STAR FORMATION: FROM OB ASSOCIATIONS TO PROTOSTARS

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1. INTRODUCTION

The study of star formation is a relatively young discipline of the field of astronomy. Up until the mid point of the twentieth century only a most rudimentary understanding of the subject was possible. This is because prior to that time there did not exist any substantive body of empirical data which could be used to critically test even the most basic hypotheses concerning stellar origins. However, as a result of impressive advances in observational technology and in our understanding of stellar evolution during the last forty years, the subject of star formation has developed into one of the most important branches of modern astrophysical research. A large body of observational data and a considerable literature pertaining to this subject now exist and a significant fraction of the international astronomical community devotes their efforts towards trying to comprehend the origins of stars and planets. Yet, despite these efforts we have yet to observationally identify, with any certainty, a single object in the process of stellar birth! Moreover, we have not yet produced a viable theory of star formation, one capable of being tested and refined by critical experiment. In many ways, stellar birth is as much a mystery today as it was forty years ago. However, there can be little doubt that during the last two decades truly revolutionary progress has been made in the quest to understand the star formation process in our galaxy. This apparent paradox in the state of our knowledge concerning stellar origins is resolved with the realization that the history of the study of star formation has been a history of the study of progressively earlier and earlier stages of stellar evolution. Indeed, it is in precisely this area of endeavor that we have learned so much.

In the 1940s and 1950s studies of star formation dealt primarily with the fossil record of star formation: clusters, OB and T associations, and the Initial Mass Function (IMF). Such studies revealed three important facts about star formation: first, star formation was occuring in the solar neighborhood in the present epoch

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of galactic history; second, not long after their formation most stars were once members of OB associations; and third, low mass stars were formed at a much greater frequency than high mass stars. In the 1960s, a great advance was made by the pioneering theoretical work of Hayashi and his collaborators in developing models for early stellar evolution, models which established that T-Tauri stars were objects in the very early stages of pre-main-sequence evolution. Impressive as all these findings were, they were fundamentally limited in what they could reveal about the star formation process because they were derived from observations of already formed stars. In an attempt to deal with this limitation considerable effort in the 1960s was devoted to studies of Herbig-Haro objects and HII regions because these objects were nebulous and presumably were associated with a much earlier phase of stellar evolution than the well developed stars in associations and clusters. These studies showed us that the formation of stars was often accompanied and followed by events and processes which were very disruptive to the original star forming material, however they revealed little about the actual process of star formation itself.

In the 1970s millimeter-wave CO observations provided astronomers with a powerful tool to directly probe the raw material of star formation. Such observations established that OB associations and therefore most stars form from Giant Molecular Clouds (GMCs). Since that time many efforts to study star formation have been directed toward probing deeper and deeper into molecular clouds, searching for earlier and earlier stages of stellar evolution, the ultimate goal being the observation of a protostar, an object in the process of assembling the bulk of the material it will contain when it ultimately reaches the main sequence as a hydrogen burning star. If current theoretical dogma and our intuition are correct, then the evolution of such objects should be dominated by collapse and infall motions of ambient molecular cloud material. Important advances in theoretical models for collapsing clouds and protostars were made during the 1970s (e.g., Larson 1973, Bodenheimer and Black 1978) and these suggested that protostars would likely be strong emitters of infrared emission. Observations during this period revealed numerous embedded infrared sources and protostellar candidates in molecular clouds. However, extensive studies of these objects during the first half of the present decade have produced the unexpected result that most are sources of energetic outflow of molecular cloud material. Convincing evidence for any inflow motions has so far eluded detection. This necessitated a revision of our understanding of both early stellar and protostellar evolution. Are protostars simultaneously sources of both outflow and infall? Do embedded infrared sources with outflow represent a new stage of early stellar evolution, a post-protostar stage? If so, where are the much sought after protostars? Such questions undoubtably will be the focus of much research during the rest of this decade. Virgorous pursuit of these questions aided by new advances in observational capabilities should lead to the identification of protostars and direct observation of stars in formation in the very near future.

Of course, this particular path of investigation from OB association to protostar has been dictated largely by the evolution of technology. Star formation occurs in the dust enshrouded wombs of molecular clouds and study of the goings on in such cold and obscured regions is only possible by observation in the millimeter, submillimeter and infrared bands of the spectrum. Such observations have become routinely possible only recently and as our technological capabilities improved so that we could more directly probe the sites of active star formation, we have discovered that early stellar evolution and star formation are much richer, complex and interesting processes than we could have imagined forty years ago. Consider, for example, that since the last IAU Symposium on Star Formation in Geneva in 1976, we have recognized the importance of giant molecular clouds, ascertained the nature of Herbig-Haro objects and discovered the energetic outflow phase of early stellar evolution. The questions we are investigating today are different than those we investigated 20-30 years ago. The questions along with the direction of our research change as technology opens new and unexplored windows in observational and physical parameter space and provides fresh insights into the star formation process. It is in this aspect that we have made fundamental advances toward an eventual comprehension of the process of stellar birth.

