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91. The accretion rate in a medium with a sound speed $c_s$ is $dM/dt = 0.95\ [c_s^3/G] = 1.0 \times 10^{-5}\ [c_s/0.35\ km\ s^{-1}]^3\ M_\odot\ year^{-1}$.
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REVIEW

# Isolated Star Formation: From Cloud Formation to Core Collapse

**Derek Ward-Thompson**

**The formation of stars is one of the most fundamental problems in astrophysics, as it underlies many other questions, on scales from the formation of galaxies to the formation of the solar system. The physical processes involve the turbulent behavior of a partially ionized medium containing a non-uniform magnetic field. Current debate centers around the time taken for turbulence to decay and the relative importance of the roles played by magnetic fields and turbulence. Technological advances such as millimeter-wave cameras have made possible observations of the temperature and density profiles, and statistical calculations of the lifetimes, of objects collapsing under their own self-gravity and those on the verge of collapse. Increased computing power allows more complex models to be made that include magnetic and turbulent effects. No current model can reproduce all of the observations.**

Stars are among the most fundamental building blocks of the universe, and yet the processes by which they are formed are not understood. Models can give different predictions for the masses, densities, and temperatures of the objects formed, even if they assume only slightly different initial conditions. The variations of the initial density, temperature, velocity, and magnetic field are crucial to the gravitational collapse of molecular clouds (the chief sites of star formation), but one of the main problems is that the initial conditions that pertain in the clouds from which stars form are still not known sufficiently accurately. This gap is currently one of the major limiting factors in the understanding of the star formation process, at least for relatively low-mass stars [$\sim$0.2 to 3 times the mass of the Sun ($M_\odot$)]. It is believed that different physical mechanisms dominate in isolated star-forming regions (which are more quasi-static) and cluster-forming regions (which are more dynamic). This review discusses isolated star formation (*1*) and leaves clustered and triggered star formation for another review (*2*). Because high-mass star formation occurs almost exclusively in clusters, this review consequently refers mainly to low-mass stars ($\leq$3 $M_\odot$). Similarly, even though a large percentage of stars exist in binaries or higher multiple systems, this review (for reasons of space) concentrates on single star formation (*3*).

In the quasi-static picture of isolated star formation, there are a number of distinct stages that can be identified, starting from the diffuse matter occupying the space between the stars, known as the interstellar medium (ISM), with a volume number density of H atoms $n \sim 1$ H atom cm$^{-3}$ (in the solar neighborhood) through to regions known as diffuse clouds, with a volume number density of H atoms $n \sim 10$ to 100 H atoms cm$^{-3}$ and temperature $\sim$30 to 50 K. The more dense parts of the ISM are known as molecular clouds, because the gas within them is primarily molecular and of higher density and lower temperature [$n \geq 10^3$ $H_2$ cm$^{-3}$, temperature ($T$) $\sim$ 20 to 30 K]. The gas is molecular for two reasons: (i) the higher density provides a shorter mean free path for collisions between the atomic gas and dust grains (the chief molecule formation mechanism is via surface interactions on dust grains) and hence a higher formation rate of molecules; and (ii) the molecules are not dissociated by the ultraviolet (UV) component of the interstellar radiation field, because the embedded dust extinguishes the UV radiation and shields the molecules (*4*); $\sim$1% of a molecular cloud's mass is in the form of silicate (with some carbonaceous) dust grains $\sim$0.1 μm in size.

The formation of molecular clouds, and particularly of giant molecular clouds (GMCs), is believed to take place in the spiral arms of galaxies in a local minimum of the Galactic gravitational potential. The magnetic field may also play a part in this, by way of a magnetic Rayleigh-Taylor instability (*5*), in which matter streams along field lines and collects in a potential minimum. GMCs generally give rise to clustered star formation, whereas smaller molecular clouds tend to form smaller numbers of more isolated stars. Very small clouds in relative isolation are often known as Bok globules, after their discoverer (*6*), and range in size from $\sim$0.01 to $\sim$1 parsecs (pc), with masses of typically $\sim$1 to 10 $M_\odot$. The dust extinguishes the background starlight, so Bok globules are seen in silhouette at optical wavelengths. Isolated star formation may also take place in the denser regions (known as cores) of larger molecular clouds, with densities of $n \sim 10^4$ to $10^6$ $H_2$ cm$^{-3}$. Once a dense core has formed in a molecular cloud, then self-gravity drives the subsequent collapse and formation of a star (or stars) within that core. However, what initiates that collapse, what are the initial conditions for the collapse, how the collapse proceeds, and what mass of star is formed as a result of a given set of initial conditions, are all matters of debate.

