Chapter 7

How are we to Understand the Small Scale Structure of the ISM?

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THE UNSOLVED PROBLEM OF STELLAR ORIGINS

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1. Introduction

We now stand at the threshold of the 21st century having witnessed perhaps the greatest era of astronomical discovery in the history of mankind. During the twentieth century the subject of astronomy was revolutionized and completely transformed by technology and physics. Advances in technology that produced radio astronomy, infrared astronomy, UV, X and γ ray astronomy, large telescopes on the ground, in balloons, aircraft and space coupled with advances in nuclear, atomic and high energy physics forever changed the way in which the universe is viewed. Indeed, it is altogether likely that future historians of science will consider the twentieth century as the Golden Age of observational astronomy. As a measure of how far we have come in the last 100 years, recall that at the turn of this century the nature of spiral nebulae and of the Milky Way itself as an island universe were not yet revealed. The expansion of the universe and the microwave background were not yet discovered and exotic objects such as quasars, pulsars, gamma-ray bursters and black holes were not even envisioned by the most imaginative authors of science fiction. The interstellar medium, with its giant molecular clouds, magnetic fields and obscuring dust was unknown. Not even the nature of stars, these most fundamental objects of the astronomical universe, was understood.

Among the greatest achievements of astronomical science in the twentieth century has been the development of the theory of stellar structure and evolution. Stars derive their enormous radiant luminosities and longevities from thermonuclear reactions which fuse hydrogen, the primary product of the Big Bang, into heavier elements. The theory of stellar evolution developed in the middle of this century, provides an elegant explanation for

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this process as well as for those that occur once stars exhaust their nuclear fuel reserves in their cores. This theory has successfully accounted for the basic physical properties of stars including their size, color, composition, variability, age, and mass. It has been extended and refined to explain planetary nebulae, white dwarfs and pulsars. Yet, as we approach the end of this century, we find that this great theory is incomplete in one very critical aspect: the *origin* of stars remains a mystery. In other words, there is, as yet, no successful theory of star formation. The question of the origin of stars is one of the oldest and most fundamental problems that has challenged mankind's oldest science. The development of a theory that can elucidate how nature turns diffuse interstellar hydrogen into dense balls of gas with just the right mass to fuse hydrogen continues to be a primary goal of modern Milky Way research.

2. What We Have Learned About Star Formation

2.1. THE CONTINUING PROCESS OF STELLAR BIRTH

That the origin of stars has remained so mysterious for so long is largely due to the fact that the process of star formation has never been directly observed either with the naked eye or the with the most powerful telescopes. Moreover, prior to the twentieth century neither the energy source nor the bulk composition of stars were known. Indeed, without knowledge of the physical nature of stars it was very difficult to develop an understanding of their origin. At the end of the nineteenth century, the depth of the mystery surrounding stellar origins was nicely summed up by the fictional character Huck Finn (in the book The Adventures of Huck Finn by Mark Twain) when he observed the stars in the night sky and wondered "*...did they just happen or was they made?*" Have the stars been around since creation or were they being made in the heavens? As far as anybody could tell at dawn of this century, the entire universe consisted of a single stellar system, stars lived forever and the question of the origin of stars was a question of cosmology. As such the problem of star formation was not susceptible to detailed scientific investigation. That is, even the most basic hypotheses concerning stellar origins could not be directly tested by observation.

Over the last half century astronomical research has led to the fundamental realization that star formation has been a continuous, ongoing process throughout the history of the Galaxy and the universe. This critical fact has been demonstrated by both theory and observation. In particular, stellar evolution theory demonstrated that certain luminous stars, OB stars, burn their nuclear fuel at such prodigious rates that they can live for only a small fraction of the lifetime of our Galaxy. The existence of such stars clearly indicates that star formation is occurring in the present epoch of Galactic history. Moreover, observations showed that OB stars were almost always members of stellar groupings called OB associations which were characterized by space densities well below the threshold for disruption by Galactic tidal forces. The dynamical ages of OB associations (10^7 yrs.) were found to be much less than the age of the Galaxy ($\sim 10^{10}$ yrs.) and comparable to the nuclear ages of the stars derived from stellar evolution theory. Such observations supplied independent confirmation that the process of star formation was active in the present epoch. The discovery of the interstellar medium of gas and dust during the early part of the twentieth century provided a crucial piece of corroborating evidence in support of the concept of ongoing Galactic star formation. Subsequent observations of interstellar material established that clouds of interstellar gas and dust had roughly stellar composition and were considerably more massive than a single star or group of stars. This revealed that the raw material to make new stars was relatively abundant in the Galaxy.

