On The Origin Of Dwarf Stars

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The origin of dwarf or low mass stars is one of the most interesting and challenging problems of modern astrophysics. In recent years advances in observational technology particularly at infrared and millimeter wavelengths, have produced an avalanche of revealing new data, unexpected discoveries and new mysteries about the process of star formation. From this new knowledge a complete empirical picture of stellar origins is being synthesized and a more profound and penetrating understanding of the physical process of star formation in our galaxy is beginning to emerge. It is now apparent, for example, that energetic bipolar outflows are a fundamental aspect of the formation of low mass stars and understanding how a star can form by the act of ejecting mass may be the key to unlocking the secrets of stellar genesis.

1. INTRODUCTION

Stars are the basic objects of the universe. Understanding how they form from interstellar clouds of gas and dust is one of the most fundamental unsolved problems of modern astrophysics. Of course, particular interest is evoked in attempts to decipher the origins of dwarf or low mass stars, like the sun, which are the most populous stars in the galaxy. Indeed, most stars which form from interstellar clouds are probably *less* massive than the sun. However, studying the formation and early evolution of stars has turned out to be a formidable challenge for astronomers. This is because stars are born within the dust enshrouded cores of giant molecular clouds. Here newly forming stars (protostars) are rendered completely invisible by the obscuration provided by the visually opaque dust which permeates these clouds. Moreover, the molecular gas which forms stars is extremely cold (i.e., 10–20 Kelvins) and can only be observed at millimeter and submillimeter wavelengths, spectral windows not opened by radio astronomers until the 1970s. As a result of these facts, the star formation process is veiled from direct observation at visual wavelengths and the classical tools of optical astronomy are ineffective probes of regions where stars are being formed. On the other hand, although dust effectively absorbs visible light emitted by buried stars and protostars, this absorbed light

L. V. Mirzoyan et al. (eds.), Flare Stars in Star Clusters, Associations and the Solar Vicinity, 347–361.

heats up the initially very cold dust and is eventually re-radiated at longer (infrared) wavelengths and escapes the cloud. Consequently, it is possible to directly probe star forming regions with observations made at infrared (and millimeter) wavelengths. Indeed, to test even the most basic hypotheses concerning stellar origins *requires* the acquisition of such long wavelength empirical data. For the most part this has only been technologically possible during the last two decades. The direct investigation of the star formation problem is, therefore, a relatively recent development of astronomical science.

During this time considerable progress toward understanding the physical process of stellar formation has been achieved. In particular, during the last 5 years fundamental advances in our knowledge of low mass star formation has taken place. Dwarf or low mass stars (i.e., $M \leq 3M_{\odot}$) provide important advantages for star formation investigations. For such stars the Kelvin-Helmholtz contraction time is considerably greater than the free-fall time of the gaseous cores from which they form. Therefore, these stars emerge from their dusty embryonic wombs before they begin to burn hydrogen in their cores, that is, well before they have reached the main sequence. Thus these stars can be observed even in the optical region of the spectrum while still in their (late) formative stages. Moreover, dwarf stars can form in isolation and are much less destructive of their natal environments than massive stars. On the other hand, dwarf stars are much fainter than high mass stars and can only be practically studied in nearby molecular clouds with the most sensitive instruments. In this paper I will review some of the more interesting new findings concerning low mass star formation that have been obtained as a result of both new observations at infrared and millimeter wavelengths and the development of new theoretical insights concerning this problem.

2. SITES OF LOW MASS STAR FORMATION

2.1 GMCs and OB Associations

In the current epoch of galactic history the vast majority of stars, both low and high mass, form in giant molecular clouds (GMCs). With extents on the order of 100 parsecs and masses often in excess of 10^5 $M_{\odot}$, GMCs are the largest objects in the galaxy and rival globular clusters as the most massive objects in the Milky Way. GMCs are clearly localized objects in the interstellar medium. They have well defined boundaries and are gravitationally bound, that is they are systems with negative total energy. *The statement that stars form in GMCs is equivalent to the statement that stars form in groups or associations.* It has long been suspected that most stars formed in the galaxy began their lives as members of associations (e.g., Roberts 1957). OB and T associations exist because stars form in spatially confined parental clouds. The question of the origin of stellar associations is in reality a question of the origin and evolution of GMCs. OB associations are formed when massive stars which form in a GMC erode, dissipate and disrupt the cloud, leaving behind the stars which formed during the cloud's lifetime. Once the gas has been cleared and removed by the O stars, the remaining stellar association becomes a fossil record of the original GMC (e.g., Duerr, Imhoff and Lada 1982). OB associations and T associations have often been thought of as being physically different types of stellar aggregates. But this is largely due to observational selection effects. Since both high mass and low mass stars predominately form in GMCs, GMCs ultimately produce stellar associations which contain a mixture of both OB and T Tauri stars (e.g., Elmegreen and Lada 1977; Lada 1987).

