Fragmentation of Interstellar Clouds and Star Formation

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Abstract

Two principal issues are addressed: the fragmentation of molecular clouds into units of stellar mass and the impact of star formation on molecular clouds. The observational evidence for fragmentation is summarized, and the gravitational instability described of a uniform spherical cloud collapsing from rest. The implications are considered of a finite pressure for the minimum fragment mass that is attainable in opacity-limited fragmentation. The role of magnetic fields is discussed in resolving the angular momentum problem and in making the collapse anisotropic, with notable consequences for fragmentation theory. Interactions between fragments are described, with emphasis on the effect of protostellar winds on the ambient cloud matter and on inhibiting further star formation. Such interactions are likely to have profound consequences for regulating the rate of star formation and on the energetics and dynamics of molecular clouds.

I. Introduction

We are far from understanding star formation. Observations are only beginning to probe the interiors of molecular clouds where star birth is occurring. Thus any attempt to present an overview of molecular clouds and star formation inevitably runs into immense gaps in our knowledge. Eventually, far infrared and milli-metre wavelength maps will improve sufficiently to provide a much more coherent physical picture. For now, one can only speculate on the most probable processes that will occur and affect cloud evolution.

Gravitational instability is the process that we understand best, and much of the emphasis here will be on describing some of its ramifications in molecular clouds. There are important aspects of molecular clouds that will not be discussed here. These include formation and destruction, as well as the trigger mechanism by which collapse and star formation is initiated. My starting point will be a molecular cloud that is undergoing gravitational collapse. One might imagine that this is relevant to the cores of cold molecular clouds, as well as to clouds that have undergone sudden compression associated with passage of a shock front induced either by a nearby supernova or a collision with another cloud. However my intention is not to des-cribe the grand design underlying molecular clouds and star formation, about which one can speculate at great length, but to focus on the physics of fragmentation. How do molecular clouds fragment into units of stellar mass? What are the observational indications and implications of fragmentation? These are the issues to be addressed here.

I commence by discussing the observational evidence for fragmentation in molecular clouds (§II). I then review the original argument by Jeans for gravitational instability, and indicate how this is modified for a uniform spherical cloud collapsing from rest (§III). Effects of finite pressure are considered, and the sig-nificance of the minimum Jeans mass for fragmentation is discussed. Next I discuss the role of magnetic fields in resolving the angular momentum problem and in making the collapse anisotropic (§IV). The con-sequences of anisotropic collapse for fragmentation theory are explored. Interactions between fragments are described, with emphasis on the interaction between newly formed protostars and the ambient cloud matter (§V). It is concluded that this interaction may have profound consequences for regulating the rate of star formation and the energetics and dynamics of molecular clouds.

II. Evidence for fragmentation

Molecular clouds are observed to contain smaller fragments. Cold clouds, such as the Taurus dark cloud, contain fragments with masses as small as ~ 1 $M_\odot$. The line widths of these fragments are often narrow, in some cases consistent with thermal support at $T \sim 10K$. Asymmetries in the overall profile of the Taurus cloud have been interpreted as evidence for systematic collapse or contraction (Myers 1981). Complexes near HII regions, while exhibiting broader line profiles, also contain fragments. At low resolution, such com-plexes as that near NGC 2264 contain fragments of ~ 100 $M_\odot$ within a molecular cloud complex that has upwards of $\sim 10^5$ $M_\odot$. One might imagine that at higher resolution, finer structure would be seen: some tentative evidence for this comes from VLA observations of embedded HII regions (van Gorkom 1981). Evidently, fragmen-tation must have occurred into stellar masses at densities in the range 10^3–10^5 cm^{-3}.

Indirect evidence that strongly supports this conjecture comes from observations by Blaauw (1978), who studied the proper motions of O stars in a young expanding association. He found that the O star position vectors in a given subgroup could be traced back to encompass a minimum volume, which he identifies with that of the cloud out of which they formed. The star density at birth is about 10^3 pc^{-3}. An equal mass of gas in the same volume would be of mean density 3×10^4 cm^{-3}. If there were a factor 10 more gas than stars at the formation epoch, as suggested by observations of the younger star formation regions near the Orion molecular cloud (Zuckerman and Palmer 1974), one infers an initial cloud density of 3×10^5 cm^{-3}, similar to the

densities inferred in cold molecular cloud cores. Rapid dispersal of this gas could account for the positive energy of the O association.

