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# RECENT PROGRESS IN THE STUDY OF YOUNG STELLAR OBJECTS

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ABSTRACT. A recent study of the young cluster NGC 2264 resulted in the discovery of ~ 300 young stellar objects in the brightness range 17< B <21. These objects were placed in the L, $T_{eff}$ diagram. When combined with previous observations of the brighter members of the cluster these data permit us to discuss the spread in stellar formation time ($\Delta t > 10 \times 10^6$ years) and the rate of star formation as a function of time and mass; low mass (< 1 $M_o$) stars form first and massive stars only later in the history of the cluster.

High spectral resolution, high signal-to-noise ratio spectra of T Tau provide a list of spectral features in which incipient emission is apparent. These features are predicted to be formed in the upper atmosphere of T Tau and, in most cases, appear strongly in emission in more advanced T Tau stars. These data provide strong support for the view that T Tau stars have pronounced chromospheres.

The same technique was applied to the Herbig Ae/Be star, HK Ori. Although this star was originally classified as Ae, our Echelle data show a variation in apparent absorption line type from early A in the blue and late F in the red. It may not be possible to model the Ae/Be stars as objects characterized by normal photospheres and an "envelope" which produces the emission line spectrum and IR excess. A study of rotational velocities for the Herbig Ae/Be stars demonstrates that the distribution of vsini values for Ae/Be stars later than B5 differs significantly from that for "normal" Be stars.

Regions containing Herbig-Haro objects have been imaged at V, R, I and Hα using the KPNO CCD. These images provide a "roadmap" for isolating the contributions of the shock-excited and scattered light components of these objects. In the case of the region near HH12, the Hα image suggests the presence of a highly collimated bipolar flow.

## I. INTRODUCTION

Understanding the star formation process is one of the fundamental problems of modern astrophysics. On a macroscopic scale, we wish to know how material is assembled to form the molecular cloud complexes which give birth to stars and the factors which control the efficiency of star formation and the initial mass function. On a microscopic scale, we want to understand how a molecular-cloud forms pre-stellar fragments, and how the fragments evolve in the course of becoming young stellar objects. We also hope to learn how frequently disks form, what role they play during the early evolutionary history of stars, and whether planetary systems are a natural consequence of the birth process.

To answer the "macroscopic" questions we must turn to external galaxies. It is in this setting that we may examine the forces which orchestrate the star-forming process and the physical factors which influence the IMF and the star-forming efficiency. The "microscopic" questions must be answered by studying nearby regions of star formation in the Milky Way. HR diagrams of young clusters can reveal the sequence of star formation within a molecular cloud complex and perhaps lead to an understanding of the fragmentation process. We can also search for and scrutinize stars in their earliest evolutionary phases. Observations of young stellar objects (YSOs) and their circumstellar environment may provide the evidence which will allow us to deduce plausible routes of evolution from pre-stellar fragment to main sequence star. It is these "microscopic" aspects of the star-formation problem which are the focus of this review.

In this contribution, we chose to present not a comprehensive review but rather to summarize a selection of our current research work on young stellar objects. When I received the invitation from the organizing committee to participate in this conference, I felt challenged to prepare a paper which would reflect my admiration for Professor Haro and his work. Haro's sensitivity and receptivity to new phenomena is a consistent feature of his astronomical contributions. While the new results presented here hardly have the force of Haros' discoveries, I hope that they will at least provoke or at best stimulate some fresh approaches to the study of young stellar objects.

## II. STAR FORMATION IN NGC 2264 -- A POSSIBLE GUIDE TO THE FRAGMENTATION SEQUENCE IN A MOLECULAR CLOUD COMPLEX

The cluster associated with NGC 2264 has played a fundamental role in studies of the early stages of stellar evolution. Walker's (1956) classical work provides a census of the stellar population in this cluster to a limiting magnitude B ~ 16.0. The color-magnitude diagram (Fig. 1) shows a well populated main sequence from spectral type O9 to B9; stars of later type fall above and to the right of the zero age main sequence (ZAMS). This latter group is identified by Walker as a population of stars so young that their luminosities derive from conversion of gravitational to thermal energy. The onset of a pre main sequence (PMS) stellar population at about type A0 was predicted by the calculations of Henyey and his collaborators (Henyey et. al. (1955)). An approximate age for the cluster stars can be estimated from the main sequence turnoff luminosity of its most luminous member, S Mon; t ~ $3 \times 10^6$ years. According to Henyey, cluster stars born at the same time as S Mon should not have reached the main sequence at types later than A0--in agreement with the morphology of the color magnitude diagram. The close agreement of Henyey's predictions and Walker's observations represents an important early triumph in the interpretation of cluster color-magnitude diagrams.

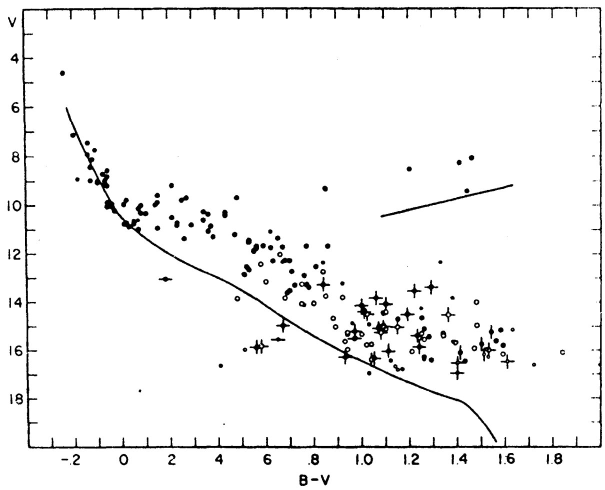



Figure 1. NGC 2264 color-magnitude diagram (Walker (1956)).

If all stars in NGC 2264 were born at the same time however, they should map a narrow locus above and to the right of the ZAMS; the observed locus in the CM diagram is instead much broader. In part, this results from the presence among the PMS population of a number of irregular, emission-line "Orion" variables. A study based on proper motion measurements (Vasilevskis, Sanders and Balz (1965)) permitted identification of cluster members brighter than B=16.5. Even if all known members of the Orion population are deleted from the CM diagram, the luminosity spread among the PMS members of NGC 2264 persists. As a consequence it appears necessary to relax the assumption that all stars in NGC 2264 were born at the same time.

Iben and Talbot (1965) undertook a study aimed at using the observed location of PMS stars in the CM diagram to deduce the star-forming history of this cluster. The observed V magnitudes and (B-V) colors for each star were transformed to luminosities (L) and effective temperatures ($T_{eff}$) by using standard relationships for main sequence stars. An age for each star was deduced by comparing its observed location in the L,$T_{eff}$ plane with computed PMS tracks. They concluded that the first stars to form in the NGC 2264 complex were of low mass; more massive stars were not formed until later in the history of the complex.