2.2 The Dynamical Nature of OB Associations

Ambartsumian (1947) was the first to recognize that the space densities of OB associations were well below the critical density for stability against disruption due to galactic tidal forces and that this had the important implication that such associations were considerably younger than the age of the galaxy. This observation provided one of the first fundamental proofs that star formation was occuring in the present epoch of galactic history. Ambartsumian showed that OB associations were gravitationally unbound and systems of *positive* total energy with expansion lifetimes on the order of 10^7 years. Based on early proper motion measurements, Ambartsumian also suggested that the associations had expansion velocities (≈ 10 km s^{-1}) well above that which could be produced by galactic tidal forces alone (Ambartsumian 1955). This lead to a number of hypotheses to explain the origin of these stellar systems of positive total energy. Ambartsumian proposed that associations were formed when massive, super-dense, "proto-stellar" bodies disintegrated producing both expanding groups of stars and their associated gas and dust (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 an association of stars which would "retain the outward motion of the material of which they were built". Oort (1954) proposed a similar solution using the expansion and compression of an HII region to create expanding clouds of gas from which new stars would form and subsequently "share the outward motions that the HII regions had imposed on these clouds". All these ideas were based on the assumption that an unbound group of stars must have formed from expanding clouds of gas.

During the last 15 years millimeter-wave CO observations have shown that OB associations form from GMCs (e.g., Elmegreen and Lada 1976, 1977; Blitz 1980) which are gravitationally bound systems with negative total energy. Clearly this invalidates the basic assumption on which the solutions proposed by Ambartsumian, Oort and Opik were based. How do GMCs with negative total energy produce unbound OB associations? The key to answering this question is provided by recent observations of star formation activity in molecular clouds. Although GMCs are extremely massive, observations indicate that during their lifetime they convert only a small fraction of their gaseous mass into stars (e.g., Duerr, Imhoff and Lada 1982; Myers *et al.* 1986). In other words the global star forming efficiency of GMCs is low, probably on the order of a few percent or less. Clearly these large clouds must be a *source* of star formation and not the product of stellar creation that Ambartsumian had originally envisioned. At the same time, GMCs are not stable to destruction and dissipation by OB stars which generate HII regions, powerful winds and possibly even supernovae while still embedded in a cloud. Indeed, calculations by Whitworth (1979) showed that O stars could disperse an entire GMC if only 4% of the cloudy material was converted to stars with an IMF typical of field stars. These considerations led Duerr, Imhoff and Lada (1982) to propose that 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 hypothesis predicts as a consequence that the velocity dispersion of association stars is on the same order as that of molecular gas in GMCs (i.e., 2-4 km s^{-1}). This prediction appears to be confirmed for the λ Ori association studied by Duerr, Imhoff and Lada by a recent measurement of the velocity dispersion of association members of about 2 km s^{-1} made by Mathieu and Latham (1990). In addition it is interesting to recall that the systematic increase in size with age of the subgroups in the Ori OB1 association (Blauuw 1964) is consistent with an expansion velocity of a few km s^{-1} for the stars. These results support the contention that the unbound state of OB associations is a result of the combination of low star formation efficiency and rapid and efficient gas dispersal. These considerations also suggest that the early proper motion measurements of associations overestimated their expansion velocities.

Figure 1 is a sketch which depicts the evolution of star formation in a GMC and the creation of an expanding association as disucssed above and by Lada (1987). First, low mass stars form throughout the cloud converting roughly 1-3% of the gaseous mass into stars. At some point massive OB stars form in the cloud and heat, ionize and disrupt the molecular gas. In a relatively short time ($\approx 10^6$ years), the OB stars disrupt the entire complex and remove the vast majority of the original binding mass of the system. The stars in the cloud, which were originally orbiting in virial equilibrium with the deep potential well of the massive GMC, respond to the rapid removal of the majority of the binding mass by freely expanding into space with their initial virial velocities. This idea that unbound associations could form from bound clouds as a result of gas dispersal was originally suggested in a lecture by Zwicky (1953) and later independently mentioned by McCrea (1955) and von Hoerner (1968) who was the first to suggest (quantitatively) that OB stars could effectively disperse star forming gas and unbind a forming stellar system. However, these proposals were not given much attention because the large expansion velocities suggested by early proper motion measurements were not easily explained in the gas dispersal scenarios (e.g., Oort 1954). With the ability to directly observe molecular clouds and their embedded populations at millimeter and infrared wavelengths, it has now become clear that the origin of expanding associations is a result of the combination of low star formation efficiency and the efficient destruction of of giant molecular clouds by OB stars. The answer to the question of the origin of expanding associations requires understanding why star formation efficiency in molecular clouds is so low (Lada 1987).