A second piece of indirect evidence that supports the occurrence of fragmentation at densities comparable to those observed in molecular clouds comes from a resolution of the angular momentum problem encountered in theories of star formation in terms of the orbital angular momentum of wide binary pairs of stars. Magnetic braking enforces corotation at low densities, but must become ineffective at high densities in part because the field undergoes ambipolar diffusion relative to the neutral component. The specific orbital angular momentum of wide binaries (with periods < 10^2 yr.) can be accounted for if angular momentum conservation first becomes effective at densities in the range 10^3 - 10^6 cm^{-3} (Mouschovias 1977). Prior to this, corotation should apply, with a specific angular momentum appropriate to that of a cloud undergoing differential rotation in the galactic gravitational field.

Additional evidence for this interpretation comes from two different observations. At least one isolated molecular cloud has recently been found to reveal evidence for undergoing magnetic braking (Goldsmith et al. 1981). Secondly, the mass function of binary secondaries with periods in the range 10^2 - 10^6 yr is indistinguishable from that of field stars. whereas that for shorter period binaries is much flatter (Abt and Levy 1976). This supports the viewpoint that such wide binaries formed by capture of field stars, whereas the close binaries formed by a different physical process, presumably by fission, that conserved the orbital angular momentum appropriate to an early phase of the collapse, presumably when magnetic braking first became ineffective.

One concludes that fragmentation into stellar mass units almost certainly has occurred at densities characteristic of molecular clouds.

III. Gravitational instability and fragmentation

It was first demonstrated explicitly by Jeans that an infinite stationary uniform self-gravitating medium is susceptible to gravitational instability. Although Jeans' argument has since been shown to be technically incorrect, it is useful to review the result here. More sophisticated analyses in fact recover an identical criterion for instability. One finds that infinitesimal perturbations of the form exp(iωt) exp(ikr) grow at a rate given by the dispersion relation

$$\omega^2 = k^2 v_s^2 - 4\pi G\rho \ .$$

Hence perturbations of wavelength exceeding

$$\lambda_J \equiv \frac{2\pi}{k_J} = \pi v_s (G\rho)^{-1/2}$$

are unstable, those with $\lambda \gg \lambda_J$ growing at a rate $\sim [\exp(4\pi G\rho)^{1/2} \ t]$.

While a similar result holds for any stationary self-gravitating system, the growth rate is drastically modified for perturbations of a cloud undergoing systematic collapse or expansion. In this case, the density ρ changes over an initial collapse (or expansion) time, which is also the time scale for the perturbation to grow. Consequently, the exponential growth rate changes to a secular growth rate. It is the convection by the principal flow of the background collapse that causes this effect. For a spherically symmetric uniform system undergoing collapse from rest, the free-fall time is

$$t_f = (3\pi/32G\rho_0)^{1/2},$$

where ρ_0 is the initial density. The perturbation growth rate is

$$\delta \equiv \delta\rho/\rho = \delta_0 (t_f-t)^{-1}$$

in the linear regime, for density perturbations of initial amplitude δ_0 (Hunter 1962). Once $\delta > 1$, self-gravity becomes important for the fluctuations, and rapid growth ensues as may be demonstrated from an exact non-linear solution. However only if the inital amplitude is sufficiently large can we reasonably expect fluctuations to become large and the collapsing cloud to fragment.

What value is required for δ_0 in order for fragmentation to occur? Since the density increases in uniform spherical collapse as $\rho = \rho_0(t_f-t)^{-2}$, we infer that fluctuations are large when $\delta \sim 1$, or at a time given by $t_f-t \sim \delta_0$, just before collapse of the entire cloud at t_f. At this instant, the mean density has increased by a factor $\rho/\rho_0 = (t_f-t)^{-2} = \delta_0^{-2}$. Hence collapse by a factor 10^4 in density is necessary for perturbations of initial amplitude $\delta_0 \sim 0.01$.

