromospheres.

10. Optical polarization measures of different classes of emission lines are needed. Such observations might help sort out lines that are formed in different regions of the envelope. Comparison, say, of the polarization measured for hydrogen, helium, and forbidden lines might lead to a qualitative understanding of the differences in the regions of formation. L. V. Kuhi is already attempting such observations. Recently, N. Woolf (unpublished) has reported the detection of variable circular polarization in a possible analog of the T Tauri class, R Mon. He argues that such polarimetric studies might be used to detect dust clouds of "planetesimal" size surrounding T Tauri-like stars. While his interpretation of these data seems to me highly problematic, further studies of this nature will certainly be of interest.

3. THE HERBIG-HARO OBJECTS

Strom et al. (1975b) reviewed some current interpretations of the H-H phenomenon as follows: Until quite recently, the H-H objects were believed to represent a very early stage of stellar or possibly protostellar evolution. This view was based on (a) the morphological characteristics of the objects - they are defined as "semistellar" patches of nebulosity characterized by a low excitation spectrum dominated by [S II] and [O II] and the Balmer lines; (b) their location in dark-cloud complexes bearing other representatives of a young stellar population; and (c) their spectroscopic similarity to circumstellar envelopes surrounding a few T Tauri stars. Various proposals have been offered to account for the observed characteristics of these objects (Herbig 1969; Magnan and Schatzman 1965); all require the presence of a stellar or protostellar object obscured from view at optical wavelengths and located within the optical nebulosity. Strom et al. (1974a,b) have suggested that the H-H objects are actually reflection nebulae, whose illuminating stars are extremely young objects located within the dense, dark-cloud material. Variations on this theme have been offered recently by others (e.g., Schwartz 1974). Their arguments rest heavily on the following observations:

1. The discovery of single infrared sources ("H-H stars") associated with multiple-component optical H-H objects; these sources are typically displaced relative to the optical objects.

2. The measurement of optical polarization for the individual knots in a complex of H-H objects (Strom et al. 1974c; Vrba et al. 1975); the

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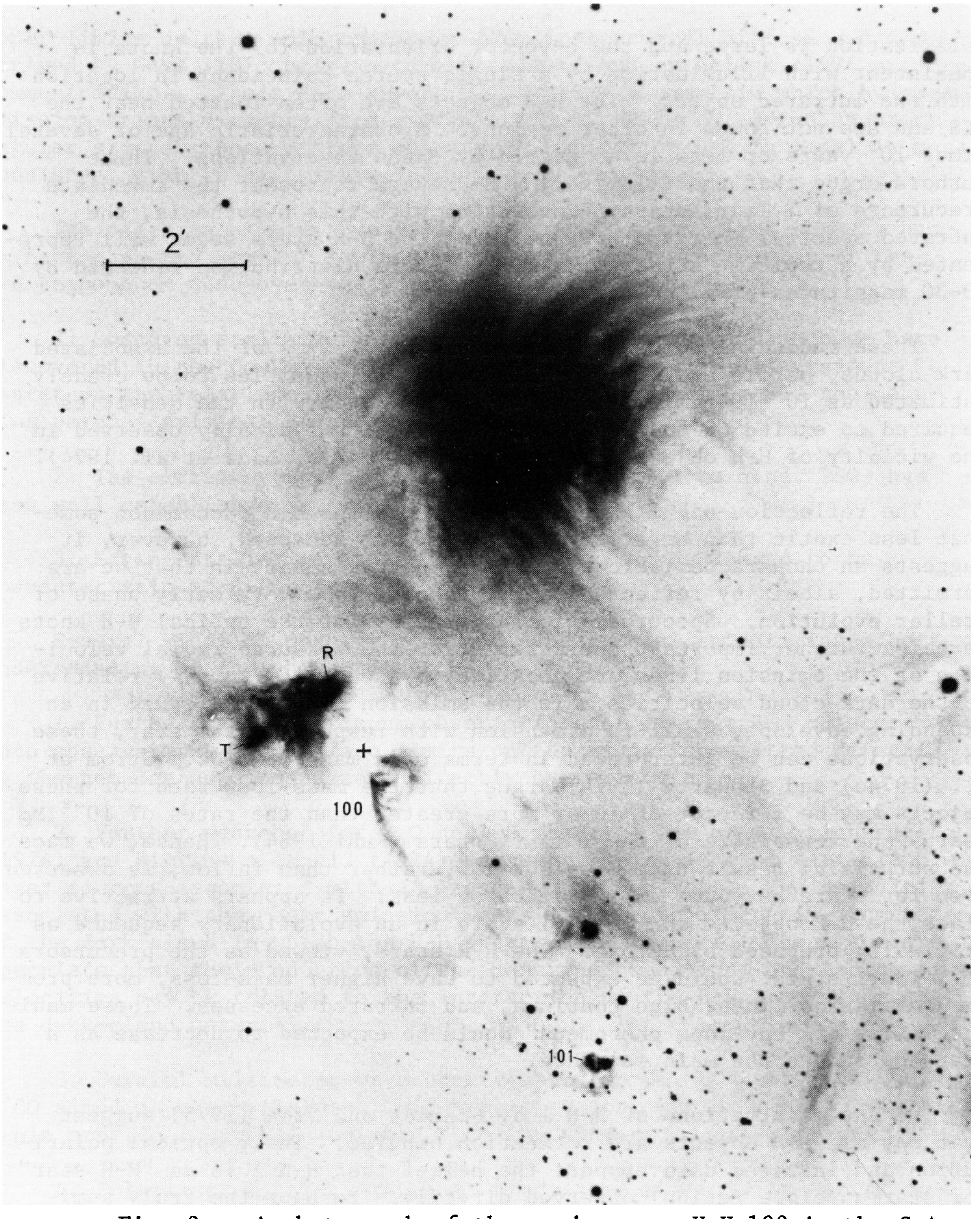