2.3 Dense Cores and Embedded Clusters

It has long been suspected that stars form in the dense cores of giant molecular clouds. In the nearest star forming regions: Taurus and Ophiuchus, comparison of millimeter-wave and infrared data has suggested that dense cores both small and large are often associated with extremely young embedded objects and are therefore often sites of recent low mass star formation (e.g., Myers 1987; Wilking and Lada 1983). Observations of these two regions further suggests that the formation of dwarf stars from dense gas occurs in two modes. In Taurus individual, relatively low mass (i.e., 2-10 $M_\odot$), cores are producing individual young stellar objects, while in Ophiuchus a single massive core ($M \approx 500\ M_\odot$) accounts for almost all the star forming activity in the region. The relative strength of magnetic fields in the dense gas may be the factor which determines which mode of star formation is dominant in a given region or cloud core (Shu, Adams and Lizano 1987).

The extent to which either one of these two regions is representative of galac-

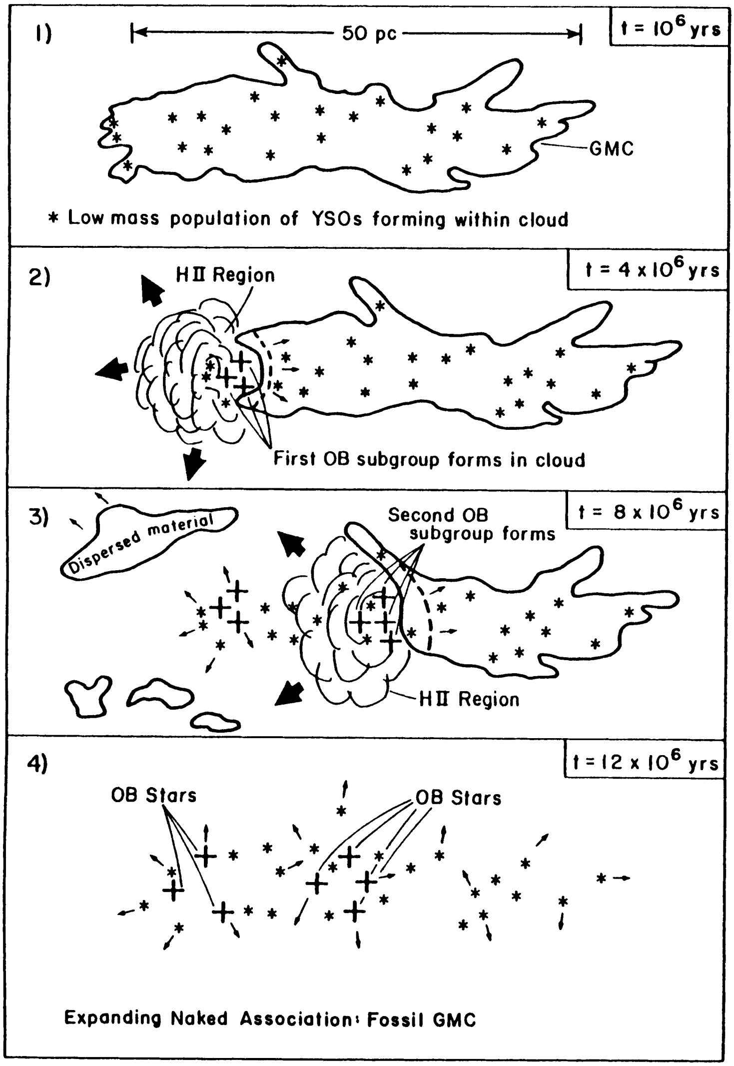

Figure 1. Probable stages in the origin of an expanding OB association from a giant molecular cloud. (Lada 1987).

tic star formation in general is unclear. Neither region is currently part of a GMC. However, the Ophiuchi cloud core is part of the Sco-Cen OB association, and perhaps the last remnant of a once larger GMC which has been mostly dissipated by the OB stars of this association. The Taurus cloud is an intermediate sized