The main stages of star formation can be summarized as follows: (i) forming a gravitationally bound core in a molecular cloud, (ii) collapse of the core under self-gravity,

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(iii) building a central starlike object (perhaps surrounded by planets), and (iv) dispersal of the remnant cloud material.

## The Dynamics of the ISM

Whether a dense core region within a molecular cloud will collapse under its own self-gravity can be determined (*4*) by evaluating its virial $\nu$

$$\nu = 2E_K - 3PV + E_G + E_M \quad (1)$$

where $E_K$ is the internal kinetic energy; $P$ is the external pressure; $V$ is the volume; $E_G$ and $E_M$ are the gravitational and magnetic potential energies of the core, respectively; and the core is assumed to be nonrotating. The significance of this relation is that it indicates whether or not a core is in equilibrium, for any general density distribution. If $\nu < 0$, then a core is said to have a mass greater than its virial mass, and it will contract unless supported by some other mechanism. If $\nu > 0$, then the core is said to have a mass less than its virial mass, and it is not gravitationally bound and will dissipate under the action of its own internal motions unless confined by an external pressure. A spherically symmetric, nonmagnetic, nonrotating pressure-confined core in equilibrium ($\nu = 0$) is known as a Bonnor-Ebert sphere (*7*, *8*).

However, this simple treatment usually implies that a quasi-static equilibrium situation is prevalent in molecular clouds. There are a number of indications that this may not be the case and that molecular clouds may well be in a state of turbulence (*9*, *10*). One specific prediction of turbulent motion in fluids is the presence of transient high-velocity material in localized regions in time and space, in a phenomenon known as intermittency. Such motions may have been observed in many clouds (*10*). The thermal velocity dispersion $\sigma_T$ of a spectral line emitted by a gas at temperature $T$ is given by Boltzmann statistics as $(kT/m)^{1/2}$, where $k$ is Boltzmann's constant and $m$ is the mean molecular weight of the observed species. Most molecular clouds have observed velocity dispersions $\sigma_o$ greater than the predicted thermal velocity dispersion $\sigma_T$. This excess is referred to as the nonthermal velocity dispersion $\sigma_{NT}$ (*11*) and is given by $\sigma_{NT}^2 = \sigma_o^2 - \sigma_T^2$.

For the smallest clouds, $\sigma_T$ dominates (*12*), but for clouds above a certain radius (typically ~0.1 pc), $\sigma_{NT} > \sigma_T$. The high-velocity emission is spatially coincident with the thermal emission, hence the two velocity components are tracing the same gas. Molecular cloud regions that have greater turbulent internal motions have more support against self-gravity. Hence, higher mass clouds tend to be more turbulent, whereas lower mass clouds can more easily survive in regions where the turbulent motions of the ISM are less pronounced.

However, this alone is not conclusive proof of turbulence in molecular clouds; for example, the high-velocity emission could be due to a high-temperature thermal component (the temperatures required would be up to $\sim 10^4$ K, for which there is no evidence in these molecular clouds). But there is another prediction of turbulence, which implies that it is present in molecular clouds. This is that scale-free turbulence should lead to a scale-free geometry, so there should be no preferred scale length in observations of molecular clouds, and structure should be seen on all scales. Molecular clouds do indeed show structure on all scales, from the small-scale resolution of modern telescopes up to the large scale of Galactic features such as spiral arms. Figure 1 shows a region of a molecular cloud illustrating apparently scale-free structure. There have been a number of claims that molecular clouds exhibit fractal structure (*13*), which is scale-free. However, one must always exercise caution in making such statements from observations and state over exactly what range of size scales the apparently fractal structure appears.

