Clustered Star Formation and the Origin of Stellar Masses

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Star clusters are ubiquitous in galaxies of all types and at all stages of their evolution. We also observe them to be forming in a wide variety of environments, ranging from nearby giant molecular clouds to the super-giant molecular clouds found in starburst and merging galaxies. The typical star in our galaxy and probably in others formed as a member of a star cluster, so star formation is an intrinsically clustered and not an isolated phenomenon. The greatest challenge regarding clustered star formation is to understand why stars have a mass spectrum that appears to be universal. This review examines the observations and models that have been proposed to explain these fundamental issues in stellar formation.

Stellar clusters are among nature's most beautiful and intriguing astronomical objects. They are associated with every type of galaxy and range from hundreds of stars, as is commonly observed for young star clusters in the disk of the Milky Way (*1–3*), to the millions of stars that populate the super star clusters (SSCs) in prototypical starburst galaxies such as M82 (*4*, *5*) and interacting galaxies such as the Antennae (*6*, *7*). Stellar clusters were also among the first systems that formed as galaxies were assembled billions of years ago, as is evidenced by the ubiquitous presence of globular star clusters around galaxies of all kinds. Globular clusters are akin to SSCs in their mass and size but are the oldest objects yet discovered in the universe, ranging in age from 12 to 15 billion years, the oldest being found in a more spherical spatial distribution in the halos of galaxies (*8*). There is also growing evidence that the stellar content of any star cluster, as measured by the mass spectrum of the stars that compose it [the initial mass function (IMF)], is fairly robust and independent of environment (*9*, *10*). Star clusters form at all epochs of galactic evolution, are associated with galaxies of all Hubble types, and have similar IMFs, which suggest a common and robust mechanism of star formation.

Stars in the Milky Way and other nearby galaxies form in cold [temperature (T) $\cong$ 10 to 20 K], self-gravitating molecular clouds whose masses lie in the range from 10^3 to $10^{6.5}$ solar masses [the Sun's mass ($M_\odot$) = 2×10^{33} g]. Infrared (IR) observations of young embedded stars within clouds (*11*) reveal that their formation is restricted to smaller regions of higher than average gas density called clumps. One of the important recent advances in star formation research is the realization that most stars form as members of star clusters within such clumps and not in isolation from one another. Star clusters are therefore not exotic novelties in the universe but are the representative products of the process of star formation.

Fortunately, astronomers do not have to look very far in order to study the formation of star clusters. One of the best studied and nearby [450 parsecs (pc) away] star clusters that is forming in our galaxy is the Orion Nebula Cluster (ONC) (*12*, *13*). Gas in the center of the cluster is being disrupted through the radiation and winds from the four luminous and massive young stars that compose the Trapezium group. The ONC consists of a central core of radius 0.2 pc, with a stellar density approaching 2×10^4 stars in a cubic parsec (pc^{-3}), that is within a lower density stellar halo that extends out to a cluster radius of 2 pc, which encloses a total of 2200 stars. For comparison, 1 pc = 3.26 light years = 3.09×10^{18} cm is the typical distance between stars in our part of the Milky Way Galaxy. Figure 1 shows a high-resolution IR image of the central portions of the ONC. A mixture of both high- and low-mass stars is present in this young cluster.

The insight that clustered, rather than isolated, star formation predominates has been gained from millimeter and submillimeter surveys of molecular clouds and their clumps (*14*), as well as from IR surveys of the embedded clusters themselves (*3*, *15*). These surveys establish that the mass spectra of clouds, clumps, and clusters are similar if not identical to one another and are notably different than the the mass spectrum of the stars formed within the clusters: the IMF. The physical processes that accompany the formation of individual stars in more isolated environments, such as the gravitational collapse of dense molecular cloud cores, the formation of protostellar accretion disks, and the production of energetic jets and outflows, are qualitatively similar to those in a strongly clustered environment. However, critical aspects of stellar formation, such as what determines the masses of stars (the IMF), and the time scale and efficiency of star formation in molecular clouds probably arise from the fact that star formation is intrinsically clustered. How and why does a small portion of the self-gravitating gas in molecular clouds turn into clusters of stars?

From Molecular Clouds to Cluster-Forming Clumps

The interstellar medium (ISM), on physical scales of 10^2 to 10^3 pc, is a reservoir of turbulent gas, magnetic fields, cosmic rays, and ionizing radiation that affects the physical properties of molecular clouds and their cluster-forming clumps. However, these attributes of the ISM arise from the combined mass and energy input of the stellar winds, ionizing radiation fields, and supernova explosions that are the hallmarks of the formation of massive stars within young star clusters. What important boundary conditions does the ISM place on the physics of molecular clouds?

First, the total pressure (P_{tot}) of the ISM consists of major contributions from the ram pressure of interstellar turbulence, as well as the pressures of magnetic fields and cosmic rays, the value being $P_{tot} \cong 2.8 \times 10^4\, k_B$ K cm^{-3}, where k_B is the Boltzmann constant (*16*). This pressure is smaller by a factor of 10^{18} than that of the atmosphere at Earth's surface. If molecular clouds are not merely transient entities but achieve rough equilibrium for a time (see later discussion), then their pressure must match that of the external ISM at the cloud boundary. A simple application of the virial theorem shows that cloud truncation by the external ISM pressure determines the cloud's size and therefore its surface density Σ, which is the mass of the cloud divided by its cross-sectional area (measured in grams per cubic centimeter), or equivalently its column density $N = \Sigma/\mu$ (the number of particles of gas per unit of area of an object, where μ is the average mass of a molecule in the cloud).

The ISM is continuously stirred by supernova explosions and stellar winds. The shock waves engendered by the supernovae accelerate galactic cosmic rays that penetrate deeply into molecular clouds and clumps and both heat and ionize them. Far-ultraviolet (FUV) photons that are produced by massive star formation, on the other hand, photoionize the less dense surface regions of a molecular

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cloud and its internal clumps, up to column densities on the order of $N \leq 10^{21.5}$ cm^{-2} (*17*). This feedback between clustered star formation and the physical properties of the ISM suggests that star formation and ISM properties probably achieve a self-regulated state.