This estimate assumes that the perturbations are always well above the instantaneous Jeans length. If they are not, growth can be suppressed (Figure 1). It is convenient to introduce the instantaneous Jeans mass defined by

$$M_J = \frac{\pi}{6} \rho \lambda_J^3 = \left(\frac{\pi^4}{6}\right) v_s^3 G^{-3/2} \rho^{-1/2}.$$

During the diffuse collapse phase, the cloud will remain approximately isothermal. Hence as the density increases, M_J will decrease. A fluctuation that is initially below the Jeans mass at the onset of collapse will eventually begin to grow when it first overtakes the Jeans mass. There is actually a minimum value for the Jeans mass, which effectively occurs when the collapse becomes adiabatic. This inevitably happens at a sufficiently high column density, when radiation trapping occurs and cooling is inhibited.
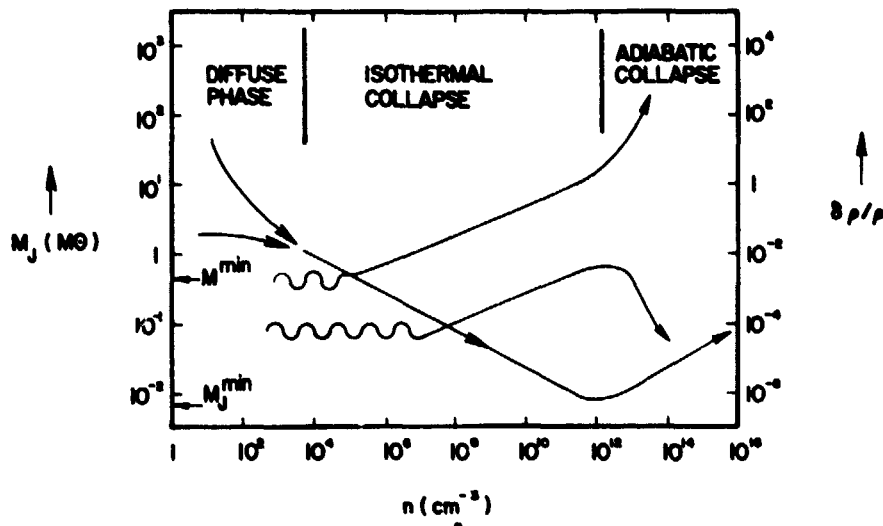

Figure 1. The fate of density fluctuations in a collapsing cloud. The Jeans mass (left ordinate) is shown as a function of density for spherical collapse using a silicate grain model. It attains a minimum value of $\sim 0.007\,M_\odot$ at a particle density of $\sim 2 \times 10^{12}\,cm^{-3}$. The evolution of the density contrast (right ordinate) is illustrated for a fluctuation containing a mass M^{min} and for one of mass $< M^{min}$ but $> M_J^{min}$.

Consider then a fluctuation of wavelength λ which only commences to grow at a time t_λ well into the collapse. In other words, at t_λ, the fluctuation mass M_λ first exceeds the Jeans mass. If the density contrast at this time is δ_λ, fragmentation will occur at an epoch t_1, say, when the background density has increased by a factor $(5/\delta_\lambda)^2$, according to a recent analysis of uniform spherical collapse (Tohline 1980). However a crucial assumption is that the collapse remains isothermal. In other words, $\rho(t_1)$ must not exceed $\rho(t_{ad})$, where the epoch at which the collapse first becomes adiabatic is denoted by t_{ad}. Fragmentation will only be effective on mass scales larger than M_λ, since smaller scales will not have separated out by t_{ad}. If their density contrast is small at this stage, the fluctuations will not survive into the adiabatic collapse phase as distinct fragments. The minimum mass fragments to form will have just become non-linear at t_{ad}. If $M_J^{min} = \rho(t_{ad})^{-1/2}$ denotes the minimum Jeans mass at t_{ad}, we infer that

$$\rho(t_{ad})/\rho(t_\lambda) > \rho(t_1)/\rho(t_\lambda) = (5/\delta_\lambda)^2$$

and the minimum mass fragment is

$$M^{min} > (5/\delta_\lambda)\,M_J^{min}.$$

This simple result leads to a considerable difficulty in understanding star formation. In addition to the fact that collapse by a density enhancement factor of about 10^5 is required for fluctuations of amplitude 1 percent from the instant that they are first Jeans unstable, the minimum fragment mass becomes uncomfortably large. To see how this arises, let us briefly review the opacity-limited fragmentation argument that defines M_J^{min}.