Turbulence can be generated in clouds by many different mechanisms. The Galactic differential rotation across a molecular cloud may introduce large-scale turbulence. On intermediate scales, the shock waves from supernovae and the stellar wind–blown bubbles around O- and B-type star associations (high-mass stars) can generate turbulence in clouds. On the smallest scales, individual stellar winds and outflows from newly formed low-mass stars are among the chief mechanisms for the injection of turbulence (*14*, *15*). The efficiency of each of these mechanisms in generating interstellar turbulence is a matter of debate. However, the decay of turbulence in clouds may be responsible for the spontaneous initiation of gravitational collapse of a molecular cloud core through the dissipation of the internal supporting turbulent motions (*16*–*22*).

## The Turbulent Decay Debate

There is an ongoing debate over the time scale on which turbulence decays in molecular clouds. A number of recent theoretical studies have concluded that turbulence decays on a short ($\sim 10^6$ years) time scale (*23*, *24*) relative to the supposed lifetime (about a few $10^7$ years) of a molecular cloud (*25*). Hence, the inference

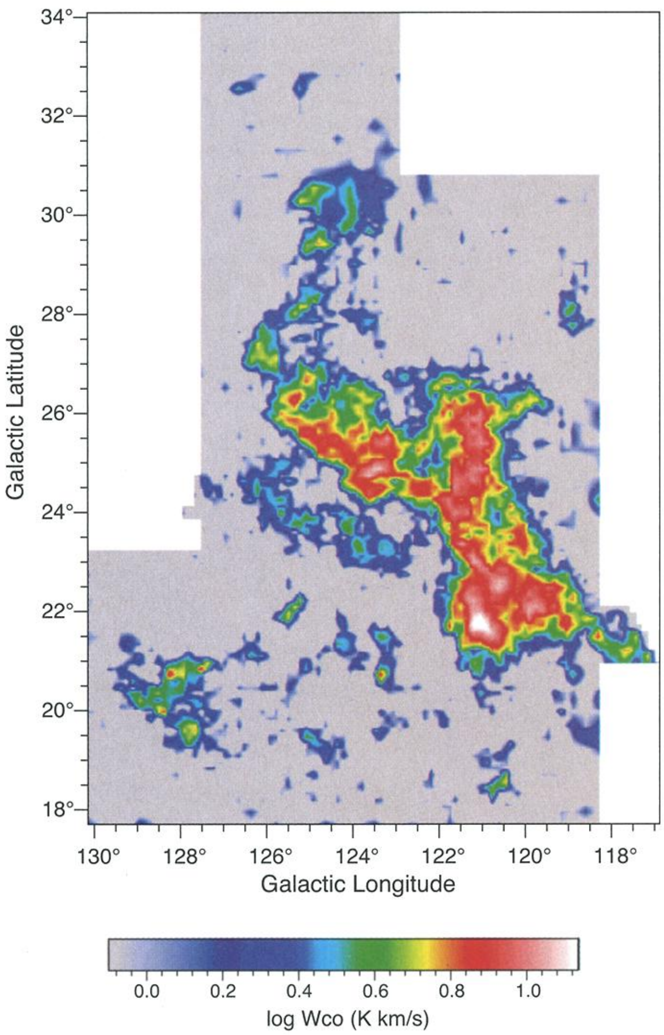


**Fig. 1.** A typical molecular cloud showing structure on a variety of scales from the resolution of the telescope to the size of the cloud (*103*). Over this range of scale sizes, the structure appears self-similar. This can be interpreted as fractal structure (*10*), which is one of the expected signatures of turbulence in the ISM. [Credit: Heithausen and Thaddeus (*103*), with additional data taken by T. M. Dame]

is that because turbulence appears to be observed in molecular clouds, then it must be continuously reinjected by one or more of the mechanisms mentioned above.

One solution to this problem is that GMCs may not be as long-lived as had been previously thought (*26*, *27*) but may themselves last for only a few $10^6$ years. This may create other problems in terms of the rapid formation rate of GMCs that is then needed, but this could be solved under the fractal (or hierarchical) scenario, in which each level of density of the medium is formed by relatively rapid compression of the slightly lower density material around it.

The alternative scenario is that not all forms of turbulence are damped out on such short time scales (*28*). Molecular clouds containing magnetic fields are subjected to the laws of fluid mechanics, modified by magnetic effects. The study of such objects is referred to as magneto hydrodynamics (MHD). Turbulence under such conditions is rather complex, and wave motions can propagate by a number of mechanisms. Sonic compression waves travel at the sound speed $c_s = (\gamma P/\rho)^{1/2}$, where $\gamma$ is the ratio of specific heats, $P$ is the pressure, and $\rho$ is the density. Alfvén waves (transverse waves traveling along magnetic field lines) have velocity $v_A = B/(4\pi\rho)^{1/2}$, where $B$ is the magnetic field strength.