Most of the molecular gas in the Milky Way is gathered in the distribution of its largest, so-called giant molecular clouds (GMCs). Molecular clouds are detected and mapped by observing millimeter emission from a trace molecule: carbon monoxide (CO). CO surveys of the Milky Way (*18*) find that GMCs range in mass from 10^5 to $10^{6.5}$ $M_\odot$. GMCs have a distinct mass spectrum; the number of clouds per unit of mass is a power law of the cloud mass, $dN_{GMC}/dM_{GMC} \propto M_{GMC}^{-1.6}$. A power law index of -1.6 arises naturally if GMCs are formed by the collision and agglomeration of smaller clouds (*18*). The range in spatial scales for GMCs seen in these surveys is 10 to 100 pc, with the median cloud (that cloud for which half of the total mass in the GMC spectrum lies above it) having a mass of 3.3×10^5 $M_\odot$ and a median radius of 20 pc. The median cloud density is then 180 cm^{-3} and the median column density is 1.4×10^{22} cm^{-2} or equivalently, 260 $M_\odot$ pc^{-2} (*19*). The pressures within molecular clouds are much higher than the ISM pressure surrounding them ($P_{GMC}/P_{ISM} \cong 20$ to 30), because these clouds are self-gravitating. Direct measurements of the strength of the magnetic field in GMCs by the Zeeman effect are difficult, but observations show that magnetic field strengths have pressures (or equivalently, energy densities) that are comparable to the self-gravitational energy of these clouds (*20*).

It is difficult to resolve molecular clouds in external galaxies because of their great distance from us. The existing surveys, however, find GMC mass spectra resembling that of the Milky Way. The Antennae (otherwise known as NGC 4038/4039), for example, represent the collision and eventual merger of two galaxies. The central regions of this system are studded with 800 to 8000 young star clusters, whose median radii are $R_{eff} = 4 \pm 1$ pc, a value similar to that of globular clusters (*6*). Many superclusters are found in this population, with masses ranging from 0.4×10^6 to 3.0×10^6 $M_\odot$ (*7*). These clusters are being produced in the supermassive molecular clouds that are present in this region: CO surveys detect about 100 molecular clouds whose masses range from 10^6 to 10^9 $M_\odot$ (*21*). A CO map of the molecular gas in the interior region of the Antennae superimposed on Hubble Space Telescope (HST) images of the young SSCs reveals how molecular clouds and cluster formation are related (Fig. 2). The mass spectrum of the molecular clouds in the Antennae has a power law form, $dN/dM \propto M^{-1.4 \pm 0.1}$ (*22*), which is in good agreement with the spectrum of GMCs in the Milky Way. The main difference between systems undergoing starbursts, such as the Antennae, and those such as the disk of the Milky Way that undergo much quieter star formation, is in the upper mass limit of the GMC mass spectrum. These observations are in accord with theoretical predictions that gas-rich systems can build supergiant molecular clouds (SGMCs) through the agglomeration of smaller clouds and that their internal clumps are massive enough to produce star clusters that lie in the globular cluster and SSC mass range (*19*). Although the dynamics of the gas varies from galaxy to galaxy, the physics of agglomeration is independent of these details and should produce a universal GMC mass spectrum. The surveys of molecular clouds in external galaxies that will become possible with completion of the Atacama Large Millimeter Array (ALMA) millimeter observatory (*23*) will provide a definitive test of this hypothesis.

Individual molecular clouds are highly filamentary and inhomogenous structures. The filaments range from about 3 to 300 pc in length and from 0.3 to 3 pc in radius (*24*, *25*). Molecular clouds have a rich substructure consisting of many elongated high-pressure regions known as molecular cloud clumps. Clumps are the actual sites of clustered star formation within molecular clouds, so understanding their genesis is particularly important for all theories of clustered star formation. The filamentary character of molecular clouds, with their clumpy substructure, can be mapped in CO gas (*26*). This structure shows up extremely well at the higher spatial resolution that is possible by mapping the emission of warm dust (which is mixed with the molecular gas) at submillimeter wavelengths. A submillimeter map (Fig. 3) of warm dust in a portion of the Orion molecular cloud (*27*), taken with the SCUBA camera at the James Clerk Maxwell Telescope (JCMT), shows a 7-pc portion of the larger Orion A molecular cloud, in which the ONC cluster is forming, and it contains a number of discrete clumps along its length.

The internal structure and dynamics of molecular clouds are circumscribed by the

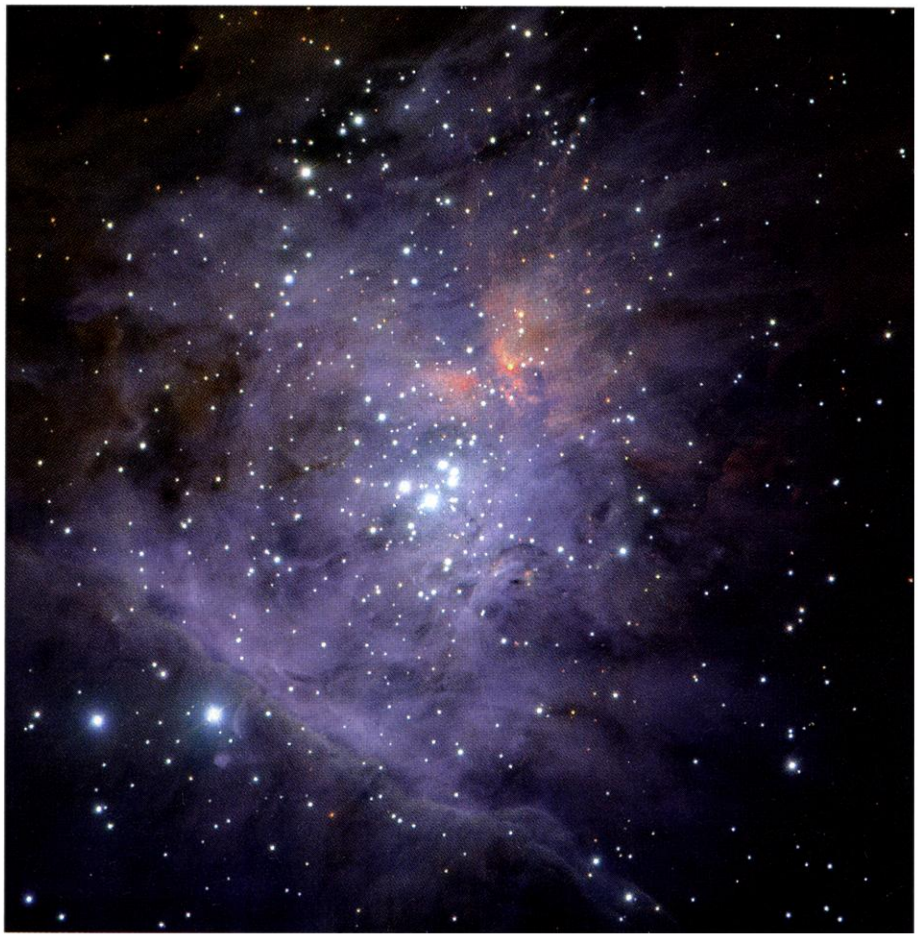

Fig. 1. A color composite mosaic image of the central part of the Orion Nebula, based on 81 images obtained with the IR multimode ISAAC instrument on the ESO Very Large Telescope at the Paranal Observatory. The famous Trapezium stars are seen near the center, and the photo also shows the associated cluster of about 1000 stars, about a million years old. [Courtesy Mark McCaughrean]