Because star formation is occurring in the present epoch, the question of the origin of stars can be investigated by direct observation. Yet, since stars form in dust shrouded cores of dark clouds, direct observation of the process of star formation has proved extremely difficult.

2.2. THE INITIAL MASS SPECTRUM OF STARS

Important clues concerning the star formation process can be gleaned from the fossil record provided by the visible, already formed stars themselves, particularly very young stars. Perhaps the most important constraint concerning the star formation process that can be derived from known properties of stars and stellar evolution theory is the Initial Mass Function (IMF). A fundamental consequence of the theory of stellar evolution is that the life history of a star is almost entirely pre-determined by its initial mass. Consequently, to understand star formation and indeed the luminosity evolution of a system of stars such as a cluster or galaxy requires a detailed knowledge of the initial distribution of stellar masses at birth. Unfortunately, stellar evolution theory by itself, is not able to predict the IMF of stars. This quantity must be derived from observations. However, to do so is not straightforward because stellar mass is not itself an observable quantity. Stellar radiant flux or luminosity is the most readily observed property of a star. However stellar evolution theory can be used to transform between luminosity and mass because of the theory's prediction of a unique mass-luminosity relation for main sequence stars. In a classic paper nearly 40 years ago Salpeter [1] used this fact and knowledge of post-main sequence stellar evolution to transform the observed luminosity function of nearby field stars into an IMF for field stars in the solar neighborhood. With the critical assumption of a constant star formation rate through galactic history he found that the IMF was well represented by a simple power-law: $\xi(log m_*) \sim m_*^{-1.35}$ for stars with masses in the range between 1-10 solar masses. The derived sign and slope of the Salpeter IMF indicates that most stars which form in the galaxy are of low mass and moreover that most of the stellar mass in our galaxy is contained in such stars. Subsequent studies, particularly by Scalo [2, 3], extended knowledge of the field star IMF to sub-solar masses and found that the IMF has a peak at about 0.3 solar masses and therefore departs from the Salpeter power-law well above the hydrogen burning limit. This indicates that there is a characteristic stellar mass of roughly 0.3 $M_\odot$ produced as a result of the process of star formation. Implicit in Salpeter's derivation of the IMF is the assumption that the form of the IMF has remained constant through Galactic history. Subsequent studies have provided no compelling evidence to refute this remarkable notion. For example, the derived mass functions of young galactic star clusters are essentially the same as the IMF of field stars. [4, 5, 6, 7]

2.3. ASSOCIATIONS, CLUSTERS AND MULTIPLE STARS

From the stellar fossil record we also know that the birth of a star is not an isolated event. Stars form in groups over a large range of spatial scales from OB associations to clusters to binary and multiple star systems. For example, on large spatial scales, study of the spatial distribution of young OB stars indicates that all OB stars are formed in stellar groups known as OB associations [8]. The spatial extents of such associations are large (10-100 parsecs) but as mentioned earlier, the mass densities of associations are well below the limit (i.e., 0.1 $M_\odot pc^{-3}$) required for tidal stability[9]. Moreover, the typical velocity dispersion of association stars (2-4 km s^{-1}) is greater than even the escape velocity due to the mutual gravitational attraction of member stars themselves. Thus, OB associations are unbound, expanding stellar systems. OB associations contain hundreds to thousands of stars. There are considerably more low mass stars than OB stars in associations and consequently most all stars that form in the galaxy likely form in OB associations. It has long been recognized that OB associations could provide important information about the star formation process since they are so young that the individual members have not had enough time to move very far from their places of birth. For example, the present sizes of OB associations must closely reflect the sizes of the clouds which spawned them[10, 11, 12] . In addition, the structure of OB associations can provide important fossil clues about the structure and even the temporal evolution of a star forming complex. One common property of OB associations is that they are sub-structured, often consisting of sub-groupings of sequentially differing age[9]. Such sub-structure has suggested that star formation proceeds through a star forming region in an ordered temporal sequence. The chain reaction like nature of the spatial-temporal structure of OB subgroups has led to the suggestion that OB subgroups are formed by a process of sequential triggering[12]. Within associations are contained stellar clusters. Such systems typically contain 50-500 stars, have mass densities in excess of the tidal disruption limit and sizes on the order of 1 parsec. Some of these clusters will remain bound and become field open clusters after the association itself disrupts. About 10% of all stars are believed to originate in such bound open clusters which have lifetimes on the order of 10^8 years.