The Stroms and their collaborators (Strom et. al. (1971), Strom et. al. (1972a)) carried out an extensive optical and infrared survey of NGC 2264 in an attempt to understand how the locations of PMS stars in the L,$T_{eff}$ plane are affected by the "envelopes" of gas and dust which appear to be quite common among PMS stars. They suggest that the effects of gas emission and dust extinction and emission on observed spectral energy distributions of PMS stars are not understood with sufficient precision to permit accurate estimates of L and $T_{eff}$. Hence Iben and Talbot's conclusion regarding the sequence of star formation should be regarded with some suspicion. Warner et. al. (1977) carried out a thorough study of those stars which appeared free of significant "envelope" effects and concluded that the spread in ages deduced by Iben and Talbot was probably correct. Their data were insufficient, however, to permit comment regarding the sequence of star formation in the cluster.

If the sequence of star formation can be established with some certainty, we should be able to constrain models of cloud fragmentation and might be able to deduce as well the evolution of physical conditions within molecular cloud complexes. Because of the potential importance of such studies to a deeper understanding of the star-forming process, Adams, Strom and Strom (1983) decided to undertake a more thorough observational examination of the NGC 2264 cluster. Their aims were first, to minimize or evaluate the effects of envelopes on the derivation of L and $T_{eff}$, and second to search for PMS members nearly 100 times fainter than those located in previous surveys. Identification of such low mass members would permit better estimates of the spread in stellar formation times and provide a wider baseline for the determination of the star-forming sequence in NGC 2264.

The first challenge is to identify PMS members in the V magnitude range from 16 to 21. Since no adequate proper motion study is yet available, secondary criteria must be used. Adams et. al. considered a star to be a PMS object if it exhibited either a) Hα in emission, b) irregular variability or c) an ultraviolet excess.

The search for Hα emission objects was based on two surveys. The first was made by "photographing" selected regions of the cluster using an intensified SIT filtered with narrow band filters "on" and "off" the rest wavelength for Hα. The second was carried out photographically using broad band R and narrow band Hα plates obtained at the Mayall 4-m telescope.

Irregular variability was established by comparing the observed brightness of each stellar image on four Mayall 4-m B plates taken over a period of 3 years.

Stars exhibiting ultraviolet excesses were identified from their location in the (U-B), (B-V) plane.

Over 4000 stellar images were examined; approximately 300 satisfied one or all of the above criteria for identification as PMS candidates. From Mayall 4-m plates taken at V, R and I, colors and magnitudes were measured for each of the PMS candidates.

We selected (V-I) as the primary indicator of $T_{eff}$. Studies of the effects of envelope emission on the spectral energy distributions of young stellar objects in the Chameleon T-association (Grasdalen et. al. (1975)) suggested that such effects are negligible for wavelengths longward of 5000 Å except for the most extreme, strong emission objects. In order to check our assumption that (V-I) was unaffected by envelope emission, we searched for a correlation between the location of a star in the V, (V-I) plane with the strength of Hα as judged from the index Hα - R deduced from our plates; none was found.

V magnitudes were transformed to luminosities by means of a bolometric correction computed as the sum of a "standard" bolometric correction appropriate to late-type dwarfs (Johnson (1966), Veeder (1974)) of a given (V-I) and an empirical correction deduced from observation of a

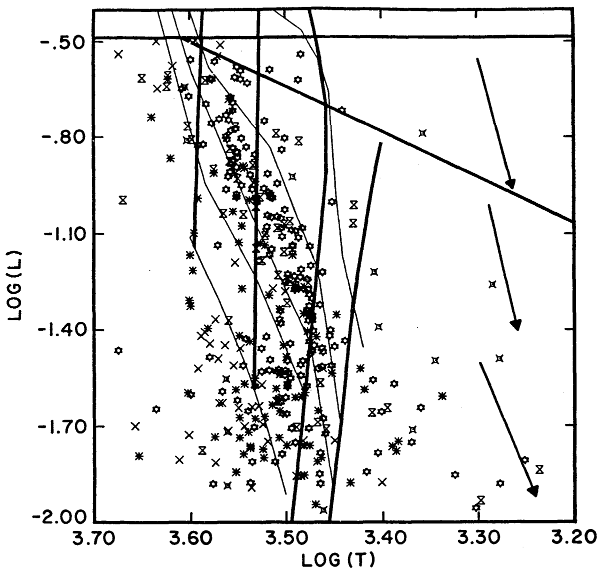



Figure 2. The L, $T_{eff}$ diagram for the lower mass stars in NGC 2264. The bold lines represent evolutionary tracks for stars of mass (from left to right in solar units): 0.5, 0.35, 0.2, and 0.1. The lighter lines indicate the isochrones (from upper right to lower left in units of $10^6$ year): 1.0, 3.0, 6.0, 10.0 and the ZAMS.

sample of 30 of our PMS candidates observed at J, H, K and L using the IRTF. The latter correction, amounting to approximately 0.3 dex in L, takes into account the average infrared excess of the PMS candidates. It implicitly assumes that the IR excess results from re-radiation by envelope dust of photospheric radiation absorbed at uv and optical wavelengths and re-radiated in the infrared.

The HR diagram for the stars in the Adams et. al. sample is reproduced in Figure 2. Superposed on the diagram are a set of PMS tracks for stars of the indicated masses adapted from Cohen and Kuhi (1979). Time constant loci are indicated for stellar ensembles characterized by ages of 1, 3, 6, and $10 \times 10^6$ years. The limit of our survey set by image saturation is also shown. From the location of each star in the HR diagram we can deduce both its age and its mass. In Figure 3, we plot, on an arbitrary scale, the star formation rate as a function of time for four mass ranges. Data for masses higher than 1 solar mass is adapted from the Iben and Talbot study.

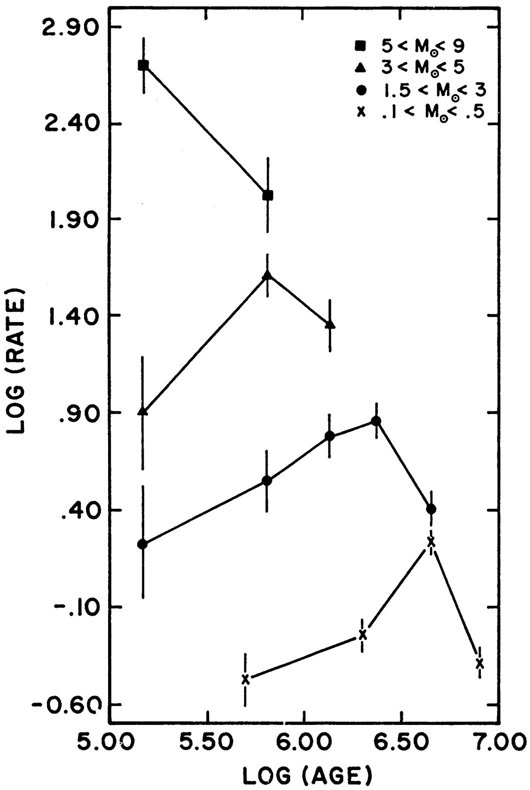



Figure 3. The star formation rate as a function of time in NGC 2264 for 4 mass ranges.