interplay between the gravitational force and the pressure forces exerted by the turbulent gas motions and well-ordered magnetic fields that pervade clouds (*28*, *29*). The thermal gas pressure within such cold clouds is too small to contribute significantly in supporting their enormous weight: thermal motions in such a gas are only ≅0.3 km s^{-1}, whereas the actual observed motions of gas in GMCs are ≅3 km s^{-1}. Similarly, rotational motions of clouds are also too small to help support them. Larson (*30*) was able to establish two important empirical cloud properties. If r represents the spatial scale of a cloud, and one measures the average column density Σ of gas on this scale, then observations show that molecular clouds tend to have a constant surface density; $\Sigma \cong$ const. Moreover, if σ is the one-dimensional velocity dispersion of the gas (related to the linewidths of CO) on this scale, then $\sigma \propto r^{1/2}$.

One explanation of these GMC properties is that clouds persist for a few free-fall times (t_{ff}) (*31*) and are roughly in equilibrium. Under these circumstances, the early work of Ebert (*32*) and Bonner (*33*) on equilibrium solutions for the structure of self-gravitating gas spheres that are truncated by external pressure P_s exerted on their surfaces shows that the column density of such a sphere depends only on the external pressure; $\Sigma = a(P_s/G)^{1/2}$, where a is a constant of order unity (*34*). The relative constancy of the ISM surface pressure over substantial portions of the disk of the Milky Way accounts for the near-constancy of molecular cloud surface densities in the galactic disk. The second Larson relation also follows naturally from such Bonner-Ebert models. These scalings do not just pertain to Bonner-Ebert spheres; they arise from virial descriptions of clouds that are highly filamentary, turbulent, and magnetized (*35*).

If molecular clouds are not merely transient structures, then their lifetimes depend on how long the magnetic fields and turbulence within them can be sustained. Magnetic fields within molecular clouds originate in the diffuse ISM and continue to thread this gas as it condenses out and becomes molecular. Molecular gas is poorly ionized, however, and is a relatively poor conductor, which leads to the leakage of magnetic flux from the gas. This arises because the Lorentz force that the magnetic fields exert on the ions in the molecular gas inevitably pushes them out of regions of higher gas density, dragging the magnetic fields out with them. The resulting magnetic or ambipolar diffusion time is ≅ 10 t_{ff}, which is a total of 10^7 years for a cloud of average density 10^2 cm^{-3}. The loss of magnetic support is much faster—less than a million years—in the high-density gas out of which clumps are made (where $n \cong 10^5$ to 10^6 cm^{-3}). Thus, although magnetic pressure support persists for a while in the bulk of molecular clouds, it is removed in less than a million years or so in regions of high column density such as the clumps.

Turbulence, the second means of pressure support against gravity, requires a sustained driving mechanism; otherwise, it is rapidly dissipated. The turbulent velocity of gas in molecular clouds is supersonic, although somewhat less than the characteristic speed for the propagation of waves along magnetic field lines if clouds are highly magnetized. Numerical simulations show that regardless of how strongly magnetized molecular clouds are, turbulence without a driving source damps out in $\leq t_{ff}$: a million years in the bulk of a GMC (*36*, *37*, *38*). It has been proposed that protostellar outflows from young stars could keep the gas stirred in this way (*39*), although this does not explain why turbulence is also observed in starless clumps.

The lifetimes of molecular clouds are important for the process of cluster formation. A relatively long life of $\geq 10^7$ years implies that the clouds themselves may evolve quasi-statically through a series of magnetically controlled equilibrium states (*40*). In this event, the formation of clumps and clusters occurs in localized regions that are sufficiently overdense so as to overwhelm the mechanisms of clump support. The difficulty with this quasi-equilibrium view of cloud physics is in finding a credible mechanism for driving the turbulence over this time span. An alternative picture proposes that clouds live no longer than a couple of crossing times (the time for a sound wave to cross the size of the cloud) before most of the star formation within them is finished—which is much shorter (*41*). In this picture, molecular clouds and their clumps are predicted to be highly transitory structures that are formed by the compression of gas in the supersonic interstellar turbulence. Clusters are quickly formed within the strongly self-gravitating regions that are created by such transient compressions. A difficulty with this latter picture is that it does not explain why star formation is observed to be so inefficient when averaged over the lifetime of molecular clouds; why isn't most of the gas compressed to the point of turning into cluster-forming clumps?

Of particular importance for cluster formation is the question of how GMCs are formed (*29*). The models differ primarily in the way in which the gas out of which the GMCs are made is gathered. The mechanisms include the for-