There are two approaches that have been generally adopted in the study of star formation in the galaxy. Investigation of global or macroscopic processes, such as spiral density waves, sequential star formation, the dynamical evolution of OB associations and clusters, and the initial mass function, on the one hand and investigation of local or microscopic processes, namely the formation and early evolution of individual objects, on the other hand. Synthesis of results from both approaches has enabled a viable scenario for the evolution of a young stellar object from outflow source to field star to be constructed. In this review I will attempt to present such a scenario for early stellar evolution based on our current understanding of the evolution of associations and clusters as well as individual young stellar objects in molecular clouds. The utility of studying the optical-infrared broadband energy distributions of embedded sources will be emphasized and the prospects of such studies for uncovering true protostars and directly deciphering the star formation process itself will be discussed.

2. THE EARLY DYNAMICAL EVOLUTION OF OB ASSOCIATIONS

Associations are loose aggregates of stars of the same physical type whose space densities are enhanced relative to that of field population of similar type stars (Blaauw 1964). However, their space densities are typically < 0.1 solar masses per cubic parsec, the critical density for a cluster to be stable aganist disruption due to galactic tides in the solar neighborhood (e.g., Bok 1934). Ambartsumian (1947) was the first to realize the important implication of this basic observation, namely that asociations were young, of order ten million years old. Since this was considerably less than the age of the galaxy, this observation provided one of the first fundamental demonstrations of the fact that star formation was occuring in the present epoch of galactic history.

Ambartsumian showed that associations were gravitationally unbound and systems of positive total energy. Determination of the actual expansion velocities of associations was then and is still a very difficult problem. The existence of runaway stars near many associations and early proper motion studies of the Sco-Cen and II Per associations suggested that expansion velocities of order 10 km/s might be characteristic. A number of hypotheses were advanced to explain the origin of these stellar systems of positive total energy. Ambartsumian proposed that associations were formed when massive, super dense bodies formed in the early history of the universe distintegrated producing both expanding groups of stars and associated gas and dust. (e.g., Ambartsumian 1955). Opik (1953) suggested that the ejecta from a supernova explosion could sweep up and compress interstellar matter into an expanding shell of gas which could then form stars which would retain the outward expansion motion of the supernova shell and form an unbound association of young stars. Oort (1954) proposed a similar solution using the expansion of an HII region rather than a supernova explosion to create expanding clouds of gas from which stars could form. All these ideas were derived from a basic common assumption that unbound groups of stars must have formed from expanding clouds of gas, that is, systems or complexes of interstellar matter with positive total energy. The question of the origin of associations was reduced to the problem of finding a mechanism for producing expanding systems of interstellar gas.

During the last ten years millimeter-wave CO observations have shown that associations form from giant molecular clouds (e.g., Elmegreen and Lada 1976, 1977, Blitz 1980) which are large (50-100 pc in their longest dimension) and massive (10,000-100,000 solar masses) complexes of molecular material. Giant molecular clouds have average mass densities of about 15 $M_\odot$ pc^{-3} and internal turbulent pressure (i.e., $\sim \rho v^2$) greatly in excess of the thermal pressure of the intercloud medium, they are clearly gravitationally confined. How is it that such bound clouds produce unbound associations? Observations of the λ Ori OB and T association led Deurr, Imhoff and Lada (1982) to propose an alternative scenario for the origin of expanding associations. This association is located within a low density HII region which is surrounded by a nearly spherical shell of interstellar gas and dust. The HII region has swept away nearly all the original molecular cloud from which the association was born allowing a fairly accurate accounting of total population of stars formed in the cloud. Assuming that the material in the swept up shell was once part of the molecular cloud that formed the association, Duerr, Imhoff and Lada compared the mass of gas in the shell to the mass of stars in the association and concluded that the star formation efficiency of the original cloud was very low (i.e., 0.2 to 0.3%). This suggested that in a relatively short time (i.e., the age of the HII region) the massive stars in the association have swept away the vast majority of the original binding mass of the system in which the stars formed. Clearly this would result in an unbound system of stars. According to Duerr, Imhoff and Lada the unbound state of associations is a natural consequence of star formation in a giant molecular cloud with a low conversion efficiency of gas into stars, followed by a rapid destruction and removal of the unprocessed gas from the system.

This scenario for the origin of unbound associations was independently discussed by von Hoerner (1968) who suggested that O stars were powerful enough to rapidly disperse a very massive star forming cloud. More detailed calculations by Whitworth (1979) showed that an entire giant cloud complex could be dispersed by O stars if only 4% of the cloudy material was converted into stars with an IMF typical of that of field stars. Calculations by Elmegreen and Lada (1977) showed that sequential OB star formation could produce even more efficient cloud dispersal. Evidence for the sequential star formation mechanism now exists for many clouds and associations (e.g., Blaauw 1964, Elmegreen 1985), a particularly lucid example being the W3/W4 molecular cloud complex (Lada et al. 1978, Thronson, Lada and Hewagama 1985).