We first conclude that star formation in NGC 2264 has proceeded for at least the last 10 million years. If the tracks of Grossman, Hays and Graboske (1971) are used, an age spread of approximately 100 million years is deduced. Independent support for an age spread of at least 10 million years is found in the Warner et. al. (1977) survey. Here the location of proper motion members of late A and early F types in the HR diagram establishes the range in formation times.

Our data also provide support for the conclusion originally drawn by Iben and Talbot: The peak rate of star formation was reached first for low mass stars. Gradually, star formation at higher masses became more favored. We cannot, of course exclude the possibility that some O and early B stars were formed 10 to 100 million years ago; their descendents would be white dwarfs, undetectable in our survey. Our results suggest that models (e.g. Norman and Silk (1980)) in which the internal energy of the cloud increases monotonically with time (perhaps as the result of energy input from the first-formed stars) seem particularly attractive.

## III. T TAURI STARS

The observed radiation from T Tau stars is assumed to derive from a normal photosphere and from an "envelope" region in which the emission lines and excess uv, optical and IR continua characteristic of these objects are supposed to be produced. Much effort in recent years has been devoted to understand the physical characteristics of the envelope region(s).

### Infrared Excesses

Mendoza (1966) was the first to point out that T Tau stars as a class had infrared fluxes far in excess of those predicted for stars of their nominal photospheric type. In his discovery paper, he suggested that T Tau stars were surrounded by dust envelopes; the grains in these envelopes absorb some fraction of the photospheric radiation emanating from the T Tau stars and re-emit the absorbed radiation at IR wavelengths. Rydgren, Strom and Strom (1976) argued that the IR excesses arise instead from hydrogen free-free emission. The authors supposed that the ionized envelope responsible for producing free-free radiation in the IR also produced the Balmer emission lines and "blue continuum" (which they associated with free-bound Paschen continuum radiation). To match the shape of the observed IR spectral energy distribution with a free-free continuum requires that the reddening law characteristic of the dark clouds which contain T Tau stars be significantly different from a "normal" extinction curve (see Carrasco, Strom and Strom (1973)). Cohen and Kuhi (1979) argue that the best available evidence precludes extreme departures from normal extinction, except perhaps for those objects buried within the denser parts of molecular cloud complexes; hence they favored the dust envelope picture.

If the same mechanism which produces the Balmer line emission also produces the free-free emission, the strength of the emission lines should be correlated with the observed IR excess. Rydgren (1980) has sought such a correlation without success. Adams, Strom and Strom (1983) took advantage of the relatively small reddening toward NGC 2264 region to effect this test in an environment where ambiguities in dark cloud reddening laws cannot affect the conclusions; the HII region surrounding the cluster has evidently propagated to sufficient depths in the molecular cloud complex to "free" once embedded T Tau stars from surrounding cloud material. The authors find no correlation between the measured Hα strength and the location of T Tau stars in the (J-H), (H-K) diagram. Such a correlation would have been expected were free-free emission responsible for the IR excesses.

The best evidence at present favors dust emission as the likely cause for the observed IR excesses. Because the T Tau stars follow a well-defined locus in a variety of IR color-color diagrams, we can further argue that the near IR radiation is dominated from emission arising in the inner regions of the dust envelope; the characteristic temperature of the emitting region is near 1300 degrees (Rydgren, Schmelz and Vrba (1982)).

Optical Properties

In 1970, Herbig (1970) suggested that an active chromosphere, beginning at log τ(5000) between -1 and -2 might be able to explain the principal phenomena characterizing stars of the T Tau class: Ca II H and K and Balmer line emission, the metallic emission lines, the ultraviolet excess, blue veiling and the IR excess. By then, it had become well established that the intensity of chromospheric emission is greater in younger stars and that an increase in chromospheric emission was apparently linked to an increase in stellar rotational velocity. The youth of the T Tau stars combined with the belief, then held (though see Vogel and Kuhi (1981)), that they were relatively rapid rotators, provided strong circumstantial encouragement for Herbig's hypothesis.

Early work following Herbig's suggestion (e.g. Dumont et. al. (1973)) centered on attempts to match the profiles of strong lines believed capable of diagnosing the structure of the lower chromosphere. Recently, Cram (1979) examined in greater detail the range of phenomena in T Tau stars which might be explained in the context of plausible chromospheric models. His approach was to assume a model photosphere/chromosphere structure by adopting, ad hoc, a temperature rise superposed on a normal model photosphere. By adjusting the location of the temperature minimum and the magnitude of the temperature rise, Cram found a set of models capable of explaining: 1) the absence of absorption lines in "advanced" (strong emission) T Tau stars; 2) the existence of an apparent "blue continuum" produced by filling in of photospheric absorption features as well as continuum emission from the chromosphere; 3) the Balmer continuum excess; 4) the presence of a strong far ultraviolet continuum; 5) the general shape of strong emission lines. His chromospheric models were unable to explain: 1) the near IR excess; 2) detailed features and asymmetries in particular strong lines; and 3) the observed Balmer decrement. Similar conclusions were reached by Calvet (1981) in her dissertation (see also this meeting).

Two years ago, we undertook (in collaboration with Roger Davis of New Mexico State University) a program aimed at obtaining high resolution, high S/N spectra of a small selection of young stellar objects. Our approach as applied to the T Tau stars was as follows: 1) obtain high spectral resolution, high signal to noise spectra; 2) subtract standard star spectra from the T Tau spectra and examine the subtracted spectra for evidence of incipient emission; 3) use the strengths of the incipient emission in lines formed at different optical depths to map the temperature-depth relation in the upper photosphere and lower chromosphere.

The initial results of this survey are reported in Davis' (1983) dissertation. Illustrated in Figure 4 is a small region near λ4300Å of a spectrum of T Tau (K0-K1 IV) obtained with the KPNO Echelle (at a dispersion ~ 5Å/mm); the accompanying spectrum is that of a K0 III star, ε Tau. In the second panel we present the spectra once again. The top spectrum (T Tau) has been slightly smoothed while the spectrum of ε Tau has been broadened to the best fit vsini value for T Tau, 18 km/sec. In the third panel, we present the difference spectrum in the sense (T Tau)-(ε Tau). Note the appearance of the two FeI lines, now seen in "emission" in the subtracted spectrum; the cores of these lines have evidently been filled in by emission. A compilation of such features is given in Table 1. In the majority, the lines which show incipient emission in T Tau are those which tend to be emission features in more extreme T Tau stars.