On small spatial scales (1-1000 AU) the radial velocity measurements of field G dwarf stars indicate that roughly 57% of all such stars have stellar companions [13, 14]. The binary fraction does not appear to depend too strongly on spectral type as studies of both M dwarfs [15] and B stars [16] have indicated. Since some binaries may have been disrupted since formation, these fractions could be lower limits to the actual fraction of binary stars produced in the star formation process. Studies of the binary populations among pre-main sequence stars show that binary stars occur even among the youngest such stars observable, indicating that the formation of binary systems occurs prior to pre-main sequence evolution, that is, during the protostellar stage as an integral part of the star formation process [17].

2.4. GIANT MOLECULAR CLOUDS: THE SITES OF STAR FORMATION

Progress in star formation research was severely limited until observations could be made at wavelengths which could penetrate the dusty veils of obscuration and directly detect the star-forming gas and dust. By the early 1970s advances in technology began to open up the infrared, millimeter and submillimeter-wave windows for astronomical exploration. With this new instrumental capability, a direct assault on the star formation problem became possible.

Twenty-five years ago, millimeter wavelength observations (mostly of the CO molecule) provided star formation research with the fundamental discovery of giant molecular clouds (GMCs). With extents on the order of 100 parsecs GMCs are the largest objects in the Milky Way. With masses often in excess of 100,000 times the mass of the sun, GMCs rival globular clusters as the most massive objects in the Milky Way. GMCs are also among the coldest objects in the universe with gas temperatures seldom exceeding 10 K. They are composed almost entirely of molecular hydrogen, contain significant amounts of interstellar dust and are permeated by magnetic fields. The linewidths of molecular emission lines observed toward GMCs are typically on the order of a few km s^{-1} and considerably greater that those ($\approx$ 0.2 km s^{-1}) expected from thermal motions in the very cold gas. The overall dynamical state of a GMC is therefore characterized by supersonic bulk motion which is thought to be of a turbulent nature. Such motion should be highly dissipative, yet GMCs maintain their supersonic dynamical states throughout their lifetimes. GMCs are also strongly gravitationally bound and cannot be supported from global collapse by thermal pressure alone. Since the lifetimes of GMCs are also considerably longer than their free–fall times, they must be supported by some agent other than thermal pressure. The magnetic fields which permeate molecular clouds may have important consequences for their dynamical states and their support against gravity. Field strengths on the order of 10–20 μG are believed typical for GMCs [18]. For typical gas densities, the Alfven speed (i.e., $V_A = \frac{B}{\sqrt{4\pi\rho}}$, where B is the field strength, and ρ is the gas density) is about 1 km s^{-1}. Although the dynamical states of the clouds are highly supersonic, this motion may be sub–Alfvenic and less dissipative than one might otherwise suppose [19]. Moreover, these field strengths are close in value to those needed to support clouds from gravitational collapse [20, 21].

Within the solar neighborhood virtually all known OB associations are found to be located within the immediate vicinity of a GMC. [22] Typically, the youngest subgroup of an OB association is found to excite an HII region or reflection nebula within the associated GMC, therefore demonstrating a *physical* relation with the cloud. This coupled with the facts that GMCs have dimensions which are comparable to if not larger than OB associations and have masses considerably greater than OB associations, suggests that OB associations and therefore most stars in the Galaxy are born in GMCs. The large difference between the stellar mass of an OB association and its associated GMC illustrates a fundamental property of star formation. Namely, that the star formation efficiency (SFE=stellar mass/(stellar + gaseous mass)) is low. The low efficiency of star formation in GMCs is of central importance for understanding the dynamical nature of OB associations. The unbound state of stellar associations is a natural consequence of star formation with a low conversion efficiency of gas to stars followed by a rapid removal of the unprocessed gas from the system [23, 24]. Such rapid gas removal is the expected consequence of O star formation within molecular clouds [25].