Figure 1 is a schematic diagram which depicts the evolution of star formation in a giant molecular cloud and the creation of an expanding association. Initially low mass stars form throughout the entire cloud complex converting on the order of 1% of the gaseous mass into stars. At some point in time massive OB stars form in the cloud and heat, ionize and disrupt the surrounding molecular gas. The formation of the OB stars can lead to both the cessation of star formation locally (Herbig 1962) and the propagation and stimulation of additional massive star formation in deeper layers of the cloud (Elmegreen and Lada 1977). Ultimately, the formation of OB stars results in the dissipation of the entire complex. Initially stars form in the deep gravitational potential well of the bound and massive giant molecular cloud. They orbit in the cloud with velocities characteristic of the turbulent molecular gas. The OB stars remove the majority of the initial binding mass (90-99%) in a relatively short time and the stars do not have time to adiabatically adjust to remain in a bound configuration. The stellar system violently relaxes and expands with an expansion velocity comparable to its initial virial velocity dispersion. Even if the system could adjust to the loss of the molecular binding mass, its stellar density would still be too low to remain stable aganist galactic tides. Because of the low star formation efficiency the members of the association must expand into the field after the residual gas is removed.

An important prediction of this scenario for producing unbound associations is that the velocity dispersion of members of an expanding association is comparable to that of the gas in the original molecular

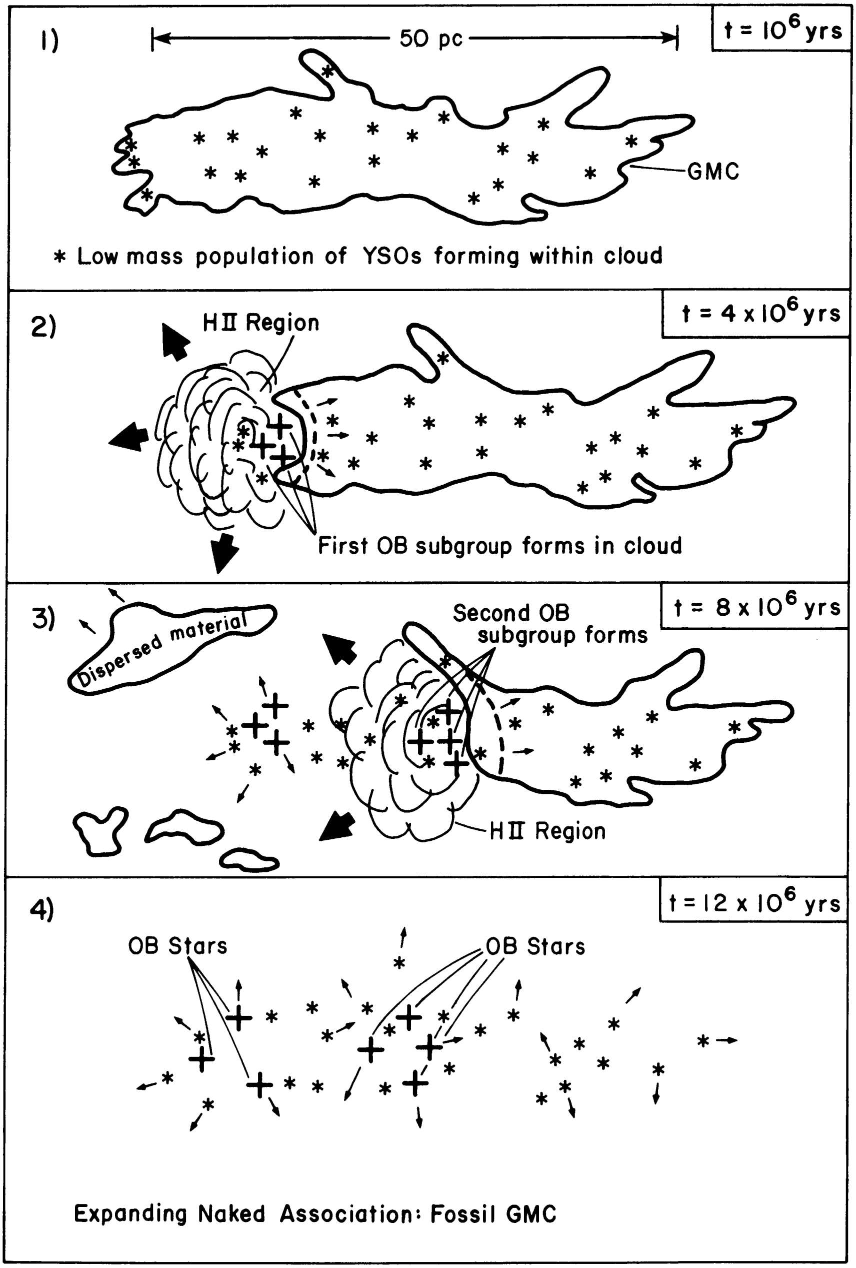


Figure 1. Probable stages in the formation of an expanding OB association from a giant molecular cloud. Low star formation efficiency in conjunction with efficient dispersal of residual, unprocessed molecular gas by OB stars result in a stellar system with positive total energy.

cloud, that is, on the order of a few km/s. Mathieu and Latham (1986) have measured the velocity dispersion of about 20 members of the λ Ori association and have found a velocity dispersion of about 2 km/s for the stars. This is very similar to the velocity widths of molecular lines from the cloudy material in the shell around the association and in giant molecular clouds in general. It is also interesting to note that the velocity dispersion of T Tauri stars in Taurus closely resembles that of the gas in the molecular cloud containing the stars (Dieter 1976, Jones and Herbig 1979). In addition the systematic increase in size with age of the three largest subgroups in the Ori OBI association (see Blaauw 1964) is consistent with an expansion velocity of a few km/s for the stars. These observations provide strong support for the contention that the unbound dynamical state of OB associations is a result of the combination of low star formation efficiency and rapid and efficient gas dispersal.

