STAR FORMATION
and the INITIAL MASS FUNCTION

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Abstract: We review the current theory for the formation of stars in molecular clouds. We also discuss the initial mass function; in particular, we present a scaling argument which produces a power-law IMF in reasonable agreement with observations.

1 Introduction

Over the course of the last decade, a fairly successful paradigm of star formation has been developed. Within this paradigm, the agreement between observations and theory is quite good, especially for the case of low-mass stars. This paradigm thus provides the cornerstone of our current understanding of the star formation process. We review this paradigm in §2. We note that disk accretion plays an important role in the formation of stars, but a viable theory of disk accretion remains lacking. However, the fundamental unresolved issue of star formation theory is the question of the initial mass function; we discuss the initial mass function in §3. We conclude in §4 with a summary and discussion of our results.

2 Star Formation in Molecular Clouds

In this section, we review the star formation paradigm which has emerged in the last decade. In this paradigm, stars form within the *cores* of molecular clouds. These core regions, which are small subcondensations within the much larger molecular clouds, evolve in a quasi-static manner through the process of ambipolar diffusion. In this process, magnetic field lines slowly diffuse outward and the central regions of the core become increasingly centrally concentrated. The magnetic contribution to the pressure support decreases with time until the thermal pressure alone supports the core against its self-gravity (at least in the central regions). At this point, the core is in an *unstable* quasi-equilibrium state which constitutes the initial conditions for dynamic collapse.

When a core begins to collapse, a small hydrostatic object (the protostar) forms at the center of the collapse flow and an accompanying circumstellar disk collects around it. This phase of evolution – *the protostellar phase* – is thus characterized by a central star and disk, surrounded by an infalling envelope of dust and gas. The characteristics of this infalling envelope largely determine the spectral appearance of the object in this phase.

As a protostar evolves, both its mass and luminosity increase; the protostar eventually develops a strong stellar wind which breaks through the infall at the rotational poles of the system and creates a bi-polar outflow. During much of this *bipolar outflow phase* of evolution, the outflow is well collimated (in angular extent) and *infall* takes place over most of the solid angle centered on the star. The outflow gradually widens in angular extent and the visual extinction to the central source gradually decreases. The outflow eventually separates the newly formed star/disk system from its parental core and the object enters *the T Tauri Phase* of evolution. The newly revealed star then follows a pre-main-sequence track in the H–R diagram and evolves toward the main-sequence.

2.1 Molecular Clouds: The Birthplace of Stars

Molecular clouds are the birthplaces of stars. These clouds are observed to be *not collapsing* as a whole, in spite of the fact that their masses are generally much larger than a Jean's mass, i.e., the self-gravity of these systems is generally much larger than the *thermal* pressure support (see, e.g., Zuckerman and Palmer 1974; Shu, Adams, and Lizano 1987). As a result, these clouds must be supported by some nonthermal means. The most viable candidates for providing this support are magnetic fields and "turbulence".

Magnetic fields are observed in these clouds (see, e.g., Heiles 1987; Goodman et al. 1989) and typically have field strengths in the range $10 - 30\ \mu$G. In addition, maps of polarization of background starlight seen through these clouds show very uniform (well ordered) structure of the polarization vectors (e.g., Goodman 1990). Since the polarization is believed to arise from scattering by dust grains which are themselves aligned with the magnetic field, well-ordered structure in the polarization maps is usually interpreted as well-ordered structure in the magnetic field itself. In other words, the magnetic field is *not* extremely tangled; it retains a more or less uniform component.

The formation of substructure within molecular clouds remains an important but largely unsolved problem. Molecular clouds are observed to have highly nonlinear substructure on virtually all resolvable spatial scales (e.g., Houlahan and Scalo 1992; Wiseman and Adams 1994). Cloud structure has been described in terms of "sheets", "filaments", and quasi-spherical "clumps" of cloud material (e.g., Blitz 1993). At present, no definitive theory exists for the formation of substructure within molecular clouds. However, if a cloud begins to collapse, a wide spectrum of wave motions can be excited (Arons and Max 1975). Nonlinear Alfvén waves (Elmegreen 1990) and nonlinear solitary waves (Adams and Fatuzzo 1993) have recently been studied and may provide part of the explanation for the observed clumpy structure.