In addition, the two modes of wave propagation couple (*29*) to form what are known as the fast and slow magnetosonic modes, with velocities $v$ corresponding to the two solutions of

$$2v^2 = v_A^2 + c_s^2 \pm [(v_A^2 + c_s^2)^2 - 4v_A^2 c_s^2 \cos^2\theta]^{1/2} \qquad (2)$$

in which the sonic disturbance is not travelling parallel to the magnetic field but instead at some angle $\theta$ to it. This equation makes the assumption of a nonrelativistic $v_A$ (a reasonable assumption in molecular clouds) and a uniform magnetic field direction relative to the source of the turbulent wave motion (this assumption may not hold true, because the magnetic fields in molecular clouds may become tangled).

The true picture of wave motions probably involves a summation of multiple modes of fast- and slow-mode waves, and so breaking them down in this way is useful. In so doing, it has been found (in analytic models using a simple geometry) that the slow-mode oscillations are not efficiently damped but are long-lived (*28*). Whether they, in turn, contribute significantly to the general level of cloud turbulence is also a matter for debate, although there is evidence to suggest that even a relatively small-amplitude slow-mode oscillation can generate large density variations in a molecular cloud (*30*). The numerical models that predict turbulence to decay (*23*, *24*) find that even the slow-mode oscillations decay rapidly, although they do not explicitly treat the neutral and ionized gas separately (in a method known as a two-fluid approximation) in the way that the analytic models do, which may account for their different conclusions. However, if the numerical finding proves correct, then either turbulence must be continuously reinjected into the ISM or molecular clouds are not as long-lived as was previously thought.

### Magnetic Fields Versus Turbulence

Magnetic fields may impede cloud collapse if the field is coupled to the gas by means of an ionized component. The mean ionization fraction of molecular clouds is $\sim 10^{-7}$, and the main method of ionization is by cosmic rays. One scenario for quasi-static contraction of a dense region of a molecular cloud involves the gradual decoupling of the magnetic field from the gas by a process known as ambipolar diffusion (*31*, *32*), in which the neutral gas drifts through the ionized gas (which is tied to the magnetic field), thereby overcoming the magnetic support and proceeding to collapse. Such models work in individual completely isolated regions (*32–35*); however, once even one massive star has been formed in a molecular cloud (even in relative isolation), the feedback from the winds and outflows from that star cause such disruption to the rest of the cloud that such a quasi-static formation mechanism may no longer be applicable. In such cases, more complex models, which take into account turbulent effects (*36*, *37*), are required (Fig. 2).

Different models make different predictions about the relative importance of magnetic fields and turbulence that can be tested by observations. One way to do this is by means of the ratio of thermal (plus nonthermal) pressure to magnetic pressure, $\beta$ (*36*, *38*). For $\beta > 1$, turbulence dominates and the field lines become heavily tangled; for $\beta \ll 1$, the magnetic field dominates and clouds form by material streaming along relatively uniform field lines (*33*, *39*), after which elongated cores form perpendicular to the magnetic field direction and cores evolve quasi-statically by ambipolar diffusion; for $0.1 \leq \beta \leq 1$, turbulence and magnetic fields have similar importance, and the magnetic field is not always perpendicular to the elongation of cores (*36*), although the initially uniform field remains the dominant component.

Some limited observational tests of these theories have been carried out. Tracing of the submillimeter polarization in isolated molecular cloud cores (*40*) shows relatively uniform magnetic field directions (*41*), suggesting that models with $\beta \leq 1$ are applicable to these regions (*39*, *42*, *43*). But the observations also find an offset between the position angle of the B field and the minor axis of each core (*40*), further suggesting that $\beta > 0.1$ (*36*), so the polarization results support the view that $0.1 < \beta < 1$.