The time evolution of a volume element in the uniform spherically collapsing cloud is defined by a locus in the temperature-density plane. The condition that the volume element be able to freely radiate away its thermal energy as it is compressed and its internal energy increases defines a relation between T and ρ that initially is almost isothermal: $T \propto \rho^{1/8}$ is actually found to apply (Silk 1977a). Since the Jeans mass can be written

$$M_J \propto constant\ (\rho/\rho^{4/3})^{3/2},$$

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and the equation of state inferred for optically thin uniform spherical collapse is $p \propto \rho^{9/8}$, one sees that the Jeans mass decreases as $M_J \propto \rho^{-5/16}$. For exactly isothermal collapse, one would have $M_J \propto \rho^{-1/2}$.

At sufficiently high density, inhibition of cooling by radiation trapping qualitatively alters this result, since the effective equation of state now resembles $p \propto \rho^{5/3}$. This is inevitable, because the column density across a Jeans mass fragment is proportional to $\rho^{1/2}$ and the optical depth eventually becomes large. The new equation of state in this adiabatic regime is derived by requiring that an isolated fragment be able to radiate away the gravitational energy acquired as it contracts. Since the cooling rate now depends on the fragment size, the evolution track in the (T, n) plane is mass-dependent. The Jeans mass now rises as $M_J \propto \rho^{1/2}$, and its minimum value occurs where the optical depth across a fragment is of order unity. Use of opacities corresponding to conventional grain models (graphite or silicates) and a solar abundance of heavy elements in grains yields a value $M_J^{min} \sim 0.005 M_\odot$ (Silk 1977a). There is a correction factor that should be incorporated due to the presence of neighbouring fragments which effectively decrease the solid angle over which an individual fragment can radiate freely (Smith 1977). This effect raises the minimum fragment mass by a factor $\sim N^{1/6}$, where N is the number of fragments in the cloud (Silk 1980).

Even in the absence of any heavy elements, opacity due to H^- formation is important. In this case, the minimum Jeans mass is $\sim 0.3 M_\odot$ (Silk 1977b). A simple expression for M_J^{min} that explicitly demonstrates the role of heavy elements is (Rees 1977, Silk 1977b)

$$M^{min} = 20 \, M_c (kT/\mu c^2)^{1/4}.$$

Here $M_c = (hc/G\mu)^{3/2} \sim 1 M_\odot$ is the Chandrasekhar mass and μ is the mean molecular weight. Provided the heavy element abundance remains above $\sim 10^{-3}$ that of the solar value, cooling occurs to below 10 K. However, at lower values, heavy element cooling is unimportant, and $T \sim 10^4$ K is maintained by Lyα cooling.

The dilemma confronting fragmentation theory is now very apparent. With $M_{min} > 10^3 \, M_J^{min}$ for $\delta \sim 0.01$, as expected in spherical collapse, it is not at all obvious how fragments of stellar mass can form. Fragments of primordial composition are entirely outside the conventional stellar mass range. Even for solar composition, stars of solar mass are excluded. Indeed, the fragments are likely to provide lower limits to the actual masses of the protostars that form. The various non-linear processes that one can imagine, including accretion of uncondensed matter and coagulation of fragments, will tend to increase the masses of fragments. This result led Tohline (1980) to conclude that Population III of primordial composition consisted not of stars but of very massive objects. Unfortunately, the little evidence one has is consistent with the notion that Population III consisted of stars, although practically all were considerably more massive than the sun. At least one halo star has been discovered with essentially zero metallicity ($10^{-4.5} Z_0$ according to Norris [1981]), and presumably is a relic of population III.