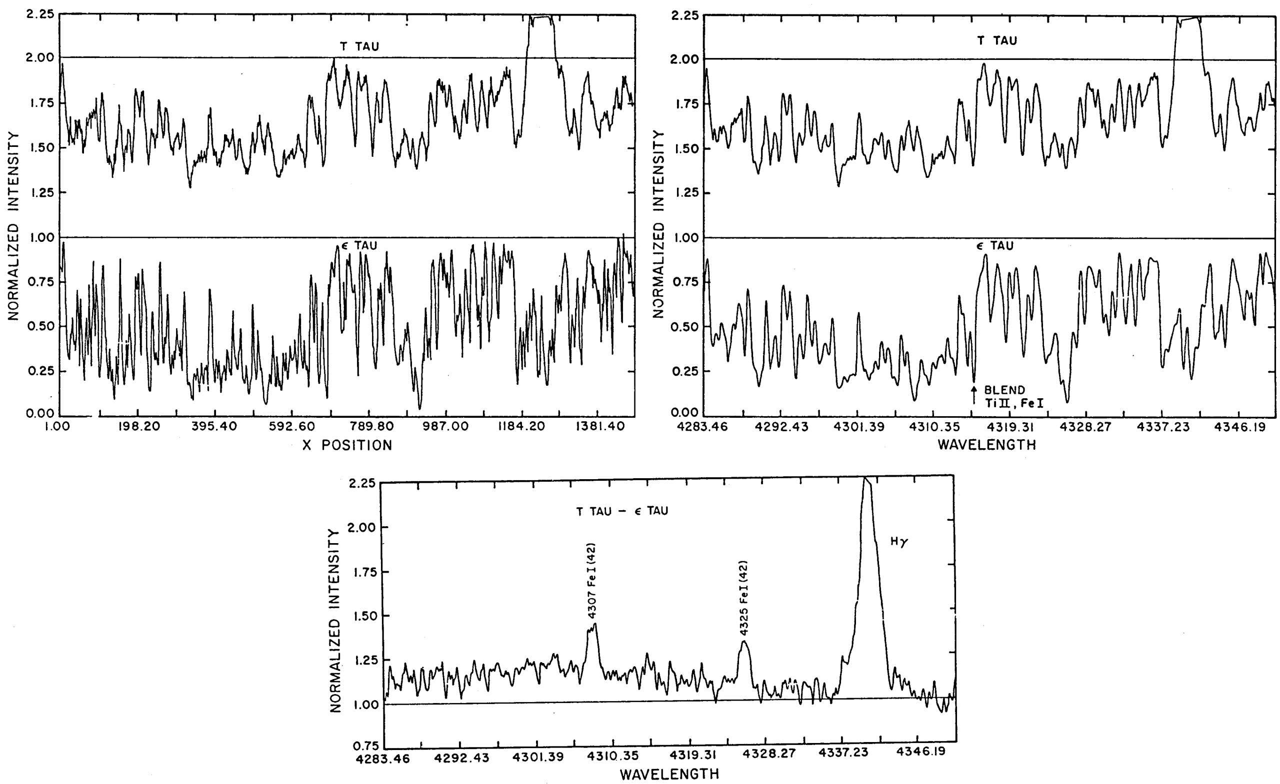



Figure 4. The three panels of this figure are respectively: a) a comparison of the original tracings of the spectra of T Tau and ε Tau; b) a comparison of the smoothed tracing of T Tau with the numerically broadened spectrum of ε Tau; and c) the resulting difference spectrum with the emission features labeled.

To determine whether the emission depends in a systematic way on the region of line formation, we constructed (at the suggestion of Duane Carbon of Kitt Peak) a plot of monochromatic optical depth, log(τ), expressed in units of τ(5000Å), the continuum optical depth at 5000Å. From this plot, we deduced that more than 70 percent of the lines estimated to form at $\tau(5000) < 10^{-4}$ were in incipient emission; the fraction of features exhibiting observable incipient emission decreased with increasing depth of formation.

We believe that these data provide strong support for the chromospheric origin of many T Tau emission features. In principle, calibrated spectra of this sort can be used to model the mean T-τ relation in the upper photospheres and lower chromospheres of T Tau stars.

Some Words of Caution Regarding Chromospheres

As mentioned above, chromospheres seem incapable of explaining the Balmer line profiles and emission line fluxes and the IR excesses. I doubt, but cannot demonstrate as yet that all of the "blue veiling" can be explained in the context of a chromospheric model.

Table 1

DIFFERENCE SPECTRA FEATURES

| Wavelength | Line ID | Appearance |
|---|---|---|
| 4045 | FeI(43) | W |
| 4063 | FeI(43) | S |
| 4068 | [SII](1F) | M* |
| 4071 | FeI(43) | M |
| 4077 | SrII(1) | M |
| 4101 | Hδ | S* |
| 4132 | FeI(43) | M |
| 4167 | MgI(15) | M |
| 4178 | FeII(28) | M |
| 4273 | FeII(27) | M |
| 4202 | FeII(42) | M |
| 4216 | SrII(1) | S |
| 4226 | CaI(2) | M |
| 4233 | FeII(27) | S |
| 4271 | FeI(42) | M |
| 4274 | CrI(1) | M |
| 4307 | FeI(42) | S |
| 4325 | FeI(42) | M |
| 4340 | Hα | S* |
| 4351 | FeII(27), MgI(14) | M |
| 4383, 4385 | FeI(41), FeII(27) | M |
| 4404 | FeI(41) | W |
| 4522 | FeII(38) | W |
| 4549 | FeII(38) TiII(82) | M |
| 4571 | TiII(82), MgII(1) | M |
| 4583 | FeII(38) | M |
| 4629 | TiII(38), FeII(37) | M |
| 4861 | Hβ | S* |
| 4951 | FeI(318) | W |
| 4957 | FeI(318) | M |
| 5041 | FeI(16) | M |
| 5051 | FeI(16) | M |
| 5123 | FeI(16) | M |
| 5167 | MgI(2) | S |
| 5169 | FeII(42) | S |
| 5172 | MgI(2) | S |
| 5197 | FeII(49) | M |
| 5208 | CrI(7), FeI(553) | W |
| 5227 | FeI(37) | M |
| 5234 | FeII(49) | M |
| 5316 | FeII(48,49) | S |
| 5328 | FeI(15) | M |
| 5241 | FeI(37) | M |
| 5397 | FeI(15) | W |
| 5429 | FeI(15) | M |
| 5434 | FeI(15) | W |
| 5446 | FeI(15) | W |
| 5875 | HeI(11) | S* |
| 5993 | OI(44) | W |
| 6191 | FeI(169) | W |
| 6300 | [OI](1F) | S |
| 6363 | [OI](1F) | W |
| 6563 | Hα | S* |
| 6717 | [SII](2F) | S* |
| 6731 | [SII](2F) | S* |

*Bright line in T Tau spectrum
W = Weak M = Moderate S = Strong

Of particular concern are those objects in which the "excess" emission in the optical and ultraviolet is comparable in luminosity to the value currently estimated for the photosphere. Should we assume that the energy per unit time deposited in the chromosphere equals or exceeds that radiated by the "photosphere"? Also, what are we to make of those objects in which changes in optical luminosity of factors of 10 or more take place on timescales of weeks or less? In most cases, the objects remain bright or faint for long periods preceding and following an "outburst" or dimming; hence flaring seems excluded. As yet, there is no evidence that a change in photospheric spectral type accompanies these dramatic brightness variations. In fact, the best evidence points to changes in the excess optical "continuum", which we are now tempted to attribute to chromospheric line and continuum emission. Can we accept models in which the chromosphere turns on and off with such apparent rapidity?