3. THE IMPORTANCE OF STAR FORMATION EFFICIENCY

The fundamental problem of star formation in OB associations does not lie in the search for a solution to origin of the expanding motions of the stars, since this is a natural consequence of star formation in giant molecular clouds with low star formation efficiency. The fundamental issue that needs to be addressed is why star formation is so inefficient in molecular clouds. Understanding this problem is intimately related to understanding the most basic physics of the star formation process itself.

At the present time it is not at all clear what the physical conditions are that conspire to produce star formation at low efficiency. This may turn out to be an extremely difficult problem to solve. However, nature may have provided a clue to the solution in the existence of bound galactic clusters. Only 10% of all stars are thought to have formed in bound clusters (e.g., Roberts 1957) and their existence suggests that in unusual circumstances the interplay of yet to be identified physical processes inside molecular clouds can lead to the formation of bound stellar groups. Apparently under certain physical circumstances, either the star formation efficiency in a cloud can become very high or stars can be formed in a high density configuration with low efficiency but with slow and benign removal of unprocessed gas (e.g., Lada, Margulis and Dearborn 1984, Wilking and Lada 1985). Whatever the case, comparative study of the physical conditions in molecular clouds producing bound clusters with those of clouds producing associations may provide the best approach to understanding this very important aspect of the star formation problem. The main difficulty in this approach is being able to identify molecular clouds that are in the process of cluster formation. If bound clusters are formed in regions where the star formation efficiency is high (25% or greater, e.g., Elmegreen 1983, Mathieu 1983, Lada, Margulis and Dearborn 1984), then determining the star formation efficiency in an appropriate volume of a molecular cloud could lead to the identification a proto-cluster. The key to this approach is to determine the "approporiate" volume within which to measure the star formation efficiency. If not chosen wisely the significance of the derived efficiency will not be clear. For example, we suspect that if one choses a small enough volume, say that encompassing the infalling envelope of a protostellar object, the star formation efficiency in that volume could approach very high values up to 100%, even though the star itself might be a member of an ultimately unbound group. A useful volume within which to measure the star formation efficiency might be that volume of a molecular cloud that contains 100 young stellar objects. That volume would be expected to be large for an association (tens of parsecs) but small (one parsec) for a cluster. The core of the Rho Ophiuchi cloud appears to be one such region where as many as 100 stars are located in a one parsec sized area and where there is also a relatively high star formation efficiency (25%, Wilking and Lada 1983). It would be clearly of interest to investigate and compare the physical conditions in regions of varying star formation efficiency. We already know that there are a number of differences between the region forming a cluster in the Ophiuchi dark cloud and the region forming a T association in Taurus, even though both are forming similar mass stars. The star formation activity is much more centrally condensed in the Ophiuchi cloud than in Taurus. The Ophiuchi dark cloud is considerably hotter (T = 35K) than the Taurus cloud (T = 10K). The origin and implication of these differences for star formation is not yet clear, but a better understanding of them is likely to provide an important key to unlocking the nature of the star forming mechanism in molecular clouds.

The concept of star formation efficiency may be as useful when considering the formation of a single object as it is for a cluster or association of stars. For example, ammonia observations of a number of isolated and nearby dense cores associated with low mass YSOs (e.g., Myers and Benson 1983, Benson, Myers and Wright 1984, Myers 1985) suggest star formation efficiencies of around 50% for regions of order .1 pc in radius. It is likely that the conditions in such cores closely resemble the initial physical conditions of a protostellar object. Indeed, one possible definition of a protostar is: that part of a molecular core within whose boundary the star formation efficiency approaches 100%. For low mass cores with masses similar to those discussed by Myers (1985) and power-law density gradients similar to an isothermal sphere, the size scale for a one solar mass protostar would be then on the order of .05 pc. High resolution molecular line and infrared observations capable of resolving such structures in nearby clouds offer the best possibility of directly detecting and studying stars in the actual process of formation. Such observations are now becoming possible and unambigous identification of protostars is likely to occur very soon. Already infrared observations are beginning to reveal new and interesting information about the nature and evolution of embedded young stellar objects.