Another consequence of the heirarchical opacity-limited fragmentation theory is that clouds fragment on a free-fall time-scale. There is considerable evidence that star formation is a much slower process. First, molecular clouds are relatively long-lived. Minimum estimates of lifetimes are $\sim 10^7$ yr, and 3×10^7 yr is probably more plausible given star formation efficiencies of order 10 percent, comparable to those observed in Taurus and Orion (Cohen and Kuhi 1979). Second, studies of the Hertzsprung-Russell diagram in open clusters indicate that low mass star formation proceeded on a longer time-scale than did massive star formation. In the case of the Pleiades, the nuclear turn-off age is 7×10^7 yr, whereas there are many stars above the lower main sequence that must have been formed some 2×10^8 yr ago (Stauffer 1980). A recent study of NGC 2264 (Strom 1981) concludes that the star formation rate increased with time as progressively more massive stars formed.

In order to attempt to reconcile fragmentation theory with star formation, two physical effects will be explored here. In §IV, the role of anisotropic collapse will be discussed. In §V, the interaction of newly formed protostars with uncondensed cloud matter will be considered.

IV. Anisotropic collapse and fragmentation

The envelope of a collapsing cloud will be more easily supported by the magnetic field, especially if it is somewhat tangled, than the cloud core. This is because the critical mass below which magnetic support is possible for a uniform spherical cloud (the "magnetic Jeans mass") is

$$M_{cr} = 6 \times 10^4 \, (B/10^{-6} g)^3 \, n^{-2} \, \xi \, M_\odot,$$

where $\xi \sim 0.3$ and $B \propto n^\kappa$, with $1/3 < \kappa < 1/2$ (Mouschovias and Spitzer 1976; Mouschovias 1976). Consequently, $M_{cr} \propto n^{-3(2/3-\kappa)}$, and is reduced in the cloud core. In §II, evidence was cited that supports the occurrence of magnetic braking up to densities characteristic of molecular cloud cores. If angular momentum is conserved during collapse at densities greater than n_b and corotation with the galaxy is enforced at lower densities, the resulting specific angular momentum of a one solar mass fragment is $j \sim 3 \times 10^{18} \, (n_b/10^6 \, cm^{-3})^{-2/3} \, cm^2 \, s^{-1}$. For the density range $10^6 > n_b > 10^3 \, cm^{-3}$, one infers that $10^{18.5} < j < 10^{20.5} \, cm^2 \, s^{-1}$, and the corresponding range in periods of binary stars if formed with this amount of orbital angular momentum is $10^{-1.5} \sim 10^{4.5}$ yr. This indicates that the angular momentum of molecular clouds resides in orbital angular momentum of wide binaries, provided that both fragmentation and magnetic braking have occurred at densities near n_b.

The collapse of cloud cores is accordingly likely to be anisotropic, contracting preferentially along field lines, since field decoupling will only occur gradually. Now the cloud, if cold, is highly Jeans unstable. The characteristic mass for gravitational instability is given by the Bonner-Ebert criterion, which takes account of the ambient pressure:

$$M_{BE} = 1.1(T/10K)^{3/2}(n/10^4 \ cm^{-3})^{-1/2} \ M_\odot$$

Thus to decide whether fragmentation occurs, we see that spherical collapse may be an unrealistic assumption. A more plausible assessment of fragmentation may be given as follows.

Consider the collapse from rest of a cloud that is initially uniform, pressure-free and oblate spheroidal. For simplicity, only a small initial deviation from sphericity is assumed. The analysis of the growth of small density perturbations is similar to that for a uniformly collapsing sphere. The collapse of the spheroid is described by two scale factors: $R(t)$ in the directions of two equal axes and $Z(t)$ in the direction of the smallest axis. The position of any point in the spheroid is then given by $r = r_0 R(t)$, $z = z_0 Z(t)$, where r and z are cylindrical coordinates and r_0 and z_0 refer to the initial position of the point. The density satisfies

$$\rho = \rho_0 (R^2 Z)^{-1},$$

where ρ_0 is the critical density. Now the spheroidal cloud, even if very nearly spherical at the onset of the collapse, becomes progressively more flattened as the collapse continues (Lin, Mestel and Shu 1965). In fact, it collapses first along the z-axis into a thin pancake. What this implies is that in the final stages of the collapse, $R(t)$ changes relatively slowly, while $Z(t) \to 0$ (in practice, the thickness will be finite because the matter will possess a certain amount of thermal energy and pressure).