3. What We Are Learning About Star Formation

3.1. DENSE CLOUD CORES AND EMBEDDED STELLAR CLUSTERS

The mean gas density of the molecular material in a GMC is about 100–300 molecules cm^{-3}, more than 19 orders of magnitude less than that of the stars which form from it! GMCs are highly structured consisting of numerous filaments, clumps and dense cores [30]. Somewhere between 1 and 10% of the mass in a GMC is contained in relatively dense (10^4 cm^{-3}) cores [26]. It has long been suspected that such cores are the sites of active star formation in GMCs [27]. This suspicion has been decisively confirmed by an extensive infrared survey of the nearby L1630 molecular cloud which found essentially all the recently formed stars in the cloud to be located in dense molecular gas [28].

The dense cores within a GMC have a spectrum of sizes and of masses. They range from small cores, with linear dimensions on the order of 0.1 parsecs and masses between 1-10 solar masses, to massive cores which are 100-1000 times more massive and have dimensions of a few parsecs[29, 30]. The mass spectrum of cloud cores seems to be power law in form, with a spectral index of about -1.6. Thus small low mass cores are more numerous than large, high mass cores. However, the mass spectrum of dense cores is qualitatively different from that of stars (whose mass *spectrum* has an index of -2.3) in that most of the dense gas within a GMC is contained within a few most massive cores [26]. This difference suggests that in the process of star formation, the stars themselves stars somehow affect the determination of their final mass. In addition, it suggests that most star formation in a GMC must take place in its most massive cores (where most of the dense gas is locked up).

This latter point seems to be corroborated by the large number of embedded star clusters revealed in recent infrared imaging surveys of GMCs [32, 33]. In particular, the extensive, well sampled 2μm survey of the L1630 cloud in Orion [31] indicates that more than 90% of the young stars formed over the entire cloud are located in three rich embedded star clusters which occupy only a very small fraction of the area of the cloud. Moreover these three clusters are physically associated with 3 of the cloud's 5 most massive dense cores [28]. *In GMCs most stars apparently form in rich star clusters from massive cores of dense molecular gas.* However, most of these clusters must be disrupted soon after they emerge from a GMC, otherwise there would be more (bound) open clusters in the field than are observed [32]. This, in turn, suggests that the star formation efficiency in cluster forming cores rarely reaches values as high as 50% [32, 34].

Young embedded star clusters provide unique opportunities to investigate the stellar initial mass function and its possible variation in space and time. Such young clusters are comprised of mainly low mass, pre-main sequence, stars which are brighter than at any other time in their subsequent evolution. Consequently, modern infrared imaging detectors on modest sized telescopes can readily detect stars at and below the hydrogen burning limit and thus completely sample the entire IMF of an embedded cluster. Observations of the infrared luminosity functions of nearby embedded clusters have found them to be surprisingly similar in form. Modeling of the luminosity evolution of clusters consisting of mostly pre-main sequence stars suggests that this similarity can be explained if 1) the underlying mass spectra of the embedded clusters are all the same and essentially identical to the field star IMF down to the hydrogen burning limit, and 2) if star formation proceeds in a continuous fashion at a more or less uniform rate over the time the clusters are embedded in molecular gas (typically 1-7 x 10^6 yrs.) [7]. Although the mass spectra of embedded clusters appear universal in form, the star formation rate and (consequently) the duration of the embedded phase can vary by more than an order of magnitude from one cluster to another. The origin of this variation is not known but may be related to environmental factors such as the presence or absence of external star formation triggers such as shock waves produced by HII regions or supernovae [7].