2.2 Molecular Cloud Cores

Molecular cloud cores represent the cloud structure on small size and mass scales. The formation of these cores occurs through the process of *ambipolar diffusion* (Shu 1983; Lizano and Shu 1989; Nakano 1985; Mouschovias 1976, 1978). This process occurs as follows: The cloud is very lightly ionized; only about one particle per million carries a charge. The charged species – the ions – are very well coupled to the magnetic field. However, the only interaction that the neutral species has with the magnetic field is through interactions with the ions. Thus, the ions can exert a force on the neutrals if and only if a drift velocity exists between the two species. The physical meaning of this result is that the ions (and hence the magnetic field) must be slowly diffusing outward relative to the neutral component, which is slowly contracting because of gravity. This process takes place on a timescale which is generally much slower than the free-fall collapse timescale of the cloud. As a result, the loss of magnetic flux provides the bottleneck in the star formation process and keeps the efficiency of star formation fairly low ($\sim$ 1%) in molecular clouds.

We stress, however, that the mass scale defined by cores in still much larger than that of the forming stars. Hence, the interstellar medium cannot provide the mass scale for star formation. Instead, these core regions provide the initial conditions for protostellar collapse. In nearby molecular cloud complexes which are forming low mass stars, these cores are observed to be nearly isothermal and slowly rotating. In our current (idealized) theory of star formation, the cloud cores (the initial state) can be described by two physical variables: the isothermal sound speed a and the (uniform) angular velocity Ω of the core. Observations of cloud cores indicate temperatures in the range $10 - 35$ K (e.g., Myers 1985) and corresponding sound speeds $a = 0.20 - 0.35$ km s^{-1}. When rotation rates are detectable, the measured angular velocity is of the order $\Omega = 1$ km s^{-1} pc^{-1} $\sim 3 \times 10^{-14}$ rad s^{-1} or larger. At spatial scales much smaller than the radius of rotational support, $R = a/\Omega \sim 0.1 - 1.0$ pc, isothermal cloud cores are highly centrally concentrated and are expected to have density profiles of the form

$$\rho = (a^2/2\pi G)r^{-2}, \tag{2.1}$$

(see Shu 1977; Terebey, Shu, and Cassen 1984).

Recent observational work (Myers and Fuller 1992) suggests that cores of higher mass have a slightly different structure than the pure isothermal model described above. For sufficiently large size scale ($r \sim$1 pc) and low density $n < 10^4$ cm^{-3}, the observed linewidths Δv in cores have a substantial nonthermal component which scales with density according to $\Delta v \propto \rho^{-1/2}$. If this velocity is interpreted as a transport speed, then a "turbulent" or "nonthermal" component to the pressure can be derived (Lizano and Shu 1989; Myers and Fuller 1992) and has the form $P = P_0 \log(\rho/\rho_0)$.

2.3 Protostellar Collapse and Radiative Signature

In this section we discuss protostars, objects still gaining mass through infall. For simplicity, we focus our discussion on low-mass protostars ($M \leq 2M_\odot$), where the radiation field is not strong enough to affect the infalling envelope and the dynamical collapse is thus decoupled from the radiation.

An isothermal cloud core will collapse from inside-out (Shu 1977), i.e., the interior of the core will collapse first and successive outer layers will follow. The collapse naturally produces a core/envelope structure, with a central hydrostatic object (the forming star) surrounded by an infalling envelope of dust and gas. This inside-out collapse progresses as an expansion wave propagates outward at the sound speed. Outside the expansion wave radius ($r_H = at$) the cloud is static; inside this radius, the flow quickly approaches free-fall velocities. The density distribution of the flow is nearly spherical outside a centrifugal radius,

$$R_C = G^3 M^3 \Omega^2 / 16 a^8, \tag{2.2}$$

the position where the infalling material with the highest specific angular momentum encounters a centrifugal barrier (Cassen and Moosman 1981; Terebey, Shu, and Cassen 1984). Inside the radius R_C, the flow becomes highly non-spherical as particles spiral inward on nearly ballistic trajectories. In the region immediately surrounding the star, the temperature is too high for dust grains to exist and an opacity-free cavity is produced (see Stahler, Shu, and Taam 1980).