Chromospheres are unlikely to explain the emission continua in the extreme cases cited above. It is my belief that models in which infall, either from a spherical envelope or an accretion disk, supplies the observed luminosity in the optical and ultraviolet merit far more careful observational and theoretical scrutiny.

## IV. THE HERBIG Ae AND Be STARS

In 1960, Herbig (1960) identified a set of young stellar objects which he believed to be higher mass counterparts of the T Tau stars. By analogy with the T Tau stars, Herbig reasoned that early-type PMS stars would be characterized by irregular variability and bright hydrogen lines. To exclude, as best possible, normal Be stars from his list of PMS objects, he demanded that members of his class of young Ae/Be stars also illuminate nearby dark cloud material, thus ensuring close association with molecular cloud complexes, the apparent birth places of stars.

Later, Strom et. al. (1972b) attempted to locate the Herbig Ae/Be stars in the L,$T_{eff}$ plane. Observed spectral types were used to estimate $T_{eff}$, while L values followed from quantitative estimates of surface gravity obtained from observation of the wings of the hydrogen lines Hγ through Hη. These authors conclude that the majority of the stars in Herbig's sample have surface gravities appropriate to pre main sequence stars. This evidence, combined with their spectrophotometric characteristics, appears to place the Herbig Ae/Be stars among the youngest known stellar objects.

Recently, Herbst et. al. (1982) carried out an extensive survey of stellar populations in the vicinity of "R-Associations"--groups of stars associated with reflection nebulae. They find a number of objects which share the spectrophotometric properties of Herbig Ae/Be stars. These objects also appear to fall above the main sequence in the color magnitude diagram but largely lie within the domain occupied by rapidly rotating Be stars. Consequently, these authors propose that the Herbig Ae/Be stars may not be PMS objects after all, but rather may be ordinary Be stars associated with dark cloud material. Davis, Strom and Strom (1983) have estimated rotational velocities for a large sample of Herbig emission stars. In Figure 5, we present two

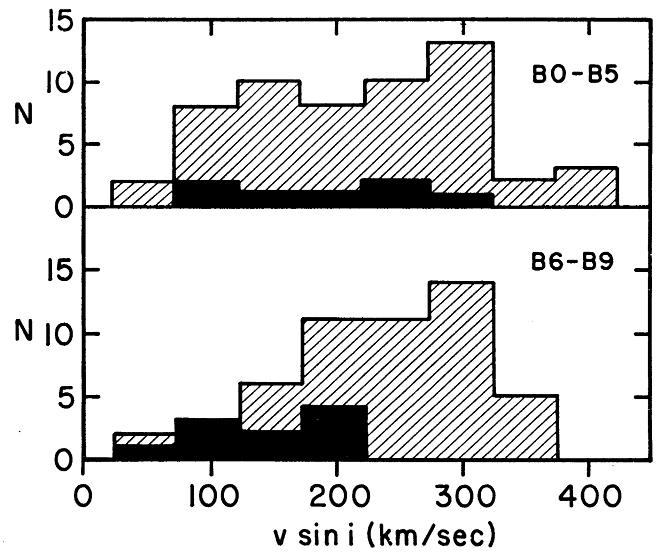



Figure 5. Two histograms showing the distribution of rotational velocities for ordinary Be stars and the Herbig Ae/Be stars. The cross hatched region shows the distribution for the ordinary Be stars, and the solid region shows that for the Herbig Ae/Be stars.

histograms summarizing the observed frequency distribution of vsini values for the Ae/Be stars of types 1) between B0 and B5 and, 2) between B6 and A0. We conclude that the Herbig emission stars of type B0 to B5 cannot be distinguished from ordinary Be stars on the basis of observed rotational velocity alone. For the much larger sample of later type Herbig emission stars, we can state with certainty that their distribution of vsini values differs significantly from that of normal Be stars; the Herbig Ae/Be stars must have an intrinsic distribution of rotational velocities peaking at much smaller values than the breakup velocity characteristic of ordinary Be stars.

To this evidence, the following points of distinction between normal and Herbig Ae/Be stars should be mentioned: 1) larger amplitude variability (at least on timescales of decades), 2) the presence of strong P Cygni profiles (BD +61 154, HD 250550, Z CMa, MWC 1080), 3) IR excesses stronger than those characteristic of "normal" Be stars, 4) the presence of Li I absorption (HK Ori and Z CMa), 5) association with molecular clouds containing other examples of young stellar objects, and 6) the presence of ultraviolet absorption features such as C IV, A III, Fe III, (Sitko et. al. (1982)) which are observed in Herbig emission stars of nominal optical spectral type much later than those in which such high excitation features normally appear.

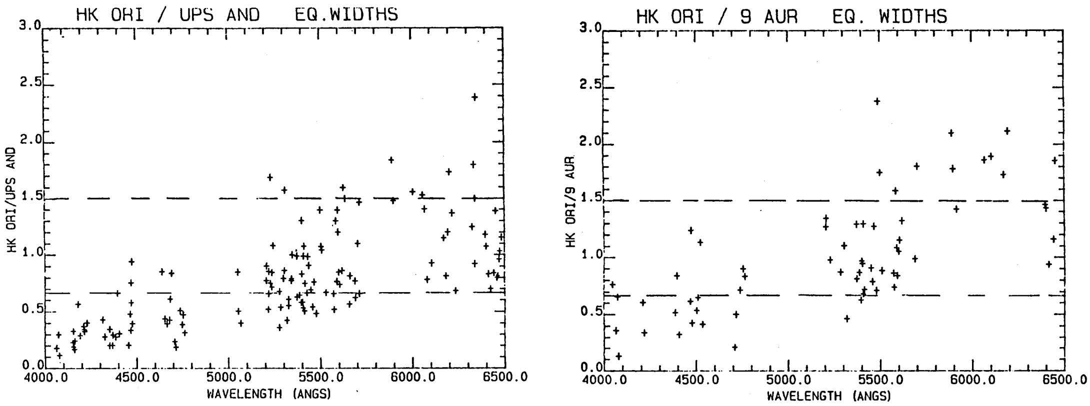
Perhaps because their spectra appear to be far simpler than those of their later-type analogs, the T Tau stars, the Herbig emission stars have thus far received less attention. As part of our program to study young stellar objects at high spectral resolution and high signal to noise, we obtained Echelle spectrograms of a selection of Herbig Ae/Be stars. We report here our initial results for HK Ori.