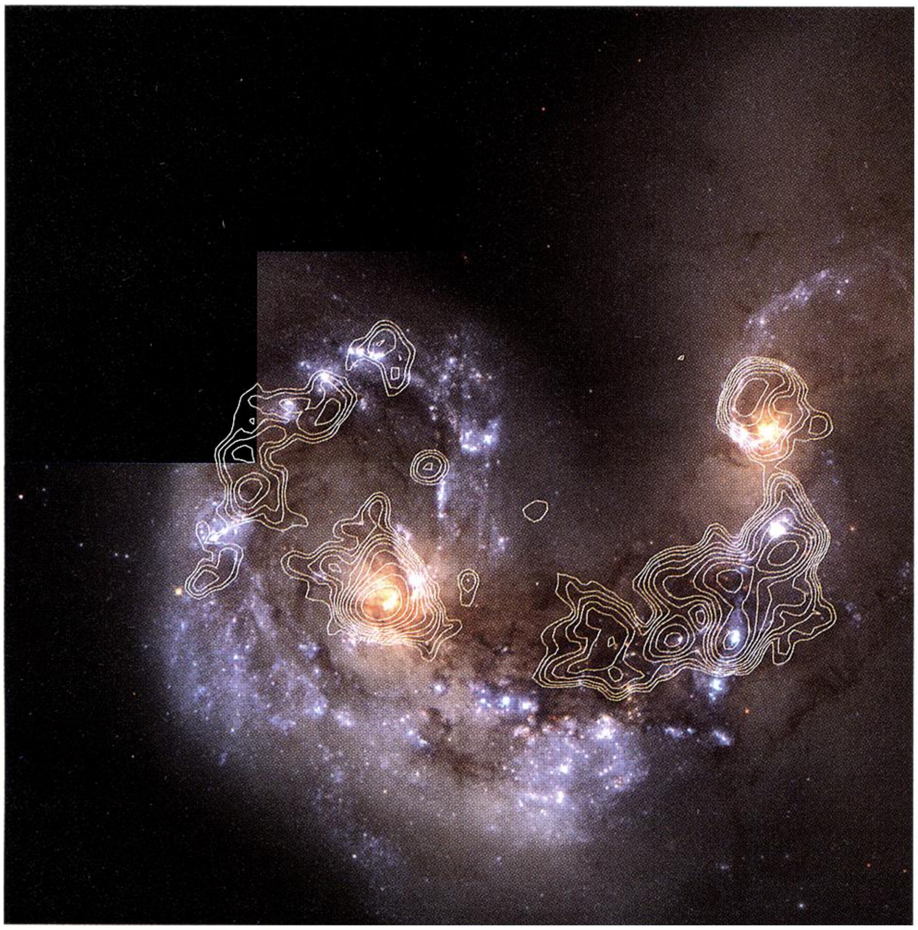

Fig. 2. A CO integrated intensity map (white contours) overlaid on a true color HST image of the Antennae galaxies (*95*) from (*21*). [Courtesy Christine Wilson] The young SSCs are the bright blue objects seen in this image.

mation of GMCs in the arms of spiral galaxies through the gravitational focusing of the orbits of smaller cloudlets and their enhanced rates of cloud-cloud collisions; the buoyancy of ordered magnetic fields that are observed in galaxies, leading to the deposition of gas in large GMC complexes along spiral arms; the appearance of a local gravitational instability of the thin cool disk of gas that makes up spiral galaxies; and the operation of clustered supernova explosions that arise from massive stars in newly formed star clusters, which can blast 1-kpc holes into the ISM, sweeping up material into dense, massive, and self-gravitating shells. Global numerical simulations of the Galactic disk show that large-scale filamentary structures can be formed in models of supernova-driven turbulence in sheared disks (*42*, *43*). In merging and starburst galaxies, huge gas complexes can be rapidly accumulated in galactic nuclei because of the large inward velocities that gas acquires through the torques that are exerted by bars that form during these collisions (*44*).

Regardless of how small or large ensembles of dense molecular clouds are produced, they all lead to a universal cloud mass spectrum. There are two general models for the universal spectrum. The first is that structure on all scales might be formed as a consequence of turbulent flow (*2*). Hydrodynamic turbulence is a top-down process that is driven, on the largest scale, by clustered supernovae and galactic shear and that cascades down through many decades to the smaller scales within molecular clouds. Universality follows from the hypothesis that turbulence in both diffuse and self-gravitating gas has a universal character. The alternative model is that molecular clouds are formed through a bottom-up process involving the collision and agglomeration of smaller clouds. This model predicts that it does not matter how the mass of gas is originally brought together: gravitational focusing, mergers of gas rich systems, and sweeping up of gas into supershells all are means by which gas can be gathered together and undergo cloud-cloud collisions. The agglomeration equations for simple collisions of self-gravitating objects (of constant surface density) or even of more uniform clouds of constant volume density turn out to have mass spectra with universal indices lying between -1.6 to -1.7 (*19*, *29*, *45*). The value of the index for the GMC mass spectrum does matter; if it were steeper than M^{-2}, for example, then most of the star-forming gas in the galaxy would be gathered in a host of low-mass clouds rather than in fewer giant clouds. This would limit the ability to make massive star clusters and high-mass stars.

Clumps and Clustered Star Formation

The substructure of filamentary molecular clouds is dominated by clumps. Surveys of clumps in different molecular clouds have established that the clump mass spectrum, as for the GMC mass spectrum, has a universal form (*14*, *46*); the number of clumps per unit of mass is $dN_{clump}/dM_{clump} \propto M_{clump}^{-1.7\pm0.1}$. Clump masses range from 1 to 3000 $M_\odot$. This is similar if not identical to the GMC mass spectrum and suggests that clumps share a similar formation process with the clouds in which they are embedded.

Models for the formation of clumps in molecular clouds include the agglomeration of smaller parcels of gas to produce clumps (*45*, *47*), the continuation of turbulent compression and fragmentation seen on larger scales and cascading down to the clump scale (*36*, *48*), and the gravitational fragmentation of larger scale filamentary clouds (*49*, *50*). Once molecular clouds have formed, it is difficult to see how turbulence that is generated on the scale of the ISM manages to penetrate into the much denser molecular gas to keep stirring the clumps. Just as waves washing up on a beach deposit their energy there, turbulent energy in the ISM may damp out or reflect from the denser clumps rather than stirring their interiors. The susceptibility of self-gravitating magnetized filaments to gravitational fragmentation was first noted in early work by Chandrasekhar and Fermi (*51*); and indeed, filamentary clouds do appear to have regularly spaced clumps that resemble beads on a necklace (Fig. 3). Fragmentation of filamentary clouds in its early stages would not readily reproduce the observed clump mass spectrum. However, the nonlinear development of such fragmentation modes involves gas flows along the filaments, which agglomerate particularly at accumulation points where filaments cross.

What kind of clumps produce star clusters? The median clump in the GMC clump mass spectrum has the following properties: a mass of 540 $M_\odot$, a radius of 0.4 pc, an average volume density of $n = 4 \times 10^4$ cm^{-3}, a surface density of $\Sigma = 1200\ M_\odot$ pc^{-2}, an associated column density of $N = 6.5 \times 10^{22}$ cm^{-3}, and an average velocity disperson of 1.1 km s^{-1} (*19*). By summing up the total mass in the clump mass spectrum, one finds that most of it is gathered in the clump with the maximum mass in the spectrum: $M_{total} \propto M_{max}^{0.4}$. Only the most massive clumps in Orion—above the median value—are observed to be forming clusters (*3*). Of particular importance is the fact that median clump mass is only a thousandth of the median GMC cloud mass. This mismatch between characteristic clump masses and those of their host molecular clouds is why clusters containing only hundreds to thousands of stars are the norm in the disk of our galaxy. In the clumps within the supergiant clouds, however, SSCs and globular clusters can form, because clumps in such clouds would then contain up to several 10^6 $M_\odot$ of gas (*19*).