However, mid-infrared observations of cores seen in absorption at 7 and 15 μm find a number of cores with sharply defined edges (*44*). Both the quasi-static models (*43*) and the turbulent MHD models (*36*) predict that only cloud cores with $\beta < 0.1$ can develop such sharp edges (*44*) and large density contrasts (*45*, *46*). So the models cannot simultaneously explain both the magnetic field data (requiring $\beta > 0.1$) and the large density contrasts with sharp edges (suggesting $\beta < 0.1$). Some attempt was made to reconcile the magnetic field observations to quasi-static models with a lower $\beta$ value (*47*) by explaining them in terms of more complex triaxial core geometries, but no complete model in-

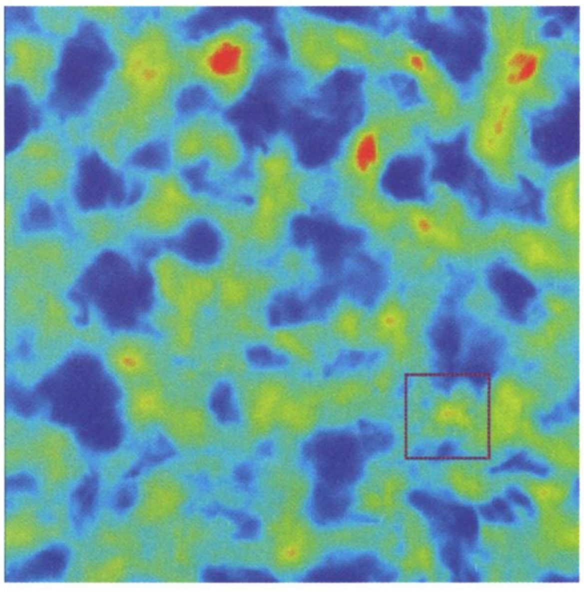

**Fig. 2.** Typical output from a turbulent MHD model (*37*). The structure appears to be similar to that observed in real molecular clouds. Detailed comparison between characteristic parameters in the output of such models and observations can lead to insights into the physical processes at work in molecular clouds, such as the relative importance of turbulence and magnetic fields in dominating the dynamics of the ISM. The core marked with a square is seen to be accreting by funneling of matter along filaments (*37*). [Credit: D. Balsara *et al.*, "A turbulent MHD model for molecular clouds and a new method of accretion onto star-forming cores," *Mon. Not. R. Astron. Soc.* **327**, 715 (2001) (Blackwell Publishing)]

corporating these geometries has yet emerged. Hence, the debate continues as to whether the magnetic field or turbulence dominates the dynamics of the initial conditions of collapse.

### Cores on the Verge of Collapse

Supernova explosions, winds and outflows from previously formed stars, and shock waves in the ISM may all trigger star formation (*2*). However, in more isolated regions, the mechanism that initiates collapse is not so clear. Detailed observations of cores on the verge of gravitational collapse and those undergoing collapse can shed light on the collapse process itself. Many cores have been studied in detail (*48–50*), based initially on catalogs of regions of optical obscuration (*51*) and subsequently observed spectroscopically in various transitions of $NH_3$, CO, and many other molecules (*52*, *53*). Some of the cores contain infrared (IR) sources (*54*), and these should be at a later evolutionary stage than cores without IR sources, because the former have presumably already formed a condensed object at the center that we see in IR emission.

We refer to such a central, condensed, roughly star-sized object as a protostar. It is believed that a protostar derives its energy from the gravitational potential energy of the collapse and that no form of nuclear fusion takes place within a protostar. The term "starless cores" (*54*) refers to cores without embedded protostars, and "preprotostellar cores" (*55*) (or "prestellar" for short) refers to cores that appear to be the most centrally condensed and hence the closest to the onset of gravitational collapse.

The arrival of the latest technology cameras that work at millimeter and submillimeter wavelengths (0.3 mm $< \lambda <$ 3 mm), such as SCUBA (the submillimeter common-user bolometer array) on the James Clerk Maxwell Telescope in Hawaii (*56*), has opened up a whole new area of observational possibilities for study of these faint, somewhat extended objects. In fact, it was found in various millimeter-wave and submillimeter-wave studies of prestellar cores (*45*, *46*, *55*) that the cores follow a similar form of density profile, with a "flat" inner region ($\rho$ = constant $\rightarrow \rho \propto r^{-1}$), steepening toward the edge ($\rho \propto r^{-2} \rightarrow r^{-5}$) (Fig. 3). Detailed comparison of these findings with quasi-static ambipolar diffusion models (*35*) showed that, although the radial density profiles of the cores are similar to those predicted by ambipolar diffusion models, the details of the time scales required by the models did not match the lifetimes calculated from the numbers detected (*45*, *46*), although these results were based on relatively small number statistics, and more recent observations may be more in line with the model predictions (*57*, *58*).