4. THE EVOLUTION OF PROTOSTARS AND YOUNG STELLAR OBJECTS

4.1 The Energy Distributions of Young Stellar Objects

In an attempt to study the nature of the embedded population of infrared sources in the core of the Ophiuchi dark cloud, infrared broad-band photometery from 1 to 20 microns was obtained for a large fraction of the sources in the cloud by Wilking and Lada (1983) and Lada and Wilking (1984). From this data Lada and Wilking (1984, hereafter, LW) constructed energy distributions [i.e., $\log(\lambda F_\lambda)$ vs. $\log(\lambda)$] for all the observed sources. From analysis of these energy distributions LW found that the infrared sources could be divided into morphological classes based on the shapes of their energy distributions. In particular three distinct classes could be identified: I- sources with broader than blackbody energy distributions which were rising longward of 2 microns wavelength; II- sources with broader than blackbody energy distributions but flat or decreasing energy distributions longward of 2 microns; III- sources whose energy distributions could be modeled with reddened blackbodies with no or little excess near infrared emission, and slight mid infrared excess emission most likely caused by the relatively cool and distant grains responsible for the observed extinction to the objects. Class I sources were all invisible and deeply embedded in the cloud. Class II and III sources were associated for the most part with visible stars a large number of which had known optical classifications. Nearly all the previously known class II sources were classified as T Tauri stars. Where available, optical classifications of the class III sources agreed very well with the effective temperatures and luminosities derived from fits of reddened blackbody functions to their energy distributions.

The LW classification scheme can be made more quantitative by defining the spectral index:

$$a = \frac{d\log(\lambda F_\lambda)}{d\log(\lambda)}$$

For class I sources $0 < a \lesssim +3$; for class II sources $-2 \lesssim a \leq 0$ and for class III sources $-3 < a \lesssim -2$. A summary of the three types of energy distributions is shown in figure 2. It is interesting to note that when classified this way all the visible objects in the Ophiuchi cloud were characterized by energy distributions with negative spectral indices. At the same time all the sources with positive spectral indices in the LW sample were invisible, as mentioned above.

Figures 3, 4 and 5 show observed examples of class I, II and III sources respectively. Except for the source L1551 IRS 5 all the sources are from the Ophiuchi sample of LW with some additional IRAS measurements for sources WL-16 and WL-22 taken from a study by Young, Lada and Wilking (1986). The observations of L1551 IRS5 are based on data presented by Cohen *et al*. (1984). It is interesting to ask if the

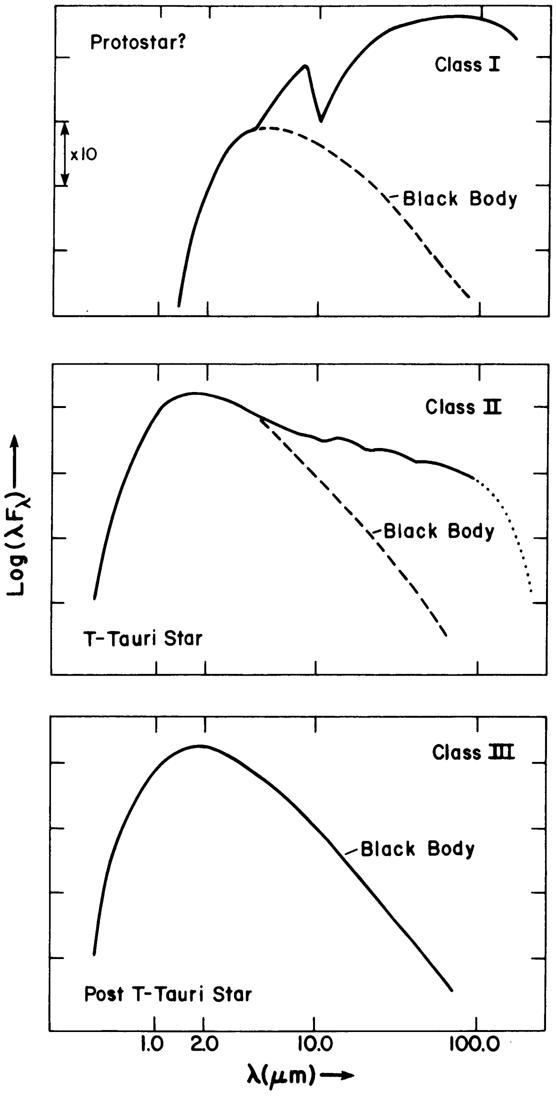
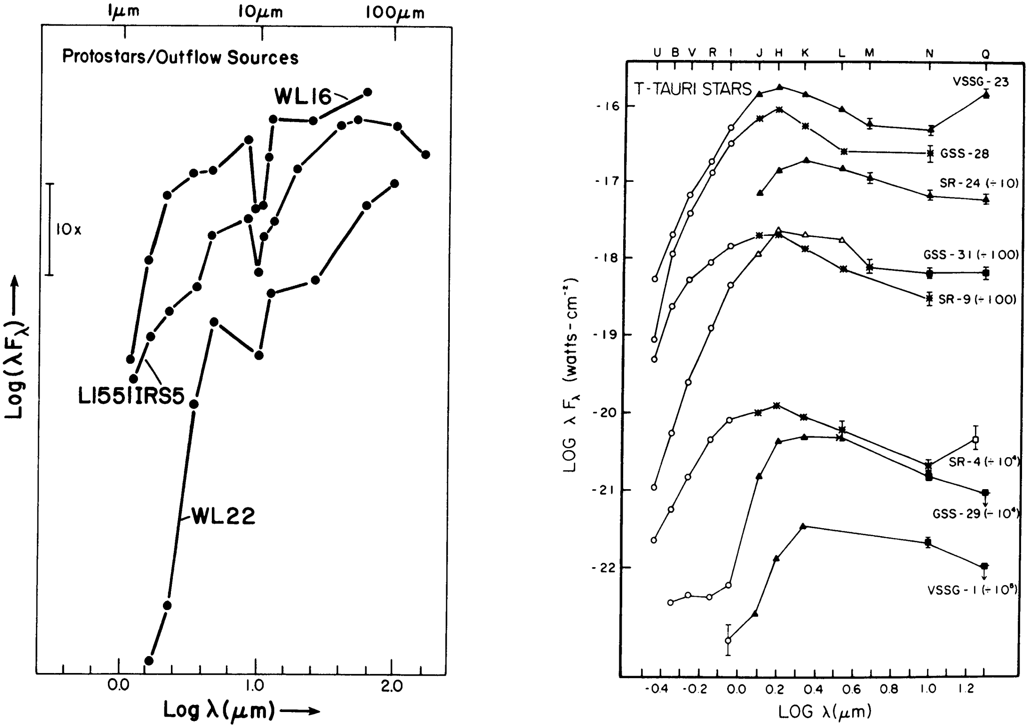