## The Unusual Case of HK Ori

HK Ori lies at the south end of a small, relatively bright triangular reflection nebula. The cloud containing this object is located within the H II rim surrounding λ Ori. The molecular cloud associated with this H II region contains over 30 Hα emission objects; several of these fall within the reflection nebula associated with HK Ori. This star was originally classified as Ae by Herbig and as an early A star by Strom et. al. (1972b). This classification is based on the appearance of the blue spectrum alone.

Echelle spectrograms of dispersion ~ 5Å/mm were obtained for HK Ori during November, 1980 and February, 1982. The spectrograms covered the wavelength range from 3800Å to 7000Å. In the blue, HK Ori appears to be an early to middle A star; in the red (longward of 5500Å), it has the appearance of a middle F-star. Li I appears prominently in absorption!

The variation of "spectral type" with wavelength is illustrated more quantitatively in Figures 6 and 7. Here we plot the ratio of observed equivalent widths for individual lines measured in HK Ori to those for υ And (F8 V) and for 9 Aur(F0 V) respectively. In Figure 6, note that the equivalent width ratios are close to unity for $\lambda > 5000$Å while at $\lambda < 4500$Å the ratios are near 0.4. In Figure 7, the equivalent width ratios are near unity for $5000 < \lambda < 5500$Å, greater than unity for $\lambda > 5500$Å and near 0.6 for lines with $\lambda < 4600$Å. In Figure 8, we illustrate the best fit linear relationship between equivalent width ratios and wavelength for HK Ori/υ And, HK Ori/9 Aur and HK Ori/21 Lyn (Al IV). Also plotted are the best fit lines to 21 Lyn/υ And, and 9 Aur/υ And equivalent width ratios as a function of wavelength. Note that the behavior of HK Ori is unique in this diagram in that the equivalent width ratios show a strong wavelength dependence. We conclude that the absorption line "type" of HK Ori varies from early A near 4000Å to late F near 6500Å.




Figures 6 and 7. The observed ratios of equivalent widths for individual lines as a function of wavelength. The ratios are in the sense HK Ori to υ And and 9 Aur respectively.

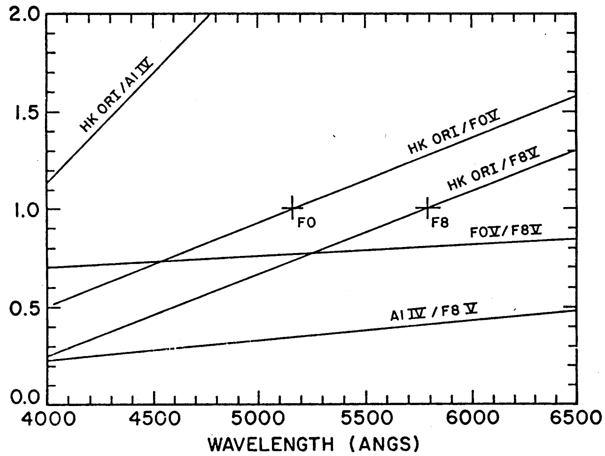



Figure 8. The variation of the ratios of equivalent widths with wavelength for 5 pairs of spectra. A detailed discussion will be found on page 209 in the text.

We can rule out veiling as the cause of these apparent variations because features such as Ca II K and Mg II 4481 are much stronger than those appropriate to an F-type star.

Lines at wavelengths longward of 5500Å show a systemic velocity (in each year of observation) equal to that of the molecular cloud to within 2 km/sec. The blue lines ($\lambda < 4500$Å) appear to be asymmetrical with extended red wings and sharper blue edges. The centroid velocity is redward displaced by ~ 30 km/sec relative to the red lines. However, the signal to noise of our blue data must be improved before these results can be accepted with certainty.

We cannot rule out duplicity (for example a main sequence A star and a pre-main sequence F star) as a plausible explanation. However, because the systemic velocity of the red features is measured to be equal to that of the cloud on 2 pairs of nights separated by over a year we can certainly exclude a close binary. If the blue features are in fact redshifted by 30 km/sec and constant with time, the binary hypothesis becomes nearly impossible to defend.

At the moment, we favor a model in which the "hot" absorption features are produced in an accreting flow.

The Herbig emission star Z CMa shares many of the same characteristics as HK Ori although thus far its spectrum has defied simple decomposition. We note as well the observations of Sitko et. al. (1981) who find evidence of anomalous high excitation absorption features in the spectra of several Herbig emission stars.

These data suggest that we view with caution simple pictures in which the observed spectra of the Herbig emission objects derive from a nearly normal photosphere and an "envelope" region responsible for producing the hydrogen line emission and perhaps the infrared excess. We would do well to scrutinize these deceptively simple objects more closely.

## V. HERBIG-HARO OBJECTS

It is now generally thought (Schwartz (1983)) that the optical radiation from Herbig-Haro objects is composed of two components: a) a low-to-moderate excitation emission line spectrum produced by shock heating of molecular cloud material by a highly supersonic stellar wind and b) a spectrum emanating from the photosphere and envelope of a young stellar object (embedded within a molecular cloud) scattered in the direction of the observer by nearby dust. In most cases, the YSO is embedded so deeply within the cloud complex that it is obscured at optical wavelengths; in a few cases it now appears as if the star responsible for exciting the HH object can be observed optically.

Recent mm-line observations of regions surrounding HH objects suggest that the winds emanating from the embedded YSO have a significant effect on the nearby molecular cloud material. A number of observers (Snell, Loren and Plambeck (1980), Edwards and Snell (1983) for example) have observed bipolar outflows extending to distances several tenths of a parsec from the embedded star.

The HH objects provide an important opportunity, therefore, to study the physical characteristics of YSOs at an early stage in their evolutionary history and to evaluate their role in influencing the internal dynamics (and possibly the future star forming activity) of molecular cloud complexes.

We have recently undertaken a program directed toward obtaining more detailed optical observations of selected molecular clouds containing Herbig-Haro objects. Our objectives are first to map the shock excited gas and second, to identify those regions of an HH object in which the scattered light spectrum from the embedded YSO dominates; if we can isolate such regions, we might learn what kinds of stars are responsible for exciting these nebulae.

Each region was imaged at V, R, I and Hα ($\Delta\lambda$ = 38Å) using the RCA CCD on the KPNO 0.9 meter telescope. The V and I filters contain virtually no emission lines known to be prominent in HH objects. Hence, they should provide a sensitive probe of the scattered light component in an HH complex. The narrow band Hα filter admits both Hα and [N II]6584, two of the strongest emission lines in typical HH objects. Thus the monochromatic image taken through this filter should provide a map of the shock excited gas associated with HH 12. The R filter admits the emission features of [O I], [N II], Hα, [S II], as well as any scattered stellar continuum. In combination with the Hα frame, it defines an index which can be used to identify Hα emission objects within the field.

The Unusual Case of HH 12

In January, 1983 we imaged a region near HH 12 in NGC 1333 and in Figure 9, we reproduce a montage of our V, R, I and Hα observations. We find that:

1) The HH 12 complex is dominated by emission from shock-excited gas. Only the red nebulosity to the east (labelled "r" in Figure 9) appears to be predominantly scattered continuum. This nebulosity is almost coincident with the infrared source "SVS 12" (Strom, Vrba and Strom (1976)) and a 100 micron source recently observed by Harvey et. al. (1983).