The mass of a clump is a necessary but not sufficient condition for deciding whether or not star formation will be initiated in it; a clump's column density is also important. Observations of the low-mass Taurus cloud show that there is a critical column density for star formation: regions with a higher column density than a critical value of $N_{cr} \cong 10^{22}$ cm^{-2} have embedded young stars, whereas those below this value are without stars (*52*). Clumps at this column density are

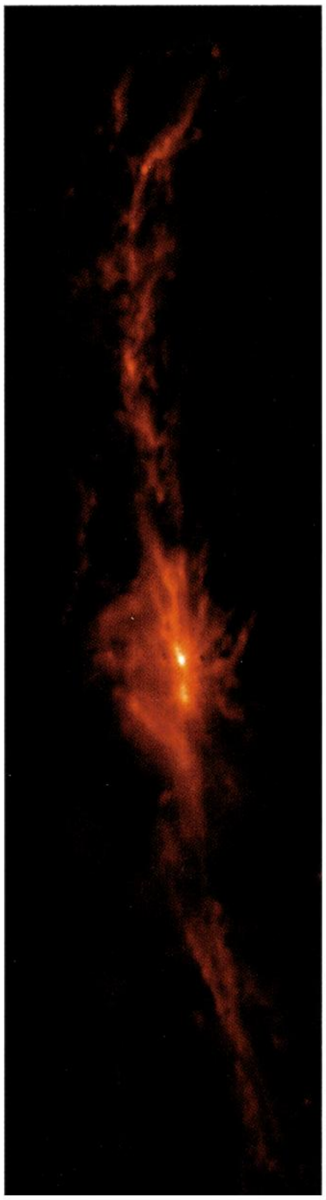

Fig. 3. A 15"-resolution 850-μm scan map 10' wide by 50', produced with SCUBA [from (*27*)]. The peak flux in the map is 150 Jy per beam; the noise is 0.04 Jy per beam. The color pallette is designed to show both the faint extended emission (darker colors) and the peak flux (in brighter orange). [Courtesy Doug Johnstone]

rather rare in a low-mass cloud such as Taurus, and this may be the reason why star formation is a rather inefficient process in many similar molecular clouds. The critical column density for star formation has not yet been investigated for other clouds but is probably higher in clouds such as Orion. The reason why column density is so important is that the self-gravity of any gas depends sensitively on it (*53*). Column densities of clouds and hence of their internal clumps are much higher within the nuclei of galaxies or in merging systems where ISM and dynamical pressures are much greater. This may be why starbursts occur there.

A survey of regions of high-mass star formation (*54*) reveals that clumps in which massive stars form have high densities with $n \cong 10^6$ cm^{-3}. These clumps have radii of R = 0.5 pc and contain 3800 $M_\odot$ of gas. Such a clump, if converted to stars with 50% efficiency, would have stellar densities of 15,000 stars per cubic parsec, which is the stellar density that one sees in the cores of globular clusters. Star formation as it occurs today in our galaxy is evidently capable of producing gas structures, at least on smaller scales, that have stellar densities rivaling those of the much more massive globular clusters. This implies that globular cluster formation is not distinguished by requiring regions of much higher external pressure than is commonly found today (*55*); such pressures can be generated in GMCs in our own ISM. Rather, it is the total amount of gas that is available to make the natal clumps within SGMCs that distinguishes SSC and globular cluster formation from the formation of clusters such as those seen in the ONC (*19*, *45*).

The gas motions that dominate in massive clumps are turbulent and are quite different than those seen in more isolated, lower mass regions (*56*). Turbulent velocities in clumps (as well as in GMCs) increase as one moves out from the center of the clump, a behavior that is completely different than in thermal pressure–supported Bonner-Ebert spheres. Two approaches have been taken to modeling clumps; the first assumes that such structures are nearly in equilibrium and the second that time-dependent simulations of clump formation in transient shock-dominated flows are important. The former models characterize the turbulent pressure of the clumps as consisting of central isothermal spheres surrounded by turbulent envelopes (*57*, *58*). An empirical equation of state for clumps, containing a single parameter, has been proposed. It features a logarithmic dependence of the pressure of turbulent gas on the gas density (*59*). These so-called logatropes are predicted to have density profiles for clumps that behave as $\rho \propto r^{-1}$ on large scales, as suggested by Larson's relations, and flatten to a constant density inside some core radius. These models fit the density structure of massive clumps: Observations reveal a range of radial density profiles of clumps from $\rho \propto r^{-1.0}$ to $r^{-1.5}$ (*60*). The empirical approach is reasonable given the absence of a rigorous theory of turbulence in highly compressible, magnetized, self-gravitating gas.

A major prediction of the logatropic and other turbulent models for clumps is that their mass infall rates during gravitational collapse are time-dependent. For logatropes, the infall rate varies with time as $dM/dt \propto t^3$. Stars with a wide range of masses from a few to tens of solar masses all form within about a million years (*61*), which is in agreement with the observations (*13*). The high pressures that accompany clumps of such high column density [for Orion clumps, these are on the order of $P_{\rm clump} \cong 2 \times 10^7\ k_{\rm B}$ K cm^{-3} (*62*)] lead to a critical mass for gravitational collapse on the order of 10 $M_\odot$, which is in the massive star regime (*59*). The high accretion rates on the order of 10^{-3} $M_\odot$ year^{-1} that arise in logatropic models will overwhelm the pressure of the intense radiation fields and winds that are produced by the massive young stars in a young cluster. This temporary supression of the destructive effects of massive star formation may be a critical factor in allowing the low-mass stars to form in a clustered environment (*63*, *64*).