Notice that there is no mass scale in this collapse scenario. Instead, the collapse flow feeds material onto the central star and disk at a well defined mass infall *rate*

$$\dot{M} = m_0 a^3 / G, \tag{2.3}$$

where $m_0 = 0.975$ is a constant (see Shu 1977). The absence of a mass scale suggests that the origin of stellar masses is determined in part by *stellar* processes rather than only by the interstellar medium (e.g., Shu, Adams, and Lizano 1987; Lada and Shu 1990; see also §3).

The radiation from forming stars is important because it allows for both a test of the underlying theory and for a means of identifying protostellar candidates. The radiation field for protostellar objects can be divided into three separate components: the star, the disk, and the infalling dust envelope. The stellar and disk components are highly attenuated by the extinction of the dust envelope and most of the luminosity is absorbed by dust grains and re-radiated at far-infrared wavelengths. Hence, the exact form of the initial star/disk spectrum is unimportant as long as the total luminosity of the system is properly determined. The protostellar luminosity has several components, although the ultimate energy source is the gravitational potential well of the star. The main uncertainty in determining the luminosity is the mechanism by which material is accreted through the disk; however, disk stability considerations place fairly tight constraints on the allowed disk accretion activity (e.g., Adams, Ruden, and Shu 1989; Shu et al. 1990). The total luminosity of the system is thus reasonably well determined and is a substantial fraction of the total available luminosity

$$L_0 = \frac{GM\dot{M}}{R_*}, \tag{2.4}$$

where R_* is the stellar radius (typically $R_* \sim$ few $R_\odot$ – see Stahler, Shu, and Taam 1980).

The diffuse radiation field of the dust envelope can be determined through a self-consistent radiative transfer calculation (Adams and Shu 1986). The theoretical spectral energy distributions calculated from this protostellar model are in good agreement with observed spectra of protostellar candidates (see Adams, Lada, and Shu 1987; Myers et al. 1987). The spectra of sources in the bipolar outflow stage of evolution are also well described by protostellar *infall* models; this result suggests that both infall and outflow are taking place simultaneously in such objects.

Protostars cannot be placed in the H–R diagram because they have no well-defined photospheric temperature: protostars have extended atmospheres and hence their spectral energy distributions are always much wider than that of a blackbody. As a result, another approach must be invoked to describe this early phase of stellar evolution. The total system luminosity L and the column density N of the infalling envelope (or, equivalently, the visual extinction A_V) are the two most appropriate physical quantities that describe the system; we therefore use the $L - A_V$ diagram to characterize the protostellar phase of evolution. The total system luminosity constitutes the vertical axis; the visual extinction $A_V = \kappa N$ of the infalling envelope constitutes the horizontal axis (which is plotted backwards). For a given initial state (i.e., a given a and Ω) a protostar will trace out a well-defined track in the diagram as time proceeds (Adams 1990).

2.4 The Protostellar to Stellar Transition

In the current star formation scenario, the transition from embedded source to optically revealed T Tauri star occurs through the action of a powerful stellar wind. Although the presence of such winds (and related outflow phenomena) are well established observationally (Lada 1985), the wind production mechanism is not yet fully understood theoretically. However, one promising approach is a centrifugally driven magnetic wind mechanism (see, e.g., Shu et al. 1994 for further discussion). Notice that these winds and the outflows they drive are crucially important for understanding the final properties of the star/disk system and hence for understanding the initial mass function (see §3).