2) Weak but continuous emission joins star 107 with HH 12. The emission extends from the southwest of this star and continues through the star to the HH object.

Previously, the object thought responsible for the excitation of HH 12 was the obscured IR star SVS 12. The apparent bridge between star 107 and HH 12 suggests to us that star 107 is instead the culprit. Proper motion observations of individual knots in HH 12 were recently obtained by Herbig and Jones (1983; this meeting). We have superposed their derived vectors on the R image in Figure 9. The measured proper motions of the knots slightly favor star 108 as the exciting source although star 107 is by no means excluded. We regard the Herbig and Jones proper motions, combined with the morphological evidence as compelling reasons to implicate star 107 as the exciting source for HH 12.

John Stocke obtained a low resolution spectrum of star 107 using the reticon scanner on the Steward 2.3m telescope. This spectrum suggests a spectral type between M0 and M2, Hα is weakly in emission. From the CCD frames, we obtain for star 107: V=17.8, (V-R)=1.42, (V-I)=2.94; hence, star 107 has $M_V$=7.4 which places it 1.5 mag above the ZAMS. It is most probably a moderately obscured late-type T Tauri star having weak Hα emission. It is quite similar in its previous lack of distinction to the low luminosity T Tauri star thought responsible for ejecting or accelerating HH 1 and HH 2 (Cohen and Schwartz (1979)). Star 107 and the Cohen-Schwartz star should alert us to the possibility that not all HH objects are buried deep within molecular cloud complexes.

The morphology of the object is highly suggestive of a bipolar outflow. Such outflows have been inferred from optical and radio studies near several HH objects. However, HH 12 may be unique in that the "bridge" from star to HH object is so manifestly plain. As a preliminary check on this hyphothesis, we obtained a spectrogram of the jet just south of star 107 using the KPNO echelle spectrograph. A 45-minute exposure revealed the Hα emission feature expected from the direct CCD image, and from it we deduce that the southern "jet" has a velocity of 77 km/sec relative to the NGC 1333 molecular cloud. The mean radial velocity of the knots in HH 12 (north of star 107) were measured by Strom, Grasdalen and Strom (1974) to be -65 km/sec. Taken together, the morphological and radial velocity data suggest that a highly collimated, bipolar mass outflow from star 107 is responsible for exciting HH 12. If we adopt an outflow velocity of 100 km/sec, the projected length of the jet on the plane of the sky (about 0.3 pc) suggests that the wind emanating from star 107 has been approximately steady for several thousand years, though the "jet" appears to precess.

It is clearly important to our understanding of the nature of outflows from young stellar objects to establish that the emission apparently emanating from star 107 represents an optical manifestation of a collimated and perhaps precessing bipolar flow. A detailed study of the velocities along the "jet" will be of importance. Further details regarding our initial study of HH 12 will be found in Strom, Strom and Stocke (1983).

The HH 29, 102 Region in L 1551

In Figure 10 we present a montage of CCD frames for the region in the Lynds 1551 cloud complex containing HH 29 and HH 102. Strom, Strom and Vrba (1976) discovered the infrared source, IRS 5, generally believed to be the exciting source for the HH nebulosity. Snell, Loren and Plambeck (1980) found evidence from CO maps of a bipolar outflow centered on IRS 5. Velocities of approach appear coincident with the large emission region to the southwest of IRS 5 and designated HH 102 by Strom et. al. (1974). Optical velocities for the nebulosity also indicate a flow in the direction of the earth.

The Hα image of our montage reveals a number of bright, presumably shock-excited clumps contained within a conical region emanating from IRS 5. At V and I we see a relatively smooth reflection nebula exterior to this region. This morphology suggests that the wind from IRS 5 has produced the conical region (perhaps a cavity) within which we observe Hα clumps shock-excited by the wind. The exterior "rim" prominent in the V and I frames maps the boundary of the present-day wind-cloud interaction. Whether or not this picture is correct, it is plain that the shock-excited and reflection components are easily distinguished in this region. It should be possible to use the "roadmap" of reflection and shock-excited domains in this and other regions to address a number of outstanding current problems in the study of HH objects. In particular, observation of the scattered light component will provide an opportunity to probe the nature of the exciting stars. With spectra of appropriate resolution, it may be possible to estimate the present-day mass flow rates from the surfaces of the exciting stars. Examination of the velocity field and shock excitation conditions should permit detailed tests of wind-cloud interaction models.

VI. ACKNOWLEDGEMENTS

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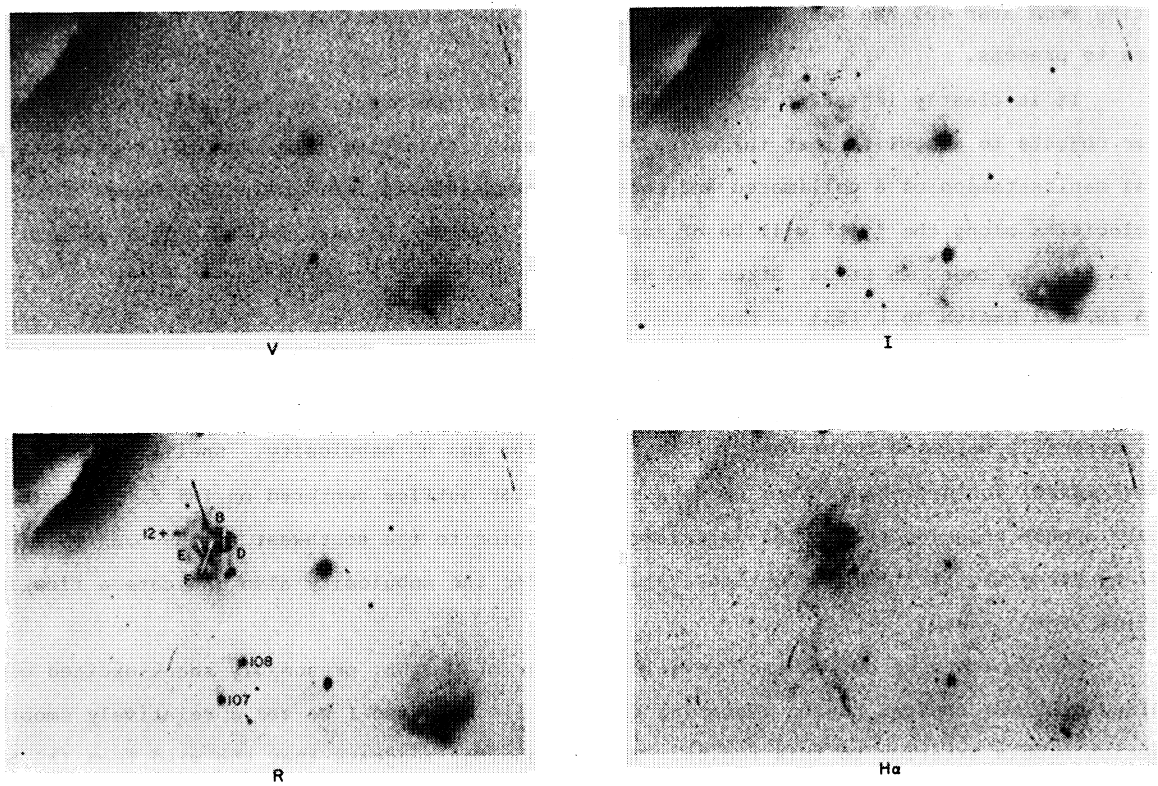


Figure 9. A montage of CCD frames for the region near HH 12. The proper motion vectors from Herbig and Jones (1983) are shown, along with the position for SVS 12, and stars 107 & 108.