Numerical simulations provide a powerful new tool for studying turbulence and star formation in clumps. Smoothed particle hydrodynamics (SPH) simulations, a particle-based method of simulating self-gravitating fluids, are used to follow the evolution of self-gravitating fluids that are subjected to an initial velocity field with a spectrum of velocity fluctuations; $P(k) \propto k^{-2}$ (where k is the wavenumber, which is inversely proportional to the wavelength of the fluctuation in question) (*48*). Networks of transitory filaments are produced along which gas and clumps flow to form denser regions. The mass spectrum of clumps produced in the hydrodynamic simulations is $dN/dM \propto M^{-1.5}$, which agrees with the observations and supports the notion that the agglomeration of smaller gas particles produces clumps. One difficulty with purely hydrodynamic treatments of molecular clouds is that the radial density profiles of such filaments are too steep to be able to fit the observations, which suggests that magnetized cloud simulations are imperative (*35*). Magnetohydrodynamic (MHD) simulations are based on finite-difference methods such as the ZEUS code. These have shown that clouds subjected to similar initial conditions develop a cascade of MHD turbulence that follows the Kolomogorov turbulence model, wherein the turbulent velocity (v) scales as $v(k) \propto k^{-5/3}$ (*38*).

There is good evidence that large-scale and rather ordered magnetic fields are associated with filaments and clumps in molecular clouds (*65*, *66*). Polarized emission is observed from molecular clouds at submillimeter wavelengths. It arises from elongated grains that are aligned with the field: Their long axes are perpendicular to the direction of the magnetic field line about which they are spinning. Maps of polarized emission can therefore be interpreted to extract the structure of the magnetic fields. The observations show that the amount of polarized emission seems to be lower toward the dense centers of filaments and their clumps, which may be evidence for helical magnetic fields in filamentary clouds that are wrapped around filaments and their clumps in a barber pole–like fashion (*67*). This field geometry may result from the twisting of the field lines by the shearing and vortical gas motions that are associated with turbulence.

The efficiency of star formation is high within the most massive clumps but low when averaged over the cloud. Clumps in the Orion cloud for example, range in mass between 8 and 500 $M_\odot$, whereas the star formation efficiency approaches 40% only in the most massive clump (*68*). Sparse star formation is found in the median, 200-$M_\odot$ clump. Given that the mass of the total Orion cloud is about 3×10^5 $M_\odot$, the star formation efficiency (SFE) for the entire cloud, defined as SFE = (stellar mass)/(stellar + gas mass) is only 0.3 % (*3*). Thus, it appears as if the SFE depends on how much gas gets above the column density that characterizes the clumps.

The degree of clustering of pre–main sequence stars in clusters can be obtained by measuring their surface density as a function of angular distance, θ, from each star. Larson was the first to measure a power-law relation $\Sigma(\theta) \propto \theta^\gamma$ for young star clusters. A recent survey of many young clusters finds that $\gamma \cong -2$ at small separations, whereas at large separations (0.1 to 1.0 pc.), there are variations from region to region with $-0.8 < \gamma < -0.1$ (*69*). The break in the power law occurs on physical scales of 0.01 to 0.1 pc. This spatial range probably does not reflect the initial conditions for isolated star formation in clusters, because a star moving at ≅1.0 km s^{-1} in such a cluster will move a distance of 1.0 pc in a million years, thereby erasing the initial conditions. Evidently, such initial conditions must be measured at earlier stages in cluster formation by studying the fluctuations in the clump gas itself.

Rough estimates of the IMF for stars that are embedded within clumps can be made by measuring the luminosity function of the strongly obscured, young stellar objects in the K-band region of the IR (*3*, *10*). The difficulty with the technique is that without knowing the effective temperatures of stars, their luminosity distributions cannot be uniquely identified with masses. Nonetheless, the young cluster IMF is consistent with the high-mass end of the IMF, for which the number of stars per unit of mass is $dN_*/dM_* \propto M_*^{-2.35}$ above 0.5 $M_\odot$ [first determined by E. Salpeter (*10*)]. The IMF in the core of the ONC cluster appears to break at $\cong$0.15 $M_\odot$ and crosses the hydrogen-burning limit into the brown dwarf mass range with a shallower dependence $dN_*/dM_* \propto M_*^{-1.43}$. Very-low-mass stars such as brown dwarfs are present; possibly even free-floating planets.

The Salpeter IMF also can describe the stellar population in one of the most massive star clusters in the Milky Way: NGC 3603, which has 50 O-type massive stars and is the densest system of high-mass stars in the Galaxy (*70*). The IMF retains this form down to the resolution limit of about 1 $M_\odot$ in NGC 3603. Alhough it has often been assumed that the IMF in starburst systems is abnormal in the sense of having a lower-mass cutoff at several solar masses, this example of a Galactic starburst does not show this predicted behavior. This suggests that the IMF is not determined by some kind of feedback effect from massive stars but perhaps reflects the initial conditions imposed by the gas in the clumps.

The time that it takes to form a star cluster can be determined by estimating the ages of stars in newly emergent clusters, such as the ONC. For this cluster, the bulk of the stars are between 10^5 and 10^6 years old (*13*). Some stars are 10^7 years old, however, which implies that the Orion cloud is at least this old. There are only a few stars that are as old as 10 million years, in comparison with the bulk that are $\leq$1 million years in several young stellar clusters. This may suggest that the rate of star formation in clumps accelerates with time (*71*) [but see (*72*)].

The observed mass spectrum of star clusters provides a direct way of constraining their formation conditions. The mass spectrum of the population of globular clusters associated with a galaxy has been measured for many different kinds of galaxies. They take the form of a broken power law similar to that of molecular clouds; the number of globular clusters per unit of globular cluster mass is $dN_{\rm glob}/dM_{\rm glob} \cong M_{\rm glob}^{-1.7\pm0.1}$ over the mass range from 10^5 to $10^{6.5}$ $M_\odot$, with a steeper power law at higher masses (*19*). The same power-law mass dependence is seen for the young SSCs that form in the Antennae (*6*). Cluster mass spectra of this form arise if globular clusters and SSCs are produced with good star formation efficiencies in the clumps within supergiant clouds; their mass spectrum simply reflects that of their progenitor clumps. Theoretical models for massive cluster formation are consistent with the observed properties of globular clusters and SGMCs (*19*, *45*).

Star-Forming Cores and the Origins of the IMF

Individual stars within clumps form within their own smaller gaseous structures, called cores (*73*). Cores in more isolated regions of low-mass star formation have physical dimensions of 0.01 to 0.1 pc, with densities $n_{\rm core} \geq 10^4$ cm^{-3} and masses of 1 to 3 $M_\odot$. Their internal velocity dispersions are dominated by thermal motions (*56*).