molecular cloud which is not part of an existing OB association. In this regard it would certainly be useful to obtain detailed knowledge of the star forming activity in another molecular cloud, preferably a nearby GMC. Recently, a complete and unbaised census of embedded stars and dense molecular gas was obtained for the massive GMC L1630 in Orion by Elizabeth Lada and colleagues (E. Lada 1990). These observations were sensitive enough to investigate both high and low mass young stellar objects and have provided significant new information concerning star forming activity in that cloud. Lada and her colleagues systematically and completely surveyed a significant fraction of the L1630 (i.e., Orion B) GMC for embedded infrared sources and for emission from CS, which is a tracer of dense molecular gas. Approximately 1000 infrared sources were detected, a significant fraction (i.e., $\approx$ 50%) of which appear to be embbeded in the cloud. Moreover, it was discovered that the vast majority ($\geq$ 90%) of these embedded sources are not uniformly distributed through the surveyed portion of the cloud. Instead, almost all the embedded stars were found to be concentrated in four isolated and spatially distinct clusters. Each of these clusters was in turn found to be coincident or nearly coincident with a massive, dense molecular core. These observations are summarized in Figure 2 (taken from E. Lada 1990) which shows the locations and extents of the embedded infrared clusters and dense molecular gas in the L1630 GMC.

These fascinating results have at least two important consequences for understanding star formation (at least for the L1630 GMC). First, the formation of stars of both high and low mass does occur in dense gas. Second, the vast majority of stars formed in the surveyed region have formed in localized centers of star forming activity or clusters. These clusters were produced in the four largest and most massive dense cores in the cloud. There is no evidence for any significant star formation activity outside these clusters. There is apparently no significant "background" mode of star formation for either high or low mass stars in which stars form in individual isolated cores like they do in the Taurus dark cloud. Star formation in these regions of L1630 is more reminiscent of that occuring in Ophiuchus where again the vast majority of newly formed stars reside in a compact cluster within a massive dense core. The clusters in L1630 appear richer than the one in Ophiuchus, however. The overall star formation efficiency in the GMC was estimated to be on the order of 3-4%. However within the volume containing the dense gas, the efficiency was considerably higher (18–30%). Interestingly enough however, Lada found that the star formation efficiency is not uniform even within the dense gas. She found that 90% of the newly formed stars were contained within only 30% of the dense molecular gas! Evidently having a high enough density to excite $J=2\rightarrow1$ CS emission is not a sufficient condition for efficient star formation. Future study of the dense gas in this GMC, where the star formation efficiency varies so much between the dense cores, could provide important clues for understanding why star formation efficiency is generally so low in GMCs.

The sites of the embedded clusters in L1630 are likely the future sites of OB subgroups which will appear when the cloud is dissipated. When they emerge, these subgroups will contain the vast majority of both high and low mass stars formed in the cloud. Whether any of these embedded clusters will ultimately form bound clusters like the Pleaides depends on the the star formation efficiency achieved in the dense core at the time of destruction and the rate at which the gas is dispersed (Tutukov 1978; Lada, Margulis and Dearborn 1984). However, if this is a typical association, most of the embedded clusters will become unbound subgroups. The