Figure 2. Proposed classification scheme for the energy distributions of embedded young stellar objects. Class I objects have broader than blackbody distributions with slopes or spectral indices which are positive longward of 2 microns wavelength; these objects may be protostars. Class II objects have broader than blackbody distributions which are flat or have negative slopes longward of two microns. Class II distributions are characteristic of T Tauri stars. Class III distributions are fit well by reddened blackbody functions and represent reddened stellar photospheres of stars very near to or on the ZAMS.



Figures 3 and 4. Observed energy distributions for typical class I and class II sources. Left hand figure (3) shows class I energy distributions and the right hand figure (4) shows examples of class II distributions.

morphologies of the energy distributions in the Ophiuchi cloud are similar to those of infrared sources in other clouds. Well determined infrared energy distributions now exist in the published literature for dozens of low to moderate luminosity (i.e., $L < 10^3\ L_{\odot}$) infrared sources from T Tauri stars to extremely red protostellar candidate sources (e.g., Rydgren, Strom and Strom 1976; Cohen and Kuhi 1979; Elias 1978; Cohen et al. 1984; Harvey, Thronson and Gatley 1979; Evans, Levreault and Harvey 1986; etc.). Examination of such data indicates that most all known infrared sources associated with low mass stars can be characterized by the classification scheme described above.

Although it is convienent for discussion purposes to divide the sources into three distinct classes, it is important to point out that in fact the energy distributions are found to vary more or less continuously in spectral index from $-3 > a > +3$. There are also a number of sources with considerable, often well defined (e.g., double-humped) structure which cannot be characterized by a single spectral index from 2-100 microns. The energy distributions of these sources appear to be intermediate between pure class I and pure class II.

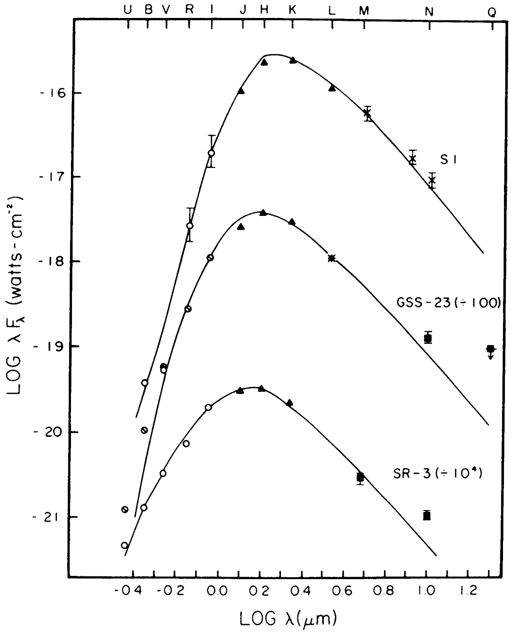


Figure 5. Class III distributions observed in the Ophiuchi cluster. Solid lines are reddened blackbody fits to the observed data. Since the extinction is well determined from the H-K color indices, the fits are reasonably unique. Effective temperatures derived from the fits agree very well with those derived independently from optical classifications (Lada and Wilking 1984).

4.2. An Evolutionary Sequence?

Does the more or less continous variation in the spectral shapes of embedded infrared sources represent a sequence of evolution for protostars and young stellar objects? Most class II and III objects are associated with visible stars, mostly T Tauri stars and PMS stars. On the other hand, most class I objects are invisible and heavily obscured. Consequently their nature is difficult to ascertain. They could be protostars, or very deeply embedded T Tauri-PMS stars or some intermediate type of object. However, it is unlikely that they are merely more heavily reddened versions of T Tauri stars because examples of such stars exist in the Ophiuchi cluster and their energy distributions are typically flat or decreasing at long wavelengths (similar to optically visible T Tauri stars but unlike class I objects), but are considerably steeper at shorter wavelengths than the visible T Tauri stars. It is possible that class I objects are protostars, although many are the driving sources of molecular outflows a circumstance that has been interpreted to indicate that such objects are in a post-protostar phase of very early stellar evolution (Wynn-

Williams 1982; Lada 1985). Recent theoretical models which predict the emergent energy distributions of low mass protostars strongly suggest that class I objects are indeed objects in the process of building up mass by the accretion of infalling circumstellar matter (Adams and Shu 1985, Shu, Lizano and Adams, this conference). In any event it appears evident and it is reasonable to assume that class I objects are in a much younger stage of development than class II sources. Since class III sources are stars with very little near in circumstellar dust it also seems reasonable to assume that they are the most removed in time from the events of stellar formation and the most evolved of the infrared sources.