Determinations of the core mass spectrum within cluster-forming clumps have only recently become possible with the use of sensitive bolometer arrays on submillimeter telescopes such as the Institut de Radio Astronomie Millimetrique (IRAM) 30-m telescope and the JCMT. The results have brought a major advance to star formation; the number of cores per unit of mass is consistent with $dN_{\rm core}/dM_{\rm core} \propto M_{\rm core}^{-2.35}$ for core masses above 0.5 $M_\odot$ in a variety of molecular cloud clumps (*62*, *74*, *75*, *76*), which is the same form as the Salpeter IMF. The core mass spectrum for the ρ Ophiuchus cloud (Fig. 4) shows a particularly good fit to this relation. Thus, the IMF is made manifest in the structure of the gas in clumps. The fact that these cores have an IMF form also suggests that a significant fraction of them are strongly self-gravitating.

Three classes of models have been proposed to explain how cores form: (i) core concentration through the loss of turbulent and magnetic support, (ii) turbulent fragmentation in highly dynamic supersonic flows, and (iii) competitive accretion between protostellar cores moving in the gravitational potential of the clump. In the first class of models, cores form where the turbulence and/or magnetic field in clumps are weakened or overwhelmed. The dense clumps would have no recourse but to grow by accretion or to simply collapse. The degree to which the magnetic field or the hydromagnetic turbulence is coupled to the gas depends on the ionization degree of the clump (typically, one ion for every 10 million neutral gas particles in the bulk of the cloud), which is determined by a combination of external cosmic rays and x-rays that are generated by protostars in the forming cluster (*77*). Even if turbulence in clumps is continuously driven from larger scales, wave damping occurs in regions of sufficiently low ionization and on sufficiently small scales because of frictional effects due to ion-neutral collisions. Magnetic turbulence can be viewed as the propagation and nonlinear interaction of wave packets. A wave that propagates in a gas consisting of ions and neutrals can only be sustained if a neutral particle collides with any ion within the oscillation period of the wave (waves are typically transverse oscillations that propagate along magnetic field lines, much like on a plucked violin string). It is easily shown that on scales of about the size of the cores, this condition breaks down and the waves are damped (*78*), implying that its corresponding dynamical pressure is reduced. Thus, a pressure imbalance can develop that drives a slow inflow from larger scales: in essence, a pressure-driven cooling flow (*79*). These motions are subsonic and occur on larger spatial scales than those of the cores.

The time scale required to form a core by the diffusive loss of the ordered magnetic field, starting from a background density of the molecular cloud (10^2 cm^{-3}), is nearly 20 millon years (*80*). Star formation is much more rapid than this in the typical densities that pertain to regions of clustered star formation ($n \cong 10^6$), where the time scale to form a core is $\leq$1 million years. A more fundamental difficulty of this concentration picture is that cores are always observed to have magnetic energies that are less than a certain critical value needed to prevent them from collapsing. Calculations suggest that cores should also lose their turbulent support rapidly. Both effects contradict the expectation of the model that support of cores can be maintained in a turbulent and subcritical

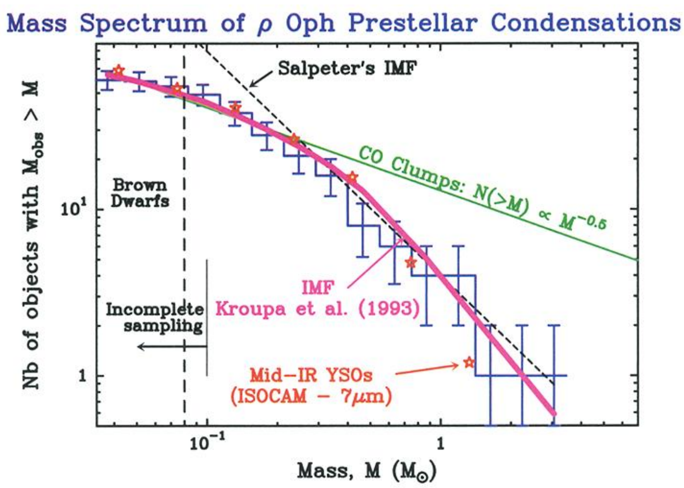

Fig. 4. Diagram showing the core mass spectrum in ρ Ophiuchus, which includes data from (*74*) as well as from (*96*). [Courtesy Phillipe André]

magnetic state until collapse sets in (*81*).

In the second class of models, turbulent fragmentation simulations produce a spectrum of fragments that form in the dense, cooling, shock wave fronts that arise in supersonic turbulence (*82*). Similarly, by identifying stars as sufficiently dense, strongly bound objects, SPH hydrodynamic simulations produce a log-normal distribution of protostellar cores (*48*). Detailed observations of the mass spectrum in the ONC at low masses show that the spectrum rises as a power law from 0.02 to 0.6 $M_\odot$ and then rolls over into the descending Salpeter IMF at masses above 1 $M_\odot$. These data are not consistent with a log-normal spectrum (*83*), so these simulations need to include relevant hydromagnetic processes.

In the third class of models, competitive accretion requires competition between embryonic protostellar cores for molecular gas as they move about in the the clump's gravitational potential (*84*). SPH simulations show that Bondi-Hoyle accretion (*85*) occurs onto a distributed set of initial objects of initial mass M_o and stellar velocity v_∞. The masses of such protostellar cores as they move about in a uniform gas density grow with time, as $M(t) = M_o/[1 - (t/t_{accr})]$. The accretion time scale t_{accr} decreases as the surrounding density increases, so that objects that move through the denser gas at the center of the clump accrete much more quickly, becoming more massive than stellar cores in the cluster periphery. Calculations have not yet reproduced the IMF and do not clarify how the initial stellar seeds, of mass M_o, are related to the observed gas cores in the clumps.

A corollary to this dynamical picture of clusters is that collisions between protostellar cores in such dense stellar environments could build up massive stars (*86*). Stellar collisions may occur in the centers of the densest clusters. This mechanism was proposed in order to overcome the difficulty of making massive stars of mass $M \geq 10\ M_\odot$ by accretion flows. The accretion rates in the turbulent clumps, however, in which massive stars prefer to form, may be high enough to smother these detrimental effects and allow high-mass star formation to occur by accretion.

A Unified Picture of Clustered Star Formation

There are three basic properties of newly formed stars that need to be explained by any theory of star formation: their mass, rotation, and magnetization. Such a theory must also explain the distribution functions associated with each of these quantities; that is, the IMF and the distributions of stellar rotation and magnetization with stellar mass. At the level of individual star formation within a core, most of the collapsing material in a slowly rotating core is first deposited in an accretion disk around the star. From there, it is accreted onto the protostar. Disks can be regarded as machines that strip gas of its angular momentum through the launching of disk winds as well as by disk turbulence (*87*, *88*). The bulk of the strong magnetic field that is observed on the scale of clumps and cores is shed by ambipolar diffusion out of the poorly ionized protostellar disks, leaving a smaller fraction that constitutes a fossil field, which is trapped within the new protostar (*89*).