When pre-main-sequence stars (often T Tauri stars) first appear in the H–R diagram, they seem to appear on a well defined locus denoted as the "stellar birthline" (Stahler 1988; Palla and Stahler 1991). The location of this birthline corresponds to stellar configurations which are capable of burning deuterium. In other words, stars appear on the H–R diagram as visible objects with just the right properties to burn deuterium. Deuterium burning produces stellar convection which, in conjunction with differential rotation in the star, can lead to dynamo action and the production of fairly large (100 – 1000 G) magnetic fields.

Since these field strengths are required for the centrifugally driven wind mechanism mentioned above, this overall picture of stars determining their own mass through the action of winds is consistent.

2.5 Pre-Main-Sequence Stars and Circumstellar Disks

Young stars are often observed to have infrared excesses in their spectral energy distributions (see, e.g., Rydgren and Zak 1987; Rucinski 1985; see also the review of Appenzeller and Mundt 1989). The most likely explanation for the infrared excess is the presence of circumstellar disks, which may be either active and have appreciable luminosity or passive and only absorb and re-radiate stellar photons.

Through fitting the spectral energy distributions of star/disk systems, we can estimate the basic physical properties of the disks (see Adams, Lada, and Shu 1988; Adams, Emerson, and Fuller 1990; Kenyon and Hartmann 1987; Beckwith et al. 1990). The results of such studies provide estimates for the masses and radii of the disks. The minimum values for the radii of these disks are $\sim$100 AU. The currently available mass estimates, which depend on the dust opacity at submillimeter wavelengths (see Beckwith et al. 1990), lie in the range 0.01 – 1.0 $M_\odot$. Notice that the estimated disk properties (radial sizes, masses, and hence angular momenta) are in good agreement with the disk properties predicted by the *protostellar* theory.

2.6 Unresolved Issues

Two fundamental problems in the current theory of star formation are the disk accretion mechanism and the stellar wind mechanism. For the disk accretion problem, dynamical studies of self-gravitating instabilities (see Adams, Ruden, and Shu 1989) are promising and may lead to the observed activity in these systems. For the wind problem, the centrifugally driven magnetic wind (see, e.g., Shu et al. 1994) is also promising, but more work is needed to complete the theory. We also stress that the current theory works well for the formation of single stars of low mass (although most stars are members of binary systems – see, e.g., Abt 1983). The extension of this theory to include the formation of binary systems and stars of higher mass is currently being studied.

3 The Initial Mass Function

The initial mass function (IMF) is perhaps the most fundamental output of the star formation process. Unfortunately, at the present time, we remain unable to calculate the initial mass function from *a priori* considerations (see, e.g., Zinnecker, McCaughrean, and Wilking 1993 for a recent comprehensive review).

In considering the calculation of the initial mass function, we can conceptually divide the process into two basic subproblems:

[A] The spectrum of initial conditions produced by the interstellar medium.

[B] The transformation between a given set of initial conditions and the properties of the final system (the newly formed star).

As discussed in §2.1, molecular clouds exhibit generally quasi-static behavior. The clouds are not observed to be collapsing as a whole; on average, the lifetime of a molecular cloud is an order of magnitude longer than the naive free-fall time. Some additional support mechanism (in addition to thermal pressure) must be present in these clouds; magnetic fields and turbulence are generally believed to play an important role. Thus, it makes sense to conceptually divide the process of determining stellar masses into the two steps given above. In the following subsections, we discuss each of these two subproblems.

3.1 The Spectrum of Initial Conditions

In the case of item **[A]** above, we must understand all of the relevant processes which occur in molecular clouds. In particular, we must understand the mechanism that selects out the distribution of properties for molecular cloud cores (recall that these cores provide the initial conditions for protostellar collapse). Unfortunately, however, our current understanding of this aspect of the problem is rather poor. Much more work on the formation of substructure within molecular clouds is needed before we can begin to predict the distribution of core properties from *a priori* considerations.