The hypothesis that the empirical sequence of spectral shapes corresponds to an evolutionary sequence of young stellar objects would be much more convincing if supported by physical arguments. Indeed, a qualitative physical evolutionary model is in fact suggested from the observed sequence. This is apparent when one considers the fact that the variation in the shape of the source energy distributions represents a variation in the amount of luminous circumstellar dust around each object. Class I sources have very large amounts of luminous circumstellar dust while class III objects have almost no luminous circumstellar dust. It is likely therefore that the inferred evolutionary sequence is a sequence of the gradual dissipation of dust and gas envelopes around newly forming or formed stars. The fact that many but not all class I objects and many but not all T Tauri stars are associated with energetic outflows and or stellar wind activity suggests that the outflow/wind phase is a transition between the protostellar stage and the T Tauri stage and that the outflow/wind is the agent that dissipates the circumstellar envelopes and drives the evolution of objects from class I to class III.

These considerations suggest the following phases of evolution for protostars and young stellar objects. First, a molecular core forms from a molecular cloud. The core is expected to have a steep density gradient and to be rotating (e.g., Adams and Shu 1986). The core becomes unstable and collapses nonhomologously from the inside out (e.g., Larson 1973, Adams and Shu 1986). The volume of the unstable core for which the star formation efficiency will ultimately be near 100% becomes a protostellar object. For a solar mass star, the initial size of the protostellar object is somewhat less than 0.1 parsec in diameter. At the center of this object a dense stellar core and disk develop and become luminous as a result of infall and accretion of material from the outer infalling envelope. Detailed radiative transfer calculations for such an object have been carried out by Adams and Shu and show that the emergent energy distributions have steep positive spectral indices in the infrared. At some point, and it is not clear when, an intense outflow develops and begins to arrest and reverse the infall of the outer envelope. The outflow first disrupts and removes the infalling envelope and then later the circumstellar disk ultimately revealing a reddened young star approaching or very near the ZAMS (i.e., a class III object).

It is interesting to consider at this point where T Tauri stars, objects with negative spectral indices (class II), fit into the evolutionary sequence outlined above. The energy distributions of class II objects are wider than those of blackbodies, indicating significant excess infrared emission at wavelengths longer than 2 microns. This emission has been shown to most likely arise from luminous dust grains (e.g., Cohen and Kuhi 1979; Rydgren and Cohen 1985) probably located a few A.U. from the stellar surface (LW). These luminous grains could be located either in a spherical shell (e.g., LW) or disk around the star (e.g., Rydgren and Cohen 1985, Harvey 1985). The fact that the infrared luminosities of T Tauri stars are often comparable to their optically derived bolometric luminosities (e.g., Rydgren, Strom and Strom 1976, Lada and Wilking 1984) is suggestive of spherically distributed dust. Radiation pressure from a low mass star is insufficient to keep a spherical distribution of dust from collapsing onto the star, and it is possible that the observed dust around class II objects represents the remnants of the original infalling envelope which formed the star. However, the energy distribution of such a remnant is not expected to be broad with a negative or zero spectral index typical of class II stars unless the density distribution of the infalling envelope is relatively flat (Harvey, Thronson and Gatley 1979).

On the other hand, the emitting dust could be stablely configured in a disk around the star. For a disk with a temperature gradient $T(r) \sim r^{-n}$, the spectral index of its energy distribution for thermal emission is equal to $2/n - 4$ (Elmegreen 1982). The energy distributions of class II objects could then be explained by disks with temperature distributions characterized by $.5 < n < .75$. A luminous accretion disk is expected to be characterized by $n = .75$ (Lynden-Bell and Pringle 1974) and Adams and Shu (1986) have shown that such a temperature gradient is expected for an optically thick disk heated by a young star. Indeed, detailed model calculations by Adams, Lada and Shu (1986) indicate that the energy distributions of many class II objects can be fit very well by a stellar photosphere plus disk combination. Moreover, recent high resolution infrared imaging of the T Tauri star HL Tau has provided strong evidence that the excess infrared emission around that object originates in a circumstellar disk (Grasdalen et al. 1984). It appears that class II sources represent objects around which the original infalling envelopes have been removed, but which have retained remnant star forming material in the form of their circumstellar disks. Such stars appear to be successfully modeled as an evolutionary transition between class I and class III objects. Support for such an interpretation is also found in the modelling of the energy distributions of the double humped sources. Adams Lada and Shu have shown that these objects can be explained as sources in which part but not all of their infalling envelope has been removed. The observed spectrum is then well fit by a self-consistent combination of central star plus disk (near infrared hump) and a partially evacuated infalling envelope (far infrared hump).