The physical process that drives the IMF, however, is different, and the two prevailing views of isolated star formation have problems in explaining it. The Jeans instability picture of isolated star formation and more generally the theory of pressure-bounded self-gravitating isothermal Bonner-Ebert spheres argue that there is a fiducial mass scale for cores (*90*). For thermally supported spheres, the critical mass above which an object goes into gravitational collapse depends on the temperature as well as the surface pressure of the cloud. If one models a core with a critical Bonner-Ebert sphere at temperatures of 10 K, one finds a critical mass of 1.2 $M_\odot$ for typical low-mass clump pressures of $P/k_B = 10^5$ K cm^{-3}, down to 0.12 $M_\odot$ at the high pressures in clumps that undergo massive star formation. Although this model predicts stellar masses that are in the right ballpark, it has little predictive power in a highly inhomogenous medium where pressures vary. There is also no natural reason why there should be a range of stellar masses extending over nearly three orders of magnitude, from brown dwarfs at less than 0.08 $M_\odot$ to massive stars at nearly 100 $M_\odot$.

In the accretion model of isolated star formation, there is a fiducial mass accretion rate that is determined by the initial conditions in the core (*40*). The accretion rate depends strongly on the sound speed of the gas and may be derived from virial arguments (*91*). For a core at 10 K, the accretion rate is $10^{-5}\ M_\odot$ year^{-1}. This model requires an additional process to cut off the accretion at some time, thereby determining the mass of the star. The favorite choice is the jets and outflows that are associated with all young stars. But what tells one piece of gas in a clump to terminate infall to produce a 0.1 $M_\odot$ star, and in the neighboring core, one of solar mass? Also, outflows from the youngest protostars are highly collimated and intercept only a limited amount of infalling gas in the infall phase.

Star formation thresholds in a turbulent medium provide a unifying model for the IMF and clustered star formation (*29*, *92*). The model is based on the fact that star formation has a critical threshold column density, N_{cr}, above which fluctuations must collapse. Turbulence continuously generates fluctuations in column density throughout a molecular cloud. Given a particular value for the critical column density for star formation, any fluctuation that exceeds this threshold would constitute a core that is destined to collapse to form a protostar. Fluctuations that occur in regions of higher than average column density—the clumps—are much closer to the threshold value and therefore have a much higher probability of exceeding the threshold. One may readily show that turbulent magnetized gas has a threshold column density above which the turbulence damps and the magnetic field is overwhelmed by the self-gravity of the gas (*92*).

Figure 5 presents an illustration of this process. Turbulent fluctuations in column density are superimposed on a larger-scale

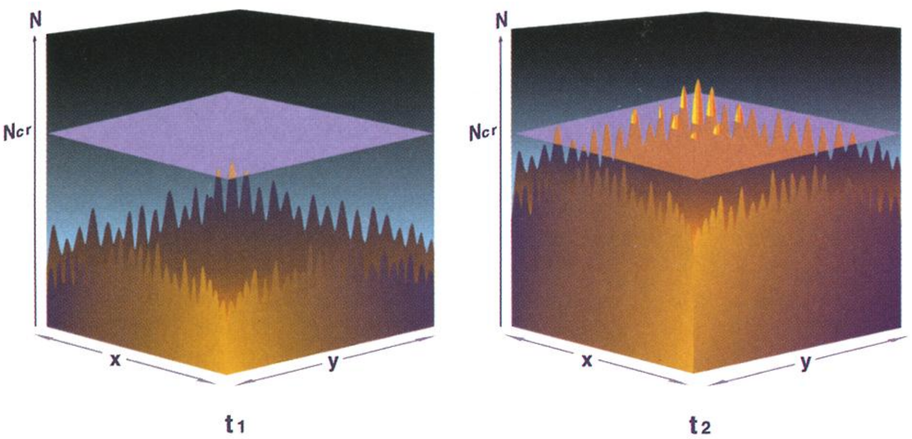

Fig. 5. Illustration of how a column density threshold, N_{cr}, for star formation leads to cluster formation in a turbulent clump. The column density of a clump is shown, with turbulent fluctuations imposed. At lower clump column densities (at time t_1), no peaks surpass threshold. At the later time t_2, the background has increased in column density, so that the peaks near its center surpass threshold and are manifest as cores. Higher column densities are illustrated with brighter orange color and lower column densities are darker in color. [Adapted from (92)]

background clump. The column density of the gas is plotted as a function of space coordinates x and y. At some moment in time t_1, the column density of the background clump is substantially below the threshold value N_{cr}. None of the fluctuations exceed the threshold, so star-forming cores do not form. At some later time t_2, the clump has increased in column density because of the agglomeration with other small clumps from the molecular cloud. The turbulent fluctuations are now closer to threshold and have a higher probability of exceeding it. Moreover, those near the center of the clump tend to have a higher excurion above the threshold, implying that these become more massive stars. This model explains why star formation is clustered and why the most massive stars are always located toward the centers of clumps. This is important because HST observations of several young clusters show that although massive stars are always observed to be grouped at cluster centers, there is simply not enough time for them to have been formed in the outskirts of a cluster and to have settled into their cores through a mass segregation process; we apparently see massive stars near to where they were formed (*93*).

Simulations of density fields allow the accurate calculation of the mass spectrum of the fluctuations that exceed threshold values (*92*). One finds that low- and high-mass spectra are power laws and are not log-normal. These calculations also show that the rate and efficiency of molecular core formation depend on the difference between the column density of the background clump and N_{cr}, as well as on the spectrum of turbulence then that fixes the IMF. This star formation threshold model, which is related to similar models for galaxy formation (*94*), also suggests why high- and low-mass stars are always mixed: It is a reflection of the statistical nature of turbulent fluctuations in the strongly gravitating environment of massive clumps. Finally, stars and clumps have different origins in this picture. Star clusters and the IMF may reflect the statistical character of turbulent fluctuations on cosmic scales. The coming decade will, without a doubt, open even more exciting vistas into this fundamental and important problem in astrophysics.

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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 [~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 ~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) ~ 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*); ~1% of a molecular cloud's mass is in the form of silicate (with some carbonaceous) dust grains ~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 ~0.01 to ~1 parsecs (pc), with masses of typically ~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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