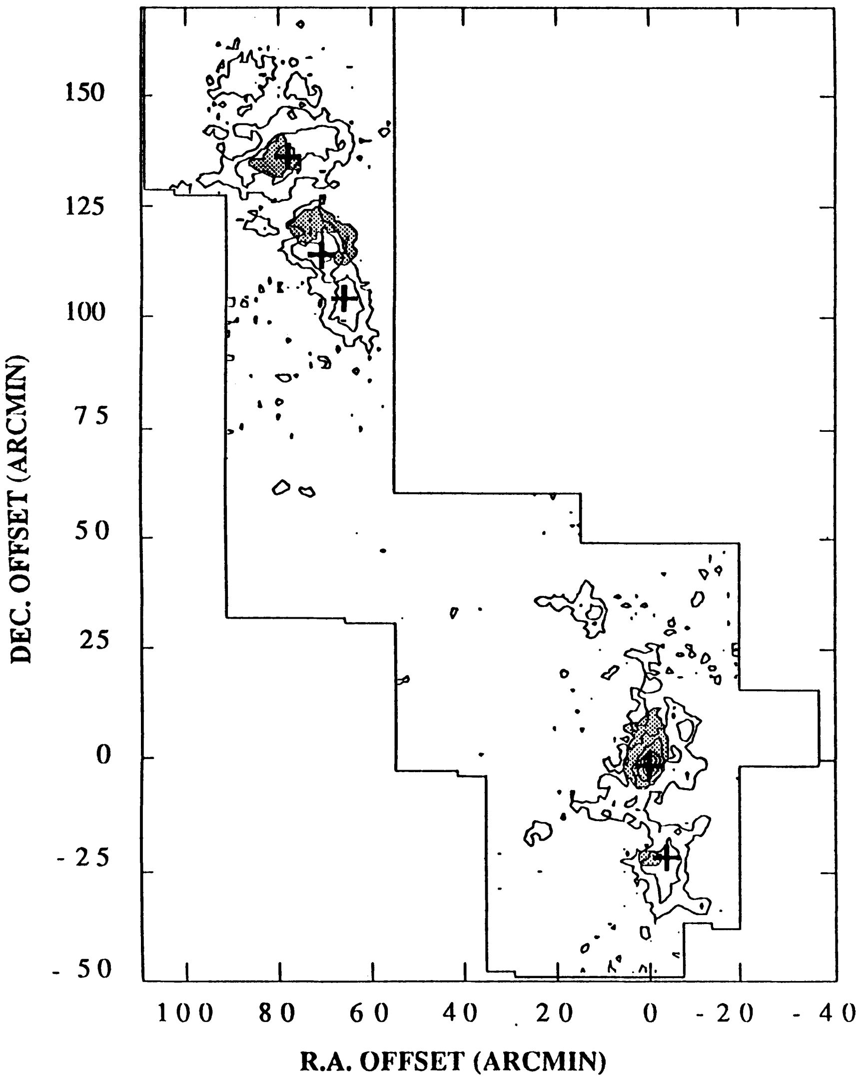

Figure 2. Locations of embedded stellar clusters and dense cores in the L1630 GMC (from E. Lada 1990). The contours represent isointensity contours of CS emission from the dense molecular gas in the cloud. The shaded regions are the extents of the embedded clusters in the cloud.

extent to which L1630 is typical of star formation in the galaxy is yet to be determined. But if studies of nearby OB associations are an indication (e.g., Blauuw

1964), many stars formed in the galaxy may have had their origins in embedded clusters within massive molecular cores and not in the relative isolation which characterizes the typical star forming core in Taurus.

3. THE NATURE OF LOW MASS YOUNG STELLAR OBJECTS

Since star formation takes place in dense molecular gas, newly forming and formed stars will be physically associated with varying amounts of molecular gas and dust. As a result, we expect buried young stellar objects (YSOs) to radiate a significant fraction of their energy in the infrared portion of the spectrum. Moreover, since the circumstellar material associated with a YSO occupies a volume of space considerably larger than the YSO itself, we expect that the emission that emerges from the cloud to be radiated over a wavelength range which is larger than that of a single temperature blackbody or stellar photosphere. In addition, since the emergent spectrum will depend on both the nature and distribution of the surrounding material, we expect the shape of the emergent infrared energy distribution (i.e., log λF_λ vs. log λ) will be a function of the evolutionary state of a YSO. Protostars will have a very different infrared signature than pre-main sequence stars which have rid themselves of most of their original star forming material.

Infrared observations of embedded YSOs have shown that their infrared energy distributions exhibit well-defined structure and can be classified in a meaningful way (Lada and Wilking 1984; Lada 1987). If one defines a spectral index $\alpha = \mathrm{dlog}\lambda \mathrm{F}_\lambda/\mathrm{dlog}\lambda$, then the spectral energy distributions (SEDs) of most known YSOs fall into three distinct morphological classes (I, II and III). These are illustrated in Figure 3. Class I sources have SEDs which are broader than a single blackbody function and for which α is positive. Class II sources have SEDs which are also broader than a single blackbody function but have values of α which are negative. Class III sources have SEDs which are characterized by negative values of α but have widths that are comparable to those of single blackbody functions, consistent with the energy distributions expected from purely reddened photospheres of young stars. Class I sources derive their steep positive spectral slopes from the presence of large amounts of circumstellar dust. These sources are usually deeply embedded in molecular clouds and rarely exhibit detectable emission in the optical band of the spectrum (e.g., Lada and Wilking 1984; Myers *et al*, 1987). However, nearly all known Class II sources can be observed optically as well as in the infrared. When classified optically Class II sources are usually found to be T Tauri stars or FU Ori stars (e.g., Rucinski 1985). Their negative spectral indices indicate that Class II YSOs are surrounded by considerably less circumstellar dust than Class I sources. Class III sources are usually optically visible with no or very little detectable excess emission at near- and mid-infrared wavelengths, (although, they may exhibit strong excesses at millimeter wavelengths, see Montmerle and Andre 1990, and this conference) and therefore little or no close-in circumstellar dust. Class III objects include both young main sequence stars and pre-main sequence stars, such as the so-called "post"-T Tauri stars (e.g., Lada and Wilking 1984) and the recently identified "naked"- T Tauri stars (e.g., Walter 1987). It is apparent from existing studies of YSOs that there is a more or less continuous variation in the shapes of SEDs from Class I to Class III (e.g., Myers *et al.*,1987, Wilking Lada and Young 1989).