Fig. 3. - A photograph of the region near H-H 100 in the CrA dark cloud (top, north; left, east). A 098-02 plate plus RG 610 filter define the effective bandpass. Note the nearly circular "white patch" in which H-H 100 is located. We believe that this region represents the high-density, placental cloud from which the H-H star was formed. We thank Dr. T. Gull for allowing us to reproduce this photograph. Permission for republication was granted by Annual Reviews Inc. (*Ann. Rev. Astron. Astrophys.* 13, 187).

polarization is large and the e-vector orientation for the knots is consistent with illumination by a single source coincident in location with the infrared object. The H-H objects are often located near the HES and are not found in older regions. A characteristic age of several times 10^5 years or less is suggested by these observations. These authors argue that the illuminating H-H stars represent the immediate precursors of T Tauri stars. Consistent with this hypothesis, the infrared spectral energy distribution of the H-H stars seems well represented by a typical "strong-emission" T Tauri distribution reddened by 20-30 magnitudes of visual extinction.

These reddening values, combined with the sizes of the associated dark clouds, permit the minimum dark-cloud gas densities to be crudely estimated as 10^4-10^5 cm^{-3}. These estimates agree with the densities required to excite CS and HCN, both of which are typically observed in the vicinity of H-H objects (Morris et al. 1974a,b; Lada et al. 1974).

The reflection-nebula hypothesis renders the H-H phenomenon somewhat less exotic than heretofore believed. If accepted, however, it suggests an uncharacteristic kindness on nature's part in that we are permitted, albeit by reflected light, to observe a very early phase of stellar evolution. Spectroscopic observations of the optical H-H knots reveal a further important characteristic: the measured radial velocities of the emission lines are negative (by up to 140 km s^{-1}) relative to the dark-cloud velocities. If the emission lines are formed in an expanding envelope, small in dimension with respect to the star, these observations can be interpreted in terms of a mass outflow. Strom et al. (1974c) and Schwartz (1974) argue that the mass-loss rate for these objects may be a factor of 10 or more greater than the rates of 10^{-8} $M_\odot$ $years^{-1}$characteristic of the T Tauri stars (Kuhi 1964). Hence, we face the surprising result that mass outflow, rather than inflow, is observed even for stars as young as 10^5 years or less. It appears attractive to place the H-H objects and T Tauri stars in an evolutionary sequence as originally proposed by Herbig. The H-H stars, viewed as the precursors of T Tauri stars, would be expected to have higher mass-loss, more prominent emission lines, blue continua, and infrared excesses. These manifestations of "envelope phenomena" would be expected to decrease as a star approaches the main sequence.

Recent observations of H-H 1 by Schmidt and Vrba (1975) suggest that not all H-H objects are reflection nebulae. Their optical polarization and infrared data support the belief that H-H 1 is an "H-H star" (or star-envelope region) observed directly. Perhaps the truly semi-stellar objects (similar to H-H 1) of the class are H-H stars viewed directly whereas the more diffuse, nebulous objects (e.g., H-H 24) represent reflection nebulae scattering the light from an obscured H-H star (Schwartz 1974; Herbig 1976 private communication). Schwartz suggests a further possibility: the emission-line spectra observed in the H-H objects are produced in a region of the dark cloud shock-heated at the interface between the highly supersonic winds and the cold cloud material. A difficulty with this interpretation is presented by the upper limits on the radio continuum flux from several diffuse H-H objects derived by Goss (1975 private communication) and by Balick (1976 private communication). Their data appear to preclude a model in which hydrogen emission arises directly from a region nearly as large as the apparent angular size of these diffuse objects; a reflection nebula model is more consistent with these observations.

The plethora of new observations and models for these objects has perhaps obscured some of the basic advances in interpretation of the H-H phenomenon made over the past decade:

1. Obscured stellar objects associated with H-H nebulae have been discovered in the course of infrared surveys; areas of disagreement center on the relationship between these stellar objects and the nebulous patches originally called H-H objects.

2. The extreme youth of these objects relative to other YSOs has been well established.

3. Strong stellar winds are now generally acknowledged to be characteristic of H-H objects.

Several kinds of observations would be crucial to deriving a better understanding of the character of H-H objects:

1. Further radio continuum observations of diffuse H-H objects. Such observations would place limits on the radiation emitted directly by the nebulae as opposed to indirectly by reflection.