Millimeter-wave spectroscopic studies using ground-based telescopes (*59*) and far-IR continuum observations (*60*) with the Infrared Space Observatory (ISO) (*61*) show that temperature gradients from the outside in are required in many cases to explain the data; that is, the core centers are cooler than their edges. It is also found that prestellar cores typically only emit radiation at wavelengths $\lambda > 100$ μm (*60*), indicating that they are cold, with typical central temperatures of only ~10 K. For $\lambda < 100$ μm, prestellar cores typically show strong continuum absorption (*44*). Comparison between the energy radiated by each core in the far-IR and the energy absorbed at shorter wavelengths (*60*) shows the energies to be of similar magnitude. Hence, there is no evidence for a central heating source in prestellar cores, and they are generally heated externally by the local interstellar radiation field.

Statistical surveys of dense cores in molecular cloud regions show that the histogram of their masses mimics the initial mass function (*2*, *62*) of newly formed stars (*63*, *64*). If these preliminary results are confirmed, then the mass of the final star must be determined at the prestellar core stage (*2*). Studies of the density profiles of prestellar cores using near- to mid-IR absorption (*44*, *65*) and submillimeter-wave emission (*66*) have found consistency with a Bonnor-Ebert density distribution (*7*, *8*) in some cases. This implies that these cores are close to equilibrium, and they have masses close to the critical mass for collapse or slightly greater than this mass.

There are already significant inward velocities in the outer layers of some prestellar cores, even though there is no evidence for a central protostar having formed, and it appears that a few percent of cores may already be contracting (*67–70*). However, the inward velocities are the same order of magnitude over a wide range of radii (*67*, *68*). This is not consistent with an accelerating free-fall collapse model, which would predict matter nearer the center to have higher infall velocity. Nevertheless, this is consistent with collapse initiated by turbulent dissipation, and this may be all the triggering that is needed to initiate collapse for low-mass stars (*16–22*).

One alternative hypothesis that has recently been proposed to explain what may initiate core collapse involves core growth (*37*). In this MHD model, a turbulent cloud forms multiple cores that are linked together by elongated structures known as filaments (*71*). Because the cloud is ionized and contains magnetic fields, the matter and field lines are coupled. Hence, the filaments are effectively flux tubes of magnetic fields as well as filaments of matter. The flux tubes serve to funnel matter down onto the cores. In this way, the cores grow until their mass exceeds their virial mass, and so they collapse. Thus far there is only limited observational evidence to support this model (*37*), although a similar model for core growth by means of accretion along filaments has also been proposed to explain binary star formation (*72*). In this model, the filaments funnel material "off center" onto the cores, thus increasing each core's angular momentum. The cores are spun up in this way and thus form a higher preponderance of binary stars (*72*).

### Collapsing Cores

A collapsing core rapidly forms a central, roughly star-sized, condensed object known as a protostar. If the collapsing core has a large initial angular momentum, it may then form a binary or multiple system. This is because as material collapses through many orders of magnitude from molecular cloud core ($r \sim 10^{15}$ m) to star ($r \sim 10^{9}$ m), conservation of angular momentum dictates that its angular velocity must increase accordingly by many orders of magnitude. Consequently, if a rapidly rotating core were able to collapse to form a single protostar, then the rotational velocity of that protostar at its equator would exceed the gravitational es-

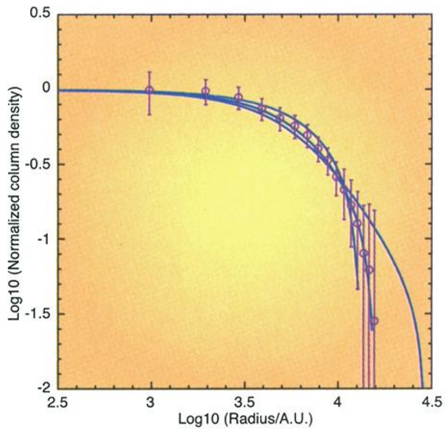


**Fig. 3.** A typical prestellar core radial density profile (*66*). Normalized column density is plotted against radius on a log-log plot (AU, astronomical units). The data are shown as circles with error bars, with theoretical model fits shown as solid curves. The flat inner profile steepens toward the edge. This type of profile is consistent with the predicted signature of a Bonnor-Ebert pressure-confined sphere (*7*, *8*). The best-fitting model of this type is shown as a blue line, with the range of fits that are consistent with the data also shown. This type of profile is also qualitatively consistent with the predictions of some ambipolar diffusion models (*43*).