It is extremely tempting to hypothesize that the empirical sequence of YSO

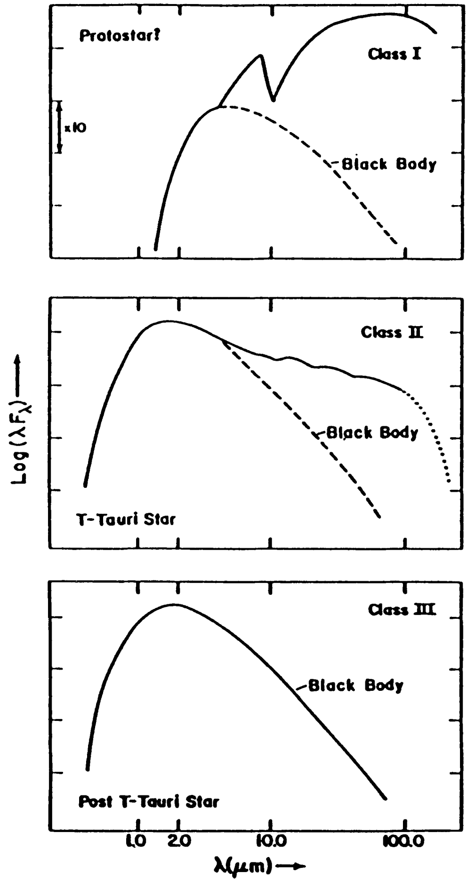

Figure 3. Classification scheme for YSO energy distributions (Lada 1987).

spectral energy distributions corresponds to an evolutionary sequence. Indeed, the variation in SED class from I to III represents a variation in the amount of luminous circumstellar dust around each object. This seems to suggest, then, that the empirical sequence of spectral shapes is a sequence of the gradual dissipation of dust and gas envelopes from around the newly forming or formed stars (Lada 1987). Recently, Adams, Lada and Shu (1987) have been able to theoretically model this empirical sequence as a more or less continuous sequence of early stellar evolution from protostar to young main sequence star using a self-consistent physical theory originally developed by Shu (1977). In this theoretical picture Class I sources are true protostars, objects undergoing accretion and assembling the bulk of the mass they will ultimately contain when they arrive on the main sequence. In particular, it is assumed that low mass protostars form from the nonhomologous, inside-out collapse of a rotating, isothermal cloud core (i.e., Shu 1977; Adams and Shu 1986). At the center of this unstable cloud a dense stellar-like core and disk develop and become luminous as a result of the infall and accretion of material from the outer infalling envelope. Detailed radiative transfer calculations show that density distribution produced by the infalling envelope and rotation results in an emergent energy distribution with a steep positive spectral index (i.e., Class I). Moreover, modeling of the *observed* energy distributions of Class I sources in Taurus suggests density distributions similar to those predicted by theory for infalling envelopes as well as the presence of circumstellar disks (Myers *et al.* 1987).

Observations of Class II SEDs indicate that the shape of the infrared portion of the spectrum is well described by a power-law form (Adams, Lada and Shu 1988). Early theoretical work by Lynden-Bell and Pringle (1974) showed that an optically thick circumstellar disk would produce a spectrum which was the superposition of a series of different blackbody functions. The shape of this composite spectrum would be power-law in form if the temperature gradient in the disk was characterized by a power-law dependence with distance from the central star. Class II SEDs are therefore found to be well modeled by just a reddened stellar photosphere surrounded by a luminous circumstellar disk, that is, by a YSO without its infalling envelope. To evolve from Class I to Class II therefore requires the removal of the infalling envelope, presumably by the action of an intense outflow as will be discussed later. Presumably, the further removal of the surrounding disk, via accretion onto the star itself, by erosion by a stellar wind or outflow, or by incoporation into planetary bodies, causes a Class II object to evolve into a Class III source. Exactly how this occurs is presently unclear (however, see Montmerle and Andre 1990).

4. ENERGETIC BIPOLAR MOLECULAR OUTFLOWS

Ten years ago millimeter-wavelength observations of the molecular gas surrounding YSOs led to the discovery of an unanticipated phenomenon of fundamental importance for understanding star formation. In addition to their global supersonic velocity fields, molecular clouds were found to contain localized regions (0.1–3 parsecs in size) where a significant amount of gas was characterized by hypersonic bulk motion. In these regions the observed widths of molecular emission lines are found to range between 10–100 km s^{-1}! These highly supersonic and super-Alfvenic velocities cannot be gravitationally (or magnetically) confined within the localized regions where they occur and they must represent unbound and expanding flows of cold molecular gas within the GMCs (e.g., Lada 1985). The regions containing the hypersonic outflows are almost always coincident with, if not centered on, the position of an embedded YSO. Well over 100 molecular outflows are now known, most within a kiloparsec of the sun. Their properties have been extensively and thoroughly reviewed in the literature (e.g., Lada 1985; Snell 1987; Fukui 1990) Briefly, the masses of such outflows are substantial, containing anywhere between 0.1 and 100 $M_\odot$. Because of the large masses contained in the molecular outflows, it is likely that the outflowing molecular gas is swept-up ambient cloud material rather than original ejecta from the driving source. More significantly, the corresponding kinetic energies of the flows are enormous, ranging between 10^{43} and 10^{47} ergs! The dynamical timescales of the flows are estimated to be between 10^3 and 10^5 years and their local formation rate is estimated to be roughly comparable to the formation rate for stars of a solar mass or greater. Taken together, these facts suggest that molecular outflows play a fundamentally important role in the star formation process.