Although we cannot calculate and predict the spectrum of initial conditions, we can measure these conditions in molecular clouds. A complete discussion of molecular clouds as star forming environments is beyond the scope of this present work. We note, however, that many groups (see Blitz 1993) have studied the clump mass spectrum of molecular clouds and have found power-law forms, i.e.,

$$\frac{dN_{\rm cl}}{dM_{\rm cl}} \sim M_{\rm cl}^{-p}\,, \tag{3.1}$$

where $p \approx 3/2$ is a rather robust value.

For our purposes here, another important property of these clouds is that they are highly non-uniform; clumpiness and structure exist on all resolvable scales. Thus, no characteristic density exists for these clouds and hence no (single) Jeans mass exists. We stress that, at least in the case of present day star formation, *the Jeans mass has virtually nothing to do with the masses of forming stars.*

3.2 Semi-Empirical Mass Formula

In order to understand the transformation between initial conditions and the final masses of the stars produced (item **[B]** above), we must know how the stellar outflow stops the inflow and separates the star/disk system from its molecular environment. In this section, we obtain an order of magnitude estimate of this process by adopting the arguments first presented by Shu, Lizano, and Adams (1987); in other words, for given initial conditions, we derive a scaling relation for the masses of forming stars.

Since we do not yet understand how high velocity outflows are produced, we must proceed in a semi-empirical manner. The flow luminosity $L_{\rm out}$ is observed to be roughly a constant fraction of the photon luminosity of the central source L_* over several decades of L_*, i.e., $L_{\rm out} = \alpha L_*$, where empirically $\alpha \sim 10^{-2}$ (Bally and Lada 1983; Lada 1985). The strength of the infall can be measured by the rate $\dot{M}_*$ at which matter falls *directly* onto the star. When the stellar radius is small compared to the centrifugal radius, $R_* \ll R_C$, the direct infall rate $\dot{M}_*$ is a small fraction of the total mass infall rate and is given by

$$\dot{M}_* = \frac{8 m_0 R_* a^{11}}{G^4 M^3 \Omega^2} \,. \tag{3.2}$$

Disk stability considerations suggest that the stellar mass M_* is some fraction γ of the total mass M which has collapsed to the central star/disk system, i.e.,

$$M_* = \gamma M \,. \tag{3.3}$$

The stellar wind must have a mass loss rate $\dot{M}_w$ with a terminal velocity comparable to the escape velocity from the surface of the star. In order for the outflow to be sufficiently strong to reverse the direct infall (with the rate $\dot{M}_*$), the mass loss rate $\dot{M}_w$ of the wind must be be comparable to $\dot{M}_*$:

$$\dot{M}_w = \delta \dot{M}_* . \tag{3.4}$$

Notice that we should really compare the ram pressure ($\sim \dot{M}_w v_w$) of the wind with that of the infall ($\sim \dot{M}_* v_*$). However, both velocities are determined by the depth of the stellar potential well and are thus comparable in magnitude; we thus divide out the velocities and incorporate any uncertainties into the parameter δ. Finally, if the winds roughly conserve energy while driving bipolar outflows, we can write

$$\dot{M}_w G M_* / R_* = \epsilon \frac{\alpha}{\beta} L_* , \tag{3.5}$$

where ϵ is a constant.

The combination of the above results then implies that the final properties of the newly formed star (at the point of evolution when its wind is capable of reversing the direct infall) are given by

$$L_* M_*^2 = 8 m_0 \gamma^3 \frac{\delta}{\epsilon} \left(\frac{\beta}{\alpha} \right) \frac{a^{11}}{G^3 \Omega^2} = \chi \frac{a^{11}}{G^3 \Omega^2} , \tag{3.6}$$

where in the second equality we have collected all of the constants into a single parameter χ. Under most circumstances, we expect the parameters γ, δ, and ϵ to be of order unity. For example, disk stability arguments suggest that $\gamma \approx 2/3$; a smaller value would correspond to a larger relative disk mass and hence an unstable system (Adams, Ruden, and Shu 1989). We find empirically that $\beta/\alpha \sim 10^2$. We thus expect that $\chi \sim 250$ is reasonable estimate.