3.2. PRE-MAIN SEQUENCE STARS AND CIRCUMSTELLAR DISKS

The formation and early evolution of stars can be broadly divided into three stages: I)- the *protostellar stage*, during which an embryonic young stellar object is being assembled out of molecular gas and dust, II)- the pre-hydrogen burning or *pre-main sequence stage*, during which the young stellar object is contracting in a quasi-static manner to the main sequence and III)- the zero age main sequence or *ZAMS stage*, when the star has reached the necessary internal densities and temperatures to begin a stable phase of hydrogen burning energy production. However, the exact sequence of events which governs the formation and early evolution of stars is quite different for high and low mass stars. In particular, high mass stars do not go through a significant pre-main sequence (i.e., a pre-hydrogen burning) phase. In fact such stars begin to burn hydrogen during their protostellar phase of evolution. The physical reason for this becomes apparent if one considers the timescales for protostellar collapse and pre-main sequence contraction. The timescale for the gravitational collapse of a cloud core, the free-fall time, is determined largely by ρ, the density of the cloud. For the typical mean density ($n \approx 10^4$ cm^{-3}) of a cloud core (of either low or high mass) the free–fall time is about 4 x 10^5 years. The time scale for pre-hydrogen burning evolution is the Kelvin-Helmholtz time which is very rapid for a high mass star (i.e., $\approx 10^4$ years for $M_* = 50\ M_\odot$) and relatively slow for a low mass star (i.e., $\approx 3\mathrm{x}10^7$ years for $M_* = 1\ M_\odot$). More importantly for high mass stars $\tau_{KH} < \tau_{ff}$ and these stars begin burning hydrogen and reach the main sequence before the termination of the infall or collapse phase of protostellar evolution. On the other hand, for low mass stars $\tau_{KH} > \tau_{ff}$ and these stars have an *observable* pre-main

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sequence stage of stellar evolution.

Because high mass stars are extremely hot and luminous they can strongly effect their surroundings even during their protostellar stages of evolution. Moreover, since high mass stars evolve very quickly and are formed only in relatively small numbers, observing their formation is a complex and difficult task. On the other hand, low mass stars are much less destructive of their natal environments, are produced in large numbers and have relatively long formation times. Consequently, they provide unique laboratories for the investigation of star formation and much more is known about their early evolution, particularly their pre-main sequence evolution, than is known about the formative stages of OB stars.

If a low mass pre-main sequence star, such as a T Tauri star, is young enough it will still be intimately associated with gas and dust associated with its birth. In such a circumstance we expect both the stellar photosphere and the natal circumstellar gas and dust to emit radiation. Since the circumstellar material is extended over a size scale considerably larger than a stellar photosphere, the emission that emerges will be characterized by a range in temperatures and have a spectral distribution that is wider than a single blackbody. The detailed shape of the emergent spectrum will depend in part on the nature and distribution of the circumstellar material. For instance, Lynden-Bell and Pringle [35] 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. T Tauri stars were long known to emit excess near-infrared light, but it wasn't until ground-based mid-infrared and space based IRAS far-infrared observations were obtained for these stars that the true nature of their continuous spectra was evident. Such observations indicated that the spectra of most T Tauri stars were power-law in shape from visible to far-infrared (IRAS) wavelengths suggesting the presence of circumstellar disks around these stars [36, 37, 38, 39].

Additional evidence for such disks comes from optical, high resolution spectral observations of forbidden-lines from these stars which often show only blue-shifted components. The lack of red-shifted lines implicated the existence of a highly opaque and flattened distribution of material around the stars [41, 42]. More direct evidence for the presence of circumstellar disks comes from observations of optical and infrared absorption lines around stars such as FU Ori [43]. These observations indicate that the circumstellar material is differentially rotating as would be expected for a disk in Keplerian motion around a central star. These putative disks have also been detected at millimeter and submillimeter wavelengths where their emission is optically thin and their masses can be measured (e.g., [40]). The masses typically range from 0.01 to 0.1 solar masses, comparable to that expected for a planet producing circumstellar disk. Other interesting evidence for circumstellar disks includes the detection of small ($\approx$ 100 AU) ionized structures around faint stars in the Trapezium cluster. These objects appear to best understood as the photo-evaporating atmospheres of circumstellar disks whose central stars find themselves too near the ionizing O star Θ^1C Ori [44]. Such structures have also been recently detected in space telescope images of the Orion nebula [45].