cape velocity and the protostar would break up. Of course, this situation cannot arise, and the core may instead form a binary system of two protostars in orbit about their common center of mass (for the remainder of this review, I will concentrate on single protostar formation for reasons of space).

Figure 4 shows a schematic of the main components of a protostellar system: the central protostar, the circumstellar disk, and the surrounding envelope (*73*). The central protostar is classified as a Class 0 protostar as long as more than half of the total mass of the system is still in the infalling envelope (*74*). After half of the mass of the envelope has fallen in, the source is referred to as a Class I protostar (*75*, *76*). Once almost all of the envelope has been accreted (or otherwise dissipated), the source is referred to as a Class II source (*75*, *76*) or classical T Tauri (CTT) star (*77*). At this stage, there is still a substantial circumstellar disk, which may go on to form planets. Finally, when the inner part of the disk has dispersed, it is known as a Class III source (*75*, *76*) or a weak-line T Tauri (WTT) star (*77*).

There are about 10 times as many Class I protostars as Class 0 protostars (*73*, *78*). This has led some to argue (*73*, *78–80*) that the Class I phase lasts about an order of magnitude longer than the Class 0 phase. This leads to the conclusion that half of the envelope accretes onto the central protostar in only one-10th of the time taken for the remaining half to accrete. This in turn leads to the idea that the accretion rate must decrease with time.

Statistics based on source number counts (*54*, *73*, *78*, *79*), coupled with stellar evolution models (*81*), yield the following predicted lifetimes and properties for each evolutionary stage: The starless and prestellar core phases together last a few $10^6$ years; the Class 0 protostellar phase then lasts a few $10^4$ years and is characterized by a high accretion rate ($\gtrsim 10^{-5}\ M_\odot\ \mathrm{year}^{-1}$), during which at least half of the final stellar mass is accreted; and the Class I protostellar phase lasts a few $10^5$ years and is characterized by a lower accretion rate ($\lesssim 10^{-6}\ M_\odot\ \mathrm{year}^{-1}$), in which the remainder of the final stellar mass is accreted. There are uncertainties in these time scales, because they are derived (at least in some cases) from relatively small number statistics of source counts (*54*, *73*, *78*, *79*), and the statistics may also be influenced by selection effects, in which we may be more likely to observe sources in some phases than others.

Spectroscopic evidence of infall has been reported in a number of Class 0 protostars (*70*, *82–84*), although the manner of the collapse cannot be uniquely ascertained from such observations. The exact form of the collapse depends almost entirely on the initial conditions (*85–87*). A decreasing accretion rate, such as that deduced from statistical observations of protostars, is obtained when the initial radial density profile is relatively flat in the center and steepens toward the edge (*86*, *88*, *89*). This is exactly the form of the density profile that is observed in prestellar cores, which leads one to believe that some degree of consistency in the various different observations is beginning to emerge (*73*).

The exact nature of the gravitational collapse of a molecular cloud core has been debated for many years, and a number of analytic models of protostellar collapse have been proposed. It was predicted theoretically early in the history of this subject (*90–92*) that the collapse should proceed at constant temperature over a wide range of size scales and that it should be scale-invariant (self-similar) in nature. A whole family of such self-similar solutions exists (*85*, *93*), which can be divided into various types. The types range from outside-in collapse (*92*, *94*), in which the outer layers begin to fall in first; to almost constant velocity solutions (*93*); to the opposite situation of inside-out collapse (*95*), in which the central regions fall in first and a collapse expansion wave spreads outward from the center. Exactly which solution nature uses is dependent on the initial conditions. It was found (*93*) that the most apparently likely solutions match the outside-in situation and that only the most unlikely initial conditions could produce the inside-out collapse scenario (*85–87*).