Recall that in uniform spherical collapse, a small density perturbation amplifies if its scale exceeds the Jeans length and results in fragmentation (that is to say, $\delta\rho/\rho$ becomes large) shortly before the cloud itself has collapsed, in fact within a fraction $1-\delta_0$ of an initial free-fall time. An interesting difference arises when we study the growth of perturbations in a spheroidal collapse. Density fluctuations that are predominantly aligned with the collapse (z) axis do not become large, whereas fluctuations that are perpendicular to the collapse axis do amplify and separate out prior to the instant of pancaking. Self-gravity dominates the final evolution of oblate perturbations but is unimportant for prolate perturbations. The rate at which the oblate perturbations grow is found to be

$$\delta \sim \delta_0 Z^{-1}.$$

An interesting difference is now seen to arise from the one-dimensional nature of oblate spheroidal collapse. Because the density increases as $\rho \propto Z^{-1}$ when $Z \to 0$, we see that the density enhancement achieved by the cloud at fragmentation ($\delta \sim 1$ in the linear theory) is

$$\rho(t_f)/\rho_0 \sim Z(t_f)^{-1} \sim \delta_0^{-1},$$

in marked contrast to the result for spherical collapse. Inclusion of a finite initial pressure which acts to delay fluctuation growth modifies this result, but less severely than in the case of spherical collapse. This is because the retardation means that the entire growth occurs when the collapse is nearly one-dimensional, and the geometrical effects dominate the growth rate. If a fluctuation is first Jeans unstable with amplitude δ_λ at an epoch t_λ, one finds that at fragmentation

$$\rho(t_f)/\rho(t_\lambda) \lesssim 2\delta_\lambda^{-1}.$$

Adopting the opacity-limited fragmentation result that fragments should have achieved density contrast of order unity prior to t_{ad}, one now infers that the minimum fragment mass

$$M^{min} > (2/\delta_\lambda)^{1/2} M_J^{min}.$$

for oblate spheroidal collapse. Since this result is valid even for initial flattenings $z_0/r_0 \sim 0.8$, one infers it is likely to apply in any realistic situation. The spherical collapse model is too highly idealized to be relevant, given any reasonable range of initial deviations from spherical symmetry as would be expected for plausible initial conditions at the onset of the collapse.

The implications for star formation are profound. For one expects the density fluctuation level to be at least $\delta \sim 0.01$ over a wide range of scales. In primordial clouds, thermal instability associated with H_2 cooling guarantees sizable fluctuations down to mass scales of a few $M_\odot$. In conventional molecular clouds, the complex history of a cloud, involving accumulation of debris from smaller clouds and evolving stars, suggests that fluctuations should be present down to scales of $\sim 1 \ M_\odot$. Moreover, the violent events inferred to be stirring up the interstellar medium (including supernova explosions and stellar winds) should also generate pressure fluctuations over a wide range of scales. These are able to penetrate $\sim \delta_\lambda^{-1}$ wavelengths into a cloud before dissipating. Consequently, for a cloud of mass M_c, one expects the fluctuation level to be $\delta_\lambda \sim (M_\lambda/M_c)^{1/3} > 0.01$ over stellar mass scales M_λ.

With $M_J^{min} \sim 0.005$ M☉ in molecular clouds and 0.3 M☉ in primordial clouds, the preceding discussion implies that fragmentation is likely to be effective on scales as small as 0.05 M☉ (molecular clouds) to 3 M☉ (primordial clouds). The implications of this result for star formation are discussed below.

V. Interaction of protostellar winds with molecular clouds

Once protostars form of mass > 1 M☉, it seems likely that their energy input to the cloud will significantly inhibit continued fragmentation. It is this effect that provides promise of understanding the apparent longevity of molecular clouds in terms of their ability to survive many free-fall times. There is considerable evidence that protostellar winds provide an important energy input, at least into localized regions of molecular clouds. In what follows, I will summarize the evidence for this, and then attempt to make some global inferences about cloud evolution and star formation.