Among young stars, circumstellar disks now appear to be ubiquitous. This is one of the most important and exciting discoveries of star formation research during the last decade. For one thing this clearly indicates the importance of the role of angular momentum in the star formation process. In addition, this discovery suggests that the conditions for planet formation are prevalent around young stars and that there are hundreds of laboratories near the Sun where direct study of the conditions that lead to planet formation is now possible.

3.3. PROTOSTARS AND BIPOLAR MOLECULAR OUTFLOWS

For low mass stars the pre-main sequence phase (i.e., Stage II) of early stellar evolution begins at the end of the protostellar phase when the build up of the star by the infall/accretion of substantial amounts of molecular cloud material is essentially over. At this point the spectral energy distribution of the star is dominated by its photospheric emission and the star emerges as an observable object, which for the first time can be plotted on the HR diagram. For a star of given mass its initial position on the HR diagram corresponds to a specific size or stellar radius. In other words, a star first becomes observable as a star and first appears on the HR diagram only after it obtains a specific maximum size which is pre-determined by its prior protostellar evolution. The initial positions of stars on the HR diagram varies with stellar mass. These positions form a locus of points on the HR diagram called the "birthline" [46]. The birthline represents the initial condition for pre-main sequence (quasi-static) contraction. It is the dividing line between the protostellar and pre-main sequence stages of stellar evolution. Stellar evolution theory does not predict the existence of the birthline. The physics which determine the birthline are the mysterious physics of protostellar evolution. Understanding the nature of protostars is, at present, the major frontier of star formation research.

It has long been recognized that the greatest progress toward understanding star formation would most certainly result from the unambiguous discovery and observation of a protostar, *an object which is in the process* *of assembling into a stellar-like configuration the bulk of the material it will contain when it resides on the main sequence as a hydrogen burning star.* Protostars are the Holy Grail of observational star formation research. To date no unambiguous identification of a protostar has been made. However, there exists an entire class of sources which are excellent candidates for such objects. These sources are often called "infrared protostars" because they emit almost all their radiant energy in the far-infrared. They are always found embedded in dense molecular cores and they are almost always invisible in the optical. Their infrared spectral energy distributions clearly indicate that these sources are surrounded by substantially more circumstellar gas and dust than are T Tauri stars. In fact infrared protostars and T Tauri stars appear to be at the opposite ends of a more or less continuous evolutionary sequence in which gas and dust are progressively removed from around a young star (i.e., T Tauri stars resemble infrared protostars stripped of their circumstellar envelopes; [24, 47]).

To a reasonable degree of detail, the energy distributions of many infrared protostars can be well fit by theoretical models of rotating isothermal spheres collapsing from the inside-out [50, 47] which greatly strengthens the suspicion that these objects are indeed protostellar in nature. Confirmation of their status as protostars would be definitive if infall motions in their circumstellar gas could be detected. Despite many attempts to search for such motions, only in two instances [48, 49] have molecular line spectra shown the signature expected from inside-out collapse, however in neither case is the evidence yet compelling. But far from being quiescent, the molecular gas around most infrared protostellar candidates has almost always been found to exhibit unequivocal evidence for *outflow* motions!

Fifteen years ago millimeter-wavelength CO observations of the molecular gas surrounding certain young stellar objects 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 [51]. The regions containing the hypersonic outflows are almost always coincident with, if not centered on, the position of an embedded infrared source.

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., [51, 52, 55, 53, 54]). Briefly, the masses of such outflows are substantial, containing anywhere between 0.1 and 100 solar masses. 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 (e.g., [56]). 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, usually an infrared protostar! Bipolar molecular outflows are individually energetic enough to disrupt cloud cores and it is suspected that they are the likely agent that drives the evolution of an embedded young stellar object from the protostellar (I) stage to the pre-main sequence (II) stage of evolution.

Although molecular outflows appear to provide the mechanism which enables a protostar to remove surrounding material and in doing so evolve into a pre-main sequence star, the high frequency of association between infrared protostars and molecular outflows poses a paradox. The statistics suggest that a significant fraction of the lifetime of a protostellar object is spent in the outflow phase. Yet, if such 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 very likely the key to understanding the basic physics of the star formation process [57].