Perhaps the most intriguing property of the molecular outflows is their tendency to appear spatially bipolar. That is, they often consist of two spatially separate lobes of emission, with one lobe containing predominantly blueshifted gas and the other predominantly redshifted gas. Furthermore, the two separating lobes are almost always more or less symmetrically situated about an embedded infrared source or young stellar object. About 75% of the known outflows are bipolar; the rest are either single-lobed, (i.e., one lobe of either predominately red or blue-shifted emisison), isotropic (i.e., one lobe but with both red and blue-shifted high velocity emission spatially coincident) or of complex morphology.

5. ENERGETIC OUTFLOWS AND STAR FORMATION

Bipolar molecular outflows are indivdually energetic enough to disrupt cloud cores and collectively powerful enough to have a significant impact on the dynamics and structure of a an entire GMC (e.g., Margulis Lada and Snell 1988). In fact the molecular outflows generated by a population of embedded YSOs may be able to generate the turbulent pressure that keeps GMCs from global collapse, thereby solving one of the outstanding problems of cloud dynamics. In any event, it is clear that molecular outflow is the likely agent that removes circumstellar material and drives the evolution of an embedded young stellar object from the Class I to the Class II stage. In this regard it is interesting to determine by direct observation the nature of the embedded sources which drive cold molecular outflows. A growing body of observational data now clearly shows that molecular outflows are most frequently associated with Class I type sources and only rarely with Class II or III objects (e.g., Lada 1985, 1988; Berrill *et al.* 1989; Snell *et al.* 1988; Margulis, Lada and Young 1989). In fact survey observations of both embedded source populations within individual clouds (Margulis, Lada and Young 1989) and among all molecular clouds (Berrill *et al.* 1989; Snell *et al.* 1988) indicate that at least half of all studied Class I objects are sources of molecular outflow. On the other hand, less than 10% of Class II and III objects are associated with molecular outflow, although many of these may still drive stellar winds (Lada 1988). This suggests that outflow activity is ignited during the Class I or protostellar phase and continues into the Class II phase where it subsequently dies out.

Although molecular outflows appear to provide the key to understanding how a Class I source removes surrounding material and in doing so evolves into a Class II source, the high frequency of association between Class I infrared sources and molecular outflows poses a paradox. The statistics suggest that a significant fraction of the lifetime of a Class I object is spent in the outflow phase. Yet, if Class I sources are true protostars, their evolution should be characterized by the *infall* of surrounding material. How can a protostar for most of its existence be simultaneously a source of infall and outflow? How can a star form by losing mass? The answer to this question is the key to understanding the basic physics of the star formation process.

The solution to this paradoxical problem may contain two crucial ingredients: angular momentum and magnetic fields. The fact that disks are found around most YSOs implicates an important role for angular momentum. The formation of a disk around a young stellar object is the natural consequence of the presence of angular momentum (even in small amounts) and its conservation in dynamically evolving cloud cores. For a rotating protostar most of the mass that ends up on the star must be accreted from the surrounding disk. In order for material to flow through the disk and onto the protostar, the material must lose both energy and angular momentum. If the mass of the disk is not much larger than that of the central object, the material in the disk should rotate differentially in Keplerian fashion. Gas falling through such a disk will reach the surface of the central star with an orbital velocity and specific angular momentum which is relatively high compared to that in the star (Shu *et al.* 1989). If this material is added to the star it will spin up the star. The star will quickly reach break up equatorial velocities at which point material can no longer be added to it. A centifugal barrier prevents the further growth of the protostar. Thus the process of star formation can only proceed if the incoming gas somehow can lose additional angular momentum in the process of accreting onto the star or if the star can somehow spin down while accretion is taking place.