The most dramatic example of the interaction of a protostellar wind with a molecular cloud is L1551, which reveals a bipolar structure with a velocity spread of > 12 km s^{-1} (Snell et al. 1980). There are associated Herbig-Haro objects whose measured proper motions project back to an infrared source at the center of the CO lobes. The total mass of high velocity gas is ~ 0.3 M☉ over an extent of ~ 0.5 pc. The luminosity of the central source is ~ 25 L☉, and is insufficient to drive the outflow by radiation pressure. Another source with similar parameters is NGC 1333 (Snell and Edwards 1981). Strong winds are also found around several much more luminous infrared sources, the best-studied example being IRc2 with a luminosity of > 10^4 L☉ and 10 M☉ of gas moving at ± 50 km s^{-1}. Other examples are CepA (Rodriguez et al. 1980) and AFGL490 (Lada and Harvey 1981). Another interesting system is that of HH1 and HH2 (Jones and Herbig 1981), where measured proper motions indicate nearly collinear motions of filaments away from a centrally located T-Tauri like star at ~ 100 km s^{-1}.

In general, bipolarity is not uncommon in pre-main-sequence objects (Calvet and Cohen 1978), and may be indicative of wind interactions with a central disk. Direct evidence for strong winds from pre-main-sequence stars has been obtained by Cohen et al. (1981), who discovered regions of extended free-free emission around several T-Tauri stars. If the outflow is spherically symmetric, a mass-loss rate $\sim 10^{-6}$ M☉ yr^{-1} is inferred for T-Tauri, for example, although this may overestimate the actual mass loss rate if the wind is anisotropic.

One is tempted to try to relate wind input of energy to one of the great mysteries about molecular clouds, namely the origin of their supersonic line widths. Overall collapse provides an untenable explanation for the line widths, and one is left with a cloud model which consists of a number of supersonically moving clumps of gas. The outstanding questions are: what drives the clump motions and how are the clumps maintained for periods > 10^7 yr? A similar difficulty is encountered both in warm molecular clouds and in dark clouds.

The most natural explanation is that protostellar winds are continuously driving mass motions (Norman and Silk 1980). Cloud longevity can be understood if the winds are not disruptive, a plausible assumption for T-Tauri stars embedded in cold clouds. Now in a dense molecular cloud, a wind at < 200 km s^{-1} will be radiative and approximately momentum conserving. One may crudely estimate the mean velocity dispersion acquired by an average volume element in a cloud of mass M_c containing M* in stars which have lost a fraction ΔM* of their mass at some characteristic wind velocity V_w as

$$\langle \Delta v \rangle \sim \left(\frac{M*}{M_c}\right)\left(\frac{\Delta M*}{M*}\right) V_w .$$

Evidently a substantial fraction of the cloud matter can be stirred up with $\langle \Delta v \rangle \sim 1$ km s^{-1} if $V_w \sim 200$ km s^{-1}, $M*/M_c \sim 0.1$ (as observed in dark clouds), and $\Delta M*/M* \sim 0.1$. For this to persist over 2×10^7 yr, a considerable part of the cloud would have to be consumed in star formation: indeed, exhaustion of cloud material may lead to the formation of a T association. On the other hand, intervention of an external trigger, perhaps associated with a nearby supernova or expanding HII region, may change the cloud evolution in a manner that will now be outlined, and form an O association.

Let us suppose that the first stars to form are T-Tauri stars. These low mass stars develop winds which will sweep up shells of material. The final radius of such a shell is limited by the ambient cloud pressure p to

$$R = \left[\frac{\dot{M}V_w}{4\pi p}\right]^{1/2} = 0.1 \frac{(\dot{M}/10^{-7} M☉ yr^{-1})^{1/2}}{(n/10^3 cm^{-3})^{1/2}} \frac{(V_w/10^2 km s^{-1})^{1/2}}{(V*/1 km s^{-1})} pc.$$

where V* is the stellar velocity dispersion and M the mean mass loss rate. The condition for such shells to grossly affect the cloud evolution and inhibit further fragmentation and star formation is that any pair of shells should intersect within the lifetime of the protostellar wind phase. This can be expressed as

$$\frac{1}{n_T \pi R^2 V_*} < \frac{M}{R} \quad \text{or} \quad n_T \gtrsim 10 \frac{(V_*/1 \text{ km s}^{-1})(n/10^3 \text{ cm}^{-3})}{(V_w/10^2 \text{ km s}^{-1})} \text{ pc}^{-3} .$$

For comparison, one of the best studied dark cloud regions in Taurus-Auriga contains aggregates of between 4 (Jones and Herbig 1980) and 30 (Cohen and Kuhi 1979) T-Tauri stars pc^{-3} detectable at $A_v < 4$.