4. What We Don't Know About Star Formation

More progress has been made toward understanding the process of star formation in the last twenty years of this century than throughout all previous history. Yet a basic theory of stellar origins still eludes us. The origin of GMCs, for instance, is a complete mystery. The overall problem of star formation can be made somewhat more manageable if we take as the initial condition the existence of a GMC. The problem can then be formulated as follows: What enables a few per cent of the otherwise dynamically stable gas and dust in a GMC to collapse and increase in density by 20 orders of magnitude to form a star? This question can be further simplified by dividing it into two parts. First, how does a GMC transform roughly 10% of its mass into dense cores with the spectrum of masses and sizes we observe? Second, how does an individual dense core transform a significant fraction ($\geq 20\%$) of its mass into either a single star or a group of stars with a spectrum of masses given by the IMF? As with the question of the origin of a GMC, the physics of dense core formation is essentially unknown. Presumably for a dense core to form, the material which forms it must lose support against gravity. If this support is provided by magnetic fields, then core formation may be possible through the slow outward diffusion of magnetic fields via a process known as ambipolar diffusion [58, 59, 60, 61]. Although this mechanism appears a promising one for the formation of lower mass cores ($\sim$ 10 $M_\odot$) it is not at all obvious that it can account for the shape of the core mass spectrum and the existence of the very massive cluster forming cores in which most stars are formed. All this seems in contradiction to the opening sentence of this section. However, when the problem of star formation is yet simplified one further step, by considering the existence of a dense molecular core as the initial condition or starting point for the formation of a single low mass star, then the progress achieved in deepening our understanding of stellar origins becomes more apparent.

In order for gas in a dense core to collapse and form a star it must become gravitationally unstable and in the process lose most of its initial magnetic flux and substantially redistribute its initial angular momentum. Consider that if the magnetic fields that thread a typical dense core were to remain frozen in the gas as it collapsed and increased in density by 19 orders of magnitude to form a star, the magnetic field at the stellar surface (i.e., $B_* = B_{cloud} \left(\frac{\rho_*}{\rho_{cloud}}\right)^{\frac{1}{2}}$) would be $\approx 10^4$ Gauss, orders of magnitude greater than that (i.e., 1 Gauss) permitted by observations of normal stars. This is usually referred to as the "magnetic flux" problem of star formation. In addition the rotational velocities of dense cores in clouds are found to be small, if observed at all (e.g., [62]). For low mass cores, which form individual stars similar in mass to the sun, the observed angular velocities are typically $\Omega \leq 3 \times 10^{-14}$ rad s^{-1}. However, the angular momentum per unit mass (i.e., $r^2\Omega$) of the slowly rotating core gas is still on the order of 10^{22} cm^2 s^{-1}, considerably in excess of that of the sun (10^{15} cm^2 s^{-1}), but not that of the outer planets of the solar system ($\sim 10^{20}$ cm^2 s^{-1}). The smooth distribution of mass in a molecular cloud core, however differs considerably from that characterizing the solar system where 99% of the mass contains less than 2% of the total angular momentum. Clearly, a significant redistribution of mass and angular momentum must occur before dense molecular cloud material can form a star. This is a modern restatement of the famous "angular momentum" problem of star formation.