2. Further searches for H_2O and OH masers. The observations of Lo (1974) and Dickinson et al. (1974) suggest the presence of variable H_2O maser sources associated with at least two H-H objects. The velocities associated with the maser emission peaks differ significantly from those of the dark cloud in which the H-H objects are located. These authors speculate that the production of the masering conditions and the observed velocities may be related to the interaction of the H-H star winds with the dark-cloud material.

3. Careful millimeter-wave observations in CS, HCN, or possibly ^{13}CO aimed at observing weak, high-velocity components. Such data would again provide important insights into the wind-cloud interaction.

4. Polarization observations in bandpasses which admit radiation primarily from emission lines (e.g., Hα, [S II]). If the emission lines are produced in the nebulous patches by the interaction of a stellar wind with dark-cloud material, then any observed polarization should be small and in general uncorrelated in direction relative to the H-H stars. If the emission lines are produced in the envelope of an H-H star and scattered in our direction, then the polarization will be large and the e-vector oriented perpendicular to a radius vector drawn to the H-H star.

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5. Synoptic observations of the variability of H-H objects and H-H stars. Such observations, if carried out over sufficient time, should allow one to correlate the variability of the H-H star and the nebulous H-H patch if the reflection nebula hypothesis is correct. The differences in light travel from an H-H star to individual scattering patches may make this task difficult in practice.

6. Detailed studies of the optical and infrared continuum spectral energy distribution of the H-H stars and objects will be of great value. The greater sensitivity of infrared detectors and the availability of devices similar to the Lick image dissector scanner should permit accurate determination of the continuum component of the H-H objects.

7. Further studies similar to those recently undertaken by Böhm et al. (1974, 1976) of the variations of emission-line strengths with time should provide important constraints on the physical conditions in the region in which the line emission is produced. Studies based on higher dispersion spectra may provide the velocity resolution necessary to deduce some properties of the H-H stellar winds and possibly the wind-dark cloud interaction.

4. A SCENARIO FOR PRE-MAIN-SEQUENCE EVOLUTION

The observations of Herbig emission stars, T Tauri stars, and H-H objects provide an empirical basis for outlining the early stages of evolution (Strom 1976).

After the initial collapse and hydrodynamic phases, a YSO is still embedded deep both within a dark-cloud complex and within its own smaller, denser, placental cloud of gas and dust. At an early age, perhaps as young as 10^4 years, the YSO develops a strong stellar wind. The winds at this stage are characterized by mass-outflow rates of 10^{-5} to 10^{-6} $M_{\odot}$ year^{-1} and by outflow velocities of several hundred km s^{-1}. The wind is probably sufficient to halt further accretion of gas and dust from the protostellar cloud. In the case of more massive stars, radiation pressure may be more important than the wind in halting accretion (Larson and Starrfield 1971). On a time scale of 10^4 to 10^5 years, the stellar winds dissipate the placental dark-cloud material. During the first stages of dissipation, light from the newly-formed star "leaks" out through small breaks in the placental cloud and illuminates patches of dark-cloud material. These illuminated patches are identified with the H-H objects. At this stage, emission from a circumstellar envelope dominates the photospheric contribution.

If the newly-formed star lies close to the boundary of the dark-cloud complex, it will first be observed at an age of $\sim 10^5$ years as an extreme T Tauri star. In some cases, however, the YSO may remain embedded within the large dark-cloud complex for times as long as $\sim 10^7$ years. The stars of higher mass next acquire the spectral characteristics of the Herbig emission stars, while those of lower mass appear as "normal"

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T Tauri stars. (However, Grasdalen [1973] argues that some high-mass stars observed early in their approach toward the main sequence are first visible as T Tauri stars. In his view, they undergo a rapid rise in luminosity [by a factor of $\sim$100] and then join their equilibrium radiative tracks, becoming Herbig emission stars. He cites FU Ori and V1057 Cyg as possible examples of this behavior.)

As the star progresses toward the main sequence, the rate of mass outflow decreases and the envelope emission decreases as well. Possibly, during this stage, the low-mass ($M \lesssim 2\ M_{\odot}$) stars lose a considerable amount of angular momentum as a consequence of the mass outflow. At ages $\sim 10^6$ years, most pre-main-sequence stars have lost their prominent, identifying spectral characteristics. Emission features are observable only by careful photometric study of Balmer lines and the Balmer continuum (Strom et al. 1971, 1972).

Because our detailed knowledge of early stellar evolution is restricted primarily to those objects for which optical data are available, we have yet to probe in any detail stages of stellar evolution earlier than several times 10^4 years. The most promising candidates for extremely YSOs which deserve further scrutiny are those luminous objects discovered in the AFCRL survey at 10 and 20 μm (Walker and Price 1975) and in detailed 10-μm maps of dark-cloud complexes, and those objects presumably related to the continuum sources discovered at radio wavelengths in dark-cloud complexes. The next few years should witness significant progress in our understanding of the earlier phases of stellar evolution as these objects receive closer observational scrutiny at higher spectral resolution.

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