This demonstrates that wind-driven shells are likely to intersect. Shell intersection will result in the formation of supersonically moving clumps, since in general intersection occurs before the shells are in pressure balance. The characteristic clump masses are 0.1-1 M☉, with sizes of $\sim$ 0.1 pc. They will only be weakly confined by ram pressure because of their low Mach numbers, and so will continously replenish the interclump medium. However, new clumps will form, and clump collisions and accretion will result in their net growth. It seems likely that within a few collision times or crossing times, say 10^6 yr, a clump will have grown sufficiently to become Jeans unstable.

Let us speculate that in the absence of any external trigger, this results in further formation of low mass stars. In this manner, the process become self-perpetuating: low mass stars form, develop winds that sweep up shells, the shells intersect and form clumps, and the clumps coalesce and form more low mass stars. The process terminates either when the gas supply is exhausted, after $> 10^7$ yr, or when an external trigger stimulates massive star formation that could catastrophically disrupt the cloud. An example of this would be a nearby supernova explosion that shocked the cloud, accelerating the rate of clump coalesence and providing enough energy input to also raise the Jeans mass substantially.

This scenario has a number of implications for cold molecular clouds. There should be embedded infrared sources with < 10 L☉, evidence for high velocity mass motions, an internal source of ultraviolet radiation that could affect dark cloud chemistry, and clumpiness on scales of 0.1-1 M☉. Its principal virtue has been to make a direct connection between two distinct but more or less coincident time-scales: star formation is non-coeval in open clusters, apparently extending over a period $> 10^7$ yr, and molecular clouds are long-lived, with lifetimes $> 10^7$ yr and greatly in excess of free-fall time-scales. This provides the basis of our model, which asserts that such a fortuitous coincidence is really due to a direct physical coupling between molecular clouds and star formation. A major bonus is that the ongoing star formation provides a substantial momentum input into molecular clouds, leading to a natural interpretation of suprathermal line widths.

VI. Conclusions

Molecular clouds undergo fragmentation at a density $< 10^5$ cm^{-3}. Several lines of evidence lead to this inference, including the density of O associations at birth and molecular observations of nearby dark clouds. It is likely that deviations from sphericity induced by collapse along magnetic field lines play an important role in the fragmentation process. Anisotropic collapse enables smaller fragments to separate out before the increasing opacity inhibits any further fragmentation. Anisotropy has a dramatic effect on fragmentation because it limits the growth rate of the background density, whereas a fluctuation grows in density mostly because of its additional self-gravity, which is more or less independent of the background kinematics.

The smallest fragments to form and survive an initial free-fall time are not at the minimum Jeans mass but must be considerably larger, since they must have been able to attain a density contrast of order unity before the collapse becomes adiabatic. A highly simplified analysis suggests that the minimum mass fragments may be ~ 0.05 M☉ in interstellar clouds; in primordial clouds, the minimum mass is likely to exceed ~ 3 M☉.

Once such fragments form and become protostars of mass > 1 M☉, they are likely to have a significant interaction with the rest of the cloud. After an initial free-fall time, only the innermost core of the cloud could have fragmented. One expects that a substantial fraction of the cloud will still be relatively diffuse at this stage, especially if magnetic support is important in the outer cloud envelope. The most effective mode of interaction is likely to be via stellar winds from pre-main-sequence stars. Observational evidence indicates that such winds may play an important role in stirring up molecular clouds.

Hence a plausible speculation is that the first strong protostellar winds can inhibit cloud collapse and fragmentation. Such winds are likely to interact and generate additional clumpiness in the cloud Clumpiness enhances fragmentation, and it seems entirely possible that protostellar winds are self-sustaining. As some winds die away, new protostars form that are capable of providing a dynamically significant momentum input into the cloud. Only when the gas reservoir is depleted as a number of massive stars form would the star formation process terminate. In this way, one might be able to understand such issues as why star formation is non-coeval, why molecular cloud lifetimes are many free-fall times, and why clouds exhibit a clumpy structure and suprathermal linewidths.

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