Equation [3.6] above provides us with a transformation between initial conditions (the sound speed a and the rotation rate Ω) and the final properties of the star (the luminosity L_* and the mass M_*). If we use "typical" values for clouds

(e.g., $a = 0.2\ \mathrm{km\ s^{-1}}$ and $\Omega \sim 3 \times 10^{-14}\ \mathrm{rad\ s^{-1}}$), we obtain stellar masses of approximately $M_* \approx 0.5\ M_\odot$, which is the typical mass of stars forming in regions with these properties. Thus, in spite of its highly idealized nature, equation [3.6] provides reasonable order of magnitude estimates for M_* as a function of initial conditions (a, Ω).

In the interpretation of the transformation [3.6], several points must be kept in mind. The right hand side of the equation depends rather sensitively on the sound speed ($\sim a^{11}$) and hence the temperature ($\sim T^{11/2}$). However, on the left hand side of the equation, we must use the luminosity vs mass relation for stars; for low mass stars on the main sequence, $L_* \sim M_*^4$, whereas for high mass stars $L_* \sim M_*$. We thus obtain (very crude) scaling relations of the form $M_* \sim a^\mu$, where $\mu \approx 11/6$ for low mass stars and $\mu \approx 11/3$ for high mass stars. Keep in mind, however, that much uncertainty has been encapsulated in the parameter χ, which should really be considered as a complicated function of all the environmental parameters. We have also characterized the initial conditions by only two physical variables (a and Ω) whereas much more complicated initial states are possible. Finally, we have ignored radiation pressure in this argument; for sufficiently massive stars ($M_* \geq 7\ M_\odot$) radiation pressure will help the outflow reverse the infall (e.g., see Wolfire and Cassinelli 1986, 1987).

3.3 A Scaling Relation for the IMF

We can now piece together all of the above arguments to construct an initial mass function (see also Silk 1994). We first note that the "turbulent" equation of state discussed in §2.2 leads to a scaling relation between the line-width Δv and the mass of the clump, i.e., $M_{\rm cl} \sim (\Delta v)^4$. Next, we interpret the line-width Δv as the effective transport speed a which determines the initial condition for star formation. If we now combine this result with the clump mass spectrum of equation [3.1] and the semi-empirical mass formula of equation [3.6], we obtain an initial mass function of the form

$$\frac{dN}{dM_*} = \frac{dN}{dM_{\rm cl}} \frac{dM_{\rm cl}}{dM_*} \sim M_*^{-\beta}\,, \tag{3.7}$$

where $\beta = 4(p-1)/\mu + 1 \approx 2/\mu + 1$ and where μ is the scaling exponent derived in the previous section. Thus, this simple argument produces a power-law IMF with an index in the range $\beta = 1.6 - 2.1$. This result compares reasonably well with the observed power-law index of the IMF which has $\beta \approx 2.35$ (see Salpeter 1955).

4 Summary and Discussion

In this review, we have outlined the current theory of star formation in molecular clouds. The theory is successful in predicting the radiative signature of forming stars of low mass. In particular, the theory predicts both spectral distributions and spatial distributions of emission which are in good agreement with observations. The theory suggests that stars, in part, determine their own masses through the action of powerful outflows. An important unresolved issue is the mechanism which produces these outflows. The presence of circumstellar disks, which often must have substantial activity, can explain the spectral appearance of newly formed stars. Another unresolved issue is the mechanism which leads to accretion through these disks. In spite of its successes, this theory still must be extended to include the formation of high mass stars and the formation of binary companions.

Finally, we remain unable to calculate and predict the initial mass function for forming stars as a function of environmental parameters, although the scaling arguments of §3 provide a start on this problem. As a result, we cannot make a clean prediction as to the expected number of brown dwarfs that should form in a given cloud. The semi-empirical mass formula [3.6] suggests that it is difficult to form brown dwarfs as single stars: small stars are not energetic enough to separate themselves from their environment. On the other hand, simulations of self-gravitating disk systems (Adams and Benz 1992) suggest that small star-like objects (brown dwarfs?) may form in circumstellar disks. Thus, the question of brown dwarf formation remains open.

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