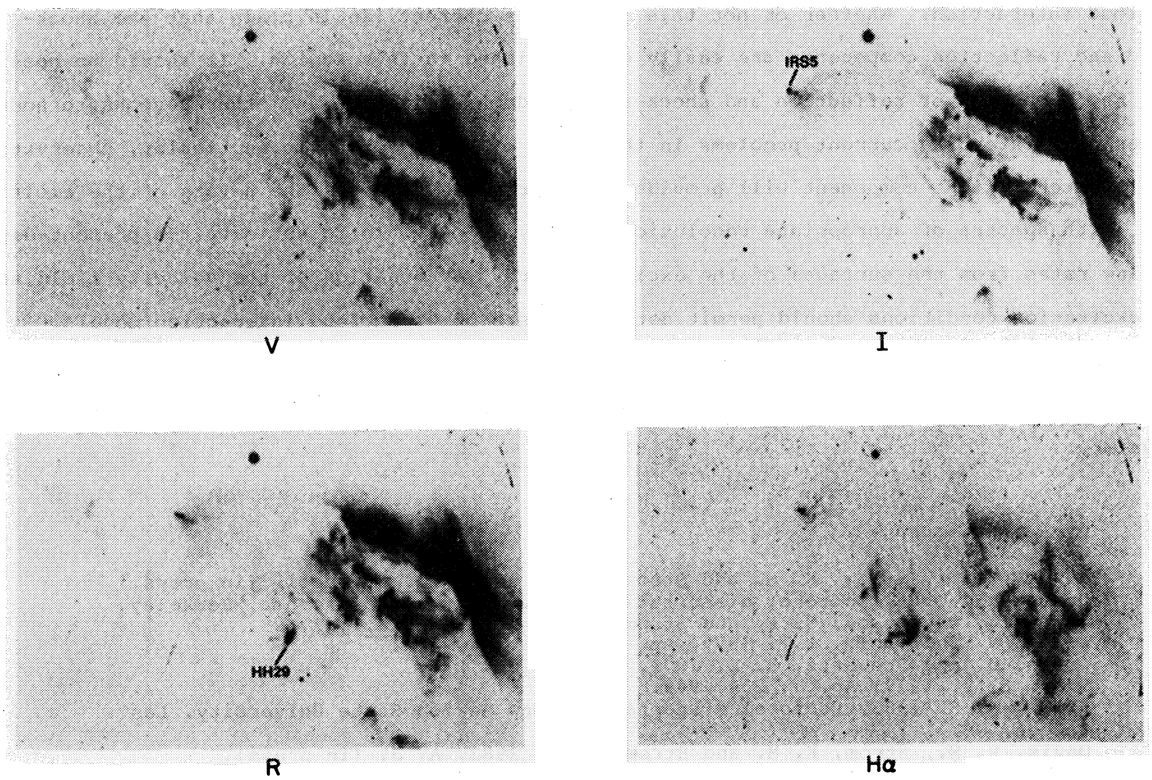


Figure 10. A montage of CCD frames for the region near HH 29 - 102 in L1551.

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## DISCUSSION

*Franco:* OB stars seem to show sequential formation. T Tau stars, however, seem to be more evenly spread in the regions of star formation. What kind of insight can we obtain from IR observations about the mechanisms that control the star formation process?

*Weaver:* Can the variation of equivalent width ratios with wavelength in the Herbig Ae/Be stars compared to normal stars be explained by an increasing blue veiling in the Ae/Be stars?

*S. Strom:* I do not think so. First, Mg II (λ4481) and the wings of the Ca II K-lines are much stronger than in an F8 star; hence the blue spectrum of HK Ori cannot result from a "veiled" F8 star. Excluding these features, a blind fit of a putative continuous "veiling" contribution yields $F_\nu \sim \nu^8$.

*Praderie:* From *IUE* high resolution spectra on 3 Ae stars, one notes several interesting phenomena in the *UV* of these stars: 1) no other emission lines than Mg II resonance lines, which have very conspicuous P Cyg profiles; 2) important Fe II spectrum, with, at some epochs, a splitting of the lines; at other epochs only asymmetric absorption lines, with velocities comparable to those provided by the Na D lines (150 km/s in AB Aur, i.e., smaller than the terminal velocity provided by Mg II lines); 3) all showing Fe III lines; 4) C IV and Si IV with deep absorption profiles (only AB Aur observed. We propose a deep chromosphere in accelerated expansion to explain Mg II profile and the C IV and Si IV absorption lines, prolongated by a colder envelope where the wind is decelerating,a dust circumstellar envelope comes next. References: Praderie *et al.* 1982; Talavera *et al.* 1982; Catala 1982; Catala *et al.* 1983.

*S. Strom:* Again, I am both fascinated and confused! It seems clear that the Herbig Ae/Be stars are surrounded by hot "chromosphere-like" envelopes. However, I must confess to a slight discomfort at identifying these regions as "atmospheres" in the sense of the star chromosphere.

*Brown:* (*Comment*) The Herbig Ae star HR 5999 shows typical chromospheric and transition region emission lines in *IUE* spectra (The *et al.*) suggesting that at least this star is partially convective. There are no indications that this is other than a typical chromosphere/transition region.

*S. Strom:* I wonder whether we can speak of solar-like chromospheres around Herbig Ae/Be stars which do not (in any conventional picture) have deep surface convection. I tend to believe that what we are seeing are features which arise in a region of temperature and density comparable to the chromospheres of T Tau stars, but which may be produced by very different physical mechanisms.

*Goodrich:* Could you comment on two possible alternative explanations of the jet visible on the last slide you showed: 1) that it is a stellar wind shocking on an irregular-outlined cloud, and 2) that it is reflection from the nearby HH-objects.

*S. Strom*: With respec to 2), the measured velocity of the southern jet is $\sim$ +100 km $s^{-1}$ relative to the cloud which I think rules out reflection. With respect to 1), we can make only morphological arguments until velocities are measured. However, the helical structure in the "jet" is shown in both the faint bridge and the bright HH 12.

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