During the last decade an appealing theory of low mass star formation has been in the process of development by Frank Shu and his students and collaborators [21]. This theoretical work represents the first detailed attempt to tie together the new empirical knowledge gained in the last two decades into a unified, coherent picture of stellar birth. Their scenario can be briefly outlined as follows. Star formation begins when a dense core, assumed to be supported by a magnetic field, becomes unstable as a result of the ambipolar diffusion of its field. By this attractive process both the support of the cloud and the magnetic flux of the star forming gas are largely removed, simultaneously solving two important problems. Once initiated in the central regions of the dense molecular core, the collapse proceeds in a non-homologous, inside-out fashion. Initially small amounts of low angular momentum material fall in along the core's rotational axis and quickly build up an embryonic, hydrostatic, stellar core. As a result of the conservation of angular momentum, infalling gas with even modest amounts of initial angular momentum is unable to fall directly onto the central stellar core and instead collapses into a rotating disk. In fact, in a typical rotating protostar, most of the material that ultimately ends up on the star must first fall into the disk and then be subsequently accreted onto the central stellar core. However, in order to flow through the disk and join onto the central star, accreting material must lose substantial amounts of energy and angular momentum. Indeed, during the protostellar stage the radiant output of the system should be completely dominated by accretion generated luminosity. Before attaching onto the star, accreting material must overcome a centrifugal barrier at the physical interface between the star and disk. According to the theoretical picture this is accomplished by the generation of an intense, centrifugally-driven, hydromagnetic, bipolar wind. This wind carries away a small amount of mass but a large amount of angular momentum and thus *enables a protostar to gain mass by simultaneously losing mass*, solving the key observational paradox mentioned earlier. As the protostar evolves, the outflow it generates sweeps up circumstellar matter and eventually reverses the infall, setting a limit to the amount of mass ultimately accreted by the protostar. Eventually, the outflow removes enough surrounding gas that the protostar star is revealed as a visible star with a circumstellar disk. The time from the initial collapse to the appearance of a visible young stellar object is only a few hundred thousand years or less. Over the next two to three million years of pre-main sequence evolution the circumstellar disk dissipates as most of its material either accretes onto the star or forms planets.

As impressive as this first attempt at a theory of star formation is, our understanding of stellar origins is still far from complete. For example, the questions of the formation of binary stars and the IMF are still unanswered. The formation of high mass stars is still not yet accounted for. A compelling picture to explain the origin of bipolar flows is still missing. It is not at all clear how the formation process of stars in rich embedded clusters differs from that of single stars, although observations suggest that it must. Observations also indicate that episodic outbursts and mass loss may be important in early stellar evolution and this is not yet adequately explained or predicted by theory. We still don't know how GMCs come into being. Clearly, the current theoretical picture is a promising foundation for a comprehensive theory of star formation. Although it is still largely a work in progress, it does provide an excellent working hypothesis for ongoing and future research. At the close of the twentieth century we find star formation to be a richer, more complex and fascinating process than could have been envisioned 100 years ago. It promises to remain a major frontier of galactic research well into the next century.

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DISCUSSION

J. Palous: What is the evidence to your statement that inside the clouds the Angular momentum is evenly distributed?

Lada: –

H. van Woerden: How can you be sure that in the trapezium cluster the low-mass stars, too, are only 10^6 years old? Is their evolution fast enough?

Lada: The Space Telescope observations provided a very large sample of faint, low mass stars which could be placed on the HR diagram, their ages were then determined from comparison with theoretical evolutionary tracks. Their rate of evolution is entirely consistent with 10^6 year old stars.

W. Verschueren: An intriguing problem in star formation studies is the possible difference in site between low and high mass star formation. Are there cores which preferentially form low mass stars and others which form high mass stars? How would you summarize the evidence regarding this problem from all observations from the past years?

Lada: <u>All</u> dense cores which form stars form low mass stars. Cores which are sufficiently massive (i.e. m $\gtrsim 100$ m$\odot$) can also form high mass stars. Evidently, the probability of forming a high mass star is directly related to the mass of a dense core, whereas low mass stars from in dense gas essentially independent of core mass. Consequently, there can be dense regions (of relatively low mass) which end up only producing low mass stars but it is very difficult to find a region that produces high mass stars without many low mass stars.

R. Wyse: Could you comment on the circumstances - and timescales and lengthscales - one should/could think of star formation as having <u>positive</u> feedback, and then on the contrary <u>negative</u> feedback.

Lada: First let me say that I don't think we fully understand all the physical circumstances which could result in positive and negative feedback in the star formation process. However, if we consider O stars, for example, we would predict that they simultaneously produce both positive and negative feedback via HII regions, stellar winds and supernovae. In this case the negative feedback, that is cloud destruction, is local and the timescale shorter than the positive feedback which presumably is star formation induced or triggered by shocks. These shocks need to propagate over larger distances and take longer time to sweep up sufficient material to trigger active star formation.

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