Molecular outflows and early stellar winds input a substantial amount of mechanical energy in molecular clouds (e.g., Lada 1985; Snell 1986, this conference) and after formation, young stellar objects may radically alter the conditions in the star forming gas, leading perhaps to conditions more conducive to the formation of high mass stars. Once high mass stars form the cloud will be disrupted and the young stars formed within will be revealed as an unbound stellar association or open cluster depending on the star forming efficiency in the original material.

5. CONCLUDING REMARKS

Considerable progress has been achieved in many aspects of star formation research in the nearly ten years since the last IAU Symposium on Star Formation in Geneva. Although we have still not yet convinced ourselves that we have actually observed a star in the process of formation, observations have unveiled a rich tapestry of astrophysical phenomena associated with the birth of stars and have altered many of our basic perceptions concerning star formation and early stellar evolution.

This review has emphasized two major areas of research where significant progress has been made. On the global scale, recent studies of associations and clusters, the fossil record of star formation, have directed our attention to the fundamental importance of the role star formation efficiency plays in the evolutionary history of young stellar groups. The mechanism for the production of expanding associations is no longer perceived as the critical issue in understanding star formation in associations as it was tweny years ago. The total positive energy of associations is now seen as a direct and natural consequence of star formation in a giant molecular cloud with low efficiency. The critical issue at the heart of the star formation problem in molecular clouds today is: why is the star formation efficiency so low?

Millimeter-wave, infrared and optical observations of young stellar objects have stimulated a major revision in our understanding of protostellar and early stellar evolution. The discovery of energetic molecular outflows and stellar winds around extremely young objects has provided a new and crucial piece in the puzzle of star formation and has lead to a reassessment of our concept of a protostar. The development of our ability to observe young stellar objects over many decades in frequency has provided new insights into their evolution. Optical-infrared energy distributions appear as a powerful tool for studying proto- and early stellar evolution. A viable scenario for the evolution of a young stellar object from protostar to field star can now be constructed. The scenario proposed here seems to be a plausible one, but it needs to be rigorously tested. There are many important questions which remain unanswered. For example, when in the evolution of a protostar does the molecular outflow turn on? Could it occur before the build up of a luminous central core? When does the outflow turn off? Why? What is the origin of the flat energy distribution observed for many class II sources? High angular resolution millimeter and submillimeter observations and high spectral resolution infrared observations should make major inroads toward the resolution of all these problems during the next decade. In particular, interferometric millimeter-wave observations may be capable of achieving sufficiently high resolution to resolve and unambigously identify the collapsing envelope of a protostar within the next few years. Impressive as such an achievement might be, it will not provide us with the solution to the problem of star formation, but more likely it will direct our attention away from the study of young stellar objects toward the quest to understand the origin of molecular cloud cores and ultimately molecular clouds themselves.

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WILSON: What about the influence of the formation of binary stars on your picture of star formation?

LADA: The qualitative picture of source evolution ignores binaries which certainly must be present. However, the effect that binaries have on the energy distributions is unclear to me. I would think that in many binary systems the masses of the components are different enough that we only observe the most luminous object. Certainly any realistic scenario of evolution for young stellar objects must eventually come to grips with this issue.

MATHIEU: I would like to make two comments on the first half of Dr. Lada's fine discussion. The first concerns the stellar kinematics of star-forming regions. Since I first gave Dr. Lada the velocity distribution of late-type stars in λ Orionis which he presented we have studied three additional star-forming regions: NGC 2264, the Trapezium cluster and the Taurus-Auriga region. Except for the Taurus-Auriga region all have radial velocity dispersions of 2-3 km/sec; the velocity dispersion of the Taurus-Auriga region is smaller. There are however substantial differences between these regions: the λ Orionis and Taurus-Auriga regions have stellar densities of a few tenths of a $M_\odot/pc^3$, NGC 2264 a stellar density of 1-10 $M_\odot/pc^3$ and the Trapezium cluster a stellar density greater than 500 $M_\odot/pc^3$. The stellar mass of the latter region is marginally sufficient to bind itself in the absence of molecular gas. I might also note that the radius of the OB association in λ Orionis is about 4 pc while the age of the system is a few million years. The indication then is that the velocity dispersion among the early stars is also of the order of 1-2 km/sec or less. A high-precision radial velocity study of early stars has begun this winter.

Secondly, we must be wary of saying that most or all stars form in OB associations. All or most stars do form in molecular clouds. But the relationship between the formation of the OB stars and the lower mass stars remains unclear. Consider again the λ Orionis region. Most of the Hα stars are concentrated about the two clouds B30 and B35. There is a notable paucity of Hα stars about the OB association itself. Also, there is no evidence for a clustering of low-mass stars about the OB stars as would be expected if the OB stars were tracers of a population of stars derived from the Miller/Scalo initial mass function. The indication then is that the initial mass function, while perhaps more or less similar from one giant molecular cloud to another is not necessarily uniform over star-forming regions within a giant molecular cloud, *e.g.* over size scales smaller than 10 pc.