Angular momentum can be carried away from a star by a stellar wind. *Consequently, a protostar may be able to gain mass only if it simultaneously loses mass.* To allow star formation to continue the rate of mass loss from the wind should be a fraction of the mass accretion rate i.e.,

$$\dot{M}_{wind} = f\dot{M}_{infall}$$

where the fraction f is determined by the physics of the wind generating mechanism. The ideal protostellar wind is one that carries away little mass but lots of angular momentum. A number of recent investigations have shown that centrifugally–driven hydromagnetic winds are potentially capable of doing the job (e.g., Pudritz 1988). Such winds could be driven from either circumstellar disks (e.g., Uchida and Shibata 1984) or from the surfaces of central protostars (e.g., Shu *et al.* 1988). It may be that star formation in a rotating, magnetic cloud cores results in the formation of protostar-disk systems which can generate powerful outflows and in doing so resolve the paradox of the protostar which gains mass by losing mass.

In conclusion, it is becoming increasingly apparent that the generation of an intense stellar wind is of fundamental significance for any scenario or theory of star formation. The wind is both necessary for star formation to proceed (by enabling accretion of material through a disk) and for providing a natural mechanism for the ultimate reversal of infall from the surrounding infalling envelope. In addition, the stellar wind and the bipolar molecular flow it generates limit the mass available to be accreted onto the protostar by clearing away the surrounding gas and dust. The wind is thus the agent that drives the evolution of a protostar from a Class I to a Class II object and determines the final mass of the forming star.

5. CONCLUDING REMARKS

Stellar formation in our galaxy is indeed a rich and wonderful physical process to investigate and behold. During the last two decades advances in observational technology have lead to remarkable progress in our quest to decipher the mysteries of stellar origins. The questions we ask today are in many ways totally different form those asked by investigators even 20 years ago. Yet, in delivering a lecture on the origin of stars here at the Byurakan Observatory one can hardly escape contemplating the legacy of Academician Ambartsumian to this field of astronomical endeavor. His pioneering work on OB associations began the modern study of star formation in our galaxy. Perhaps most interesting and impressive however, was Ambartsumian's intuition about the importance of the role of expansive motions in the star formation process. Although, many of his ideas about the origin of stars and clouds appear with the light of modern evidence to be wrong (and this may not be too suprising given the paucity of relevant observational information available in the 50's and 60's), his basic belief that expansion, explosion and outflow were fundamental to the phenomenon of stellar origins seems to be borne out by the the most recent knowledge provided by modern observation and theory. As Newton first thought, gravity is, after all, at the heart of the process. However, because nature has also provided magnetic fields, angular momentum and perhaps other ingredients we do not yet fully appreciate, the story of the origin of stars has turned out to be more bizzare, mysterious and interesting than anyone (except perhaps Academician Ambartsumian) could have imagined 50 years ago.

6. ACKNOWLEDGEMENTS

I am grateful to the Organizing Committee of IAU Symposium No. 137 for inviting me to speak at and participate in this conference and for providing the basic financial support which made my participation possible. I also thank the University of Arizona Committee For Foreign Travel for assistance with travel support. I thank Frank Shu and Elizabeth Lada for enlightning discussions. Some of the research described here was supported, in part, by NSF Grant AST 8815753.

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BLAAUW: Do you consider the formation of clusters like the Pleiades, h and chi Persei etc. to fit in with the general scenario you described, i.e. extremes of a more or less continuous spectrum of formation efficiency, or should we invoke a different mechanism?

LADA: Bound clusters must form in cores which have high efficiencies and which are more gently disrupted than OB starforming cores, that is, bound clusters cannot contain O stars in them when they form. Clearly, since only 10% of all stars were formed in bound clusters,the conditions that give rise to bound cluster formation must be in some sense "special". So far we know of only one region where the star formation efficiency (SFE) is large. In Ophiuchus the SFE is about 20%. The general conditions there are much different than those in Taurus where the SFE is about 2%, so indeed different mechanisms are operating. However, E. Lada's observations of Ori B suggests that most stars are formed in cores similar to those in Ophiuchus, unlike the conditions in Taurus. But only a few of these cores will ever produce bound groups. The formation of massive stars in most cores may explain why they do not end up with bound groups. Tidal disruption by the parental GMC may also disrupt young clusters at an early stage.

BLAAUW: Might not the high efficiency just referred to be counteracted by the violent outflow phenomena you described at the end?

LADA: Evidently in cores which produce bound clusters, factors which give rise to disruption are suppressed. For example, O stars cannot have formed in bound clusters: they are too disruptive.

BLAAUW: Might the outflow phenomena give rise to secondary star formation?

LADA: Yes, it is certainly possible although we do not yet have a clear example of this happening.

GIAMPAPA: What is the mass of the disk compared to the mass of the star? How does that fraction vary from high mass to low mass stars? (Do massive stars have massive disks and are low mass stars characterized by very low mass disks?)

LADA: For T Tauri stars disk masses are on the order of 0.1 Mo or less (i.e. they are generally less massive than the star itself). How that fraction varies between stars of different masses is not yet clear.