More recently, the collapse of relatively flat-centered density distributions, as suggested by the observations, have been studied (*88*, *89*). For any flat-centered initial density profile, there is a pause between the onset of freefall collapse and the beginning of accretion onto a central point mass. This form of collapse is consistent with the inferred lifetimes and observed density profiles of prestellar cores and Class 0 protostars, with observations in prestellar cores of roughly constant contraction velocities over a wide range of radii, and with the lifetimes and accretion rates derived for Class 0 and Class I protostars. Consequently, such models provide some insight into the nature of protostellar collapse, although they do not necessarily shed much light on the dominant physical processes at work. Furthermore, there is still one major inconsistency in all of the models.

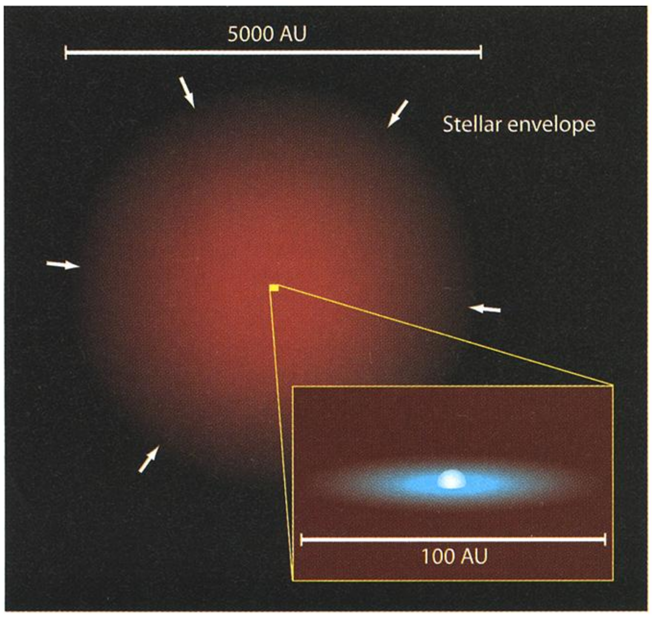


**Fig. 4.** The main components of a protostellar source: (i) the central condensed protostar, with radius of a few solar radii ($\sim 10^9$ m); (ii) the circumstellar disk, with radius $\sim 100$ AU ($\sim 10^{13}$ m); and (iii) the surrounding envelope, with radius $\sim 5000$ AU ($\sim 10^{15}$ m) (*73*). Matter accretes from the envelope onto the protostar (via the disk) as the protostar evolves.

## The Luminosity Problem

There is a problem with observations of the luminosities of Class 0 and I protostars (*96*), in the following sense: Their low luminosities imply low accretion rates if the material is accreting directly onto the protostellar surface (*81*), and low accretion rates imply long lifetimes that are incompatible with the relatively small number of known protostars. One possible solution in the case of Class I sources is that the accretion rate remains low throughout the Class I phase, and most of the residual protostellar envelope is dissipated in some way other than by being accreted onto the central protostar; for example, it might be converted into lower-mass companions (*97–99*).

Alternatively, it can be explained by arguing that accretion takes place in a fairly uniform manner from the envelope onto a circumstellar disk and is then episodic in nature from the disk onto the central protostar (*100*). Short-lived (and therefore infrequently observed) rapid accretion episodes could be interspersed with long periods of slow or even negligible accretion, during which matter piles up at the inner edge of the accretion disk. Thus, protostars would spend the majority of their time in a lower luminosity phase, only flaring up briefly when the accretion disk becomes unstable and matter is rapidly deposited onto the protostar (*79*, *100*).

Flaring episodes have been observed in T Tauri stars, and are known as FU Orionis events, after the first such star to be observed, but no known Class 0 or I protostar has been observed in such a phase. This potential solution to the luminosity problem will be able to be tested by the next generation of millimeter-wave interferometers, such as ALMA [the Atacama Large Millimetre Array (*101*)], which will be able to resolve detail on scales smaller than the accretion disks of nearby newly formed stars. In addition, forthcoming satellites, such as the planned European Space Agency Herschel mission (*102*), will give higher resolution far-IR observations, permitting detailed analysis of cores on the verge of collapse, which will give more details of the initial conditions of protostar formation and help to answer some of the other fundamental questions raised in this paper.

### References and Notes


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