25. A prominent theory—the so-called efficient markets hypothesis—holds that publicly available information about a firm will be transmitted rapidly into market outcomes as the stock price fully adjusts to reflect the influence of this information [E. Fama, L. Fisher, M. Jensen, R. Roll, *Int. Econ. Rev.* **10**, 1 (1969)]. K. J. Arrow [*Econ. Inquiry* **20**, 1 (1982)] cites empirical evidence on futures markets, indicating that the operation of these markets may be imperfect.
26. J. Pratt, H. Raiffa, R. Schlaifer, *Introduction to Statistical Decision Theory* (McGraw-Hill, New York, 1965).
27. D. A. Berry and B. Fristedt, *Bandit Problems: Sequential Allocation of Experiments* (Chapman and Hall, London, 1985).
28. When C is bad, 0.5 person is saved on average. When C is good, 90% of the trials succeed and 1.9 people are saved on average; 10% of the trials fail and after the switch to A, 0.5 person is saved on average. The expected value is 1.13.
29. L. Roberts, *Science* **243**, 1553 (1989); L. B. Lave, *ibid.* **236**, 291 (1987); L. Lave, Ed., *Quantitative Risk Assessment in Regulation* (Brookings Institution, Washington, DC, 1982).
30. A. Nichols and R. Zeckhauser, *Regulation* **10**, 13 (1986).
31. A. Wildavsky, *Searching for Safety* (Transaction Publishers, New Brunswick, NJ, 1988).
32. Data provided by Ministry of Health and Welfare, Japan.
33. The President's Council of Economic Advisers recently concluded that "In many cases, government control of risk is neither efficient nor effective." [*Economic Report of the President* (U.S. Government Printing Office, Washington, DC, 1987), p. 207.]
34. If very good information is available, one can use the more refined measure of cost per quality-adjusted life year (QALY) saved, thus taking into account both the number of person-years gained and their quality [R. J. Zeckhauser and D. S. Shepard, *Law Contemp. Probl.* **39**, 5 (1976)].
35. J. F. Morrall, *Regulation* **10**, 30 (1986).
36. A New York Times/CBS News Poll asked people if they agreed with the statement "Protecting the environment is so important that requirements and standards cannot be too high, and continuing environmental improvements must be made regardless of cost." Seventy-four percent of the public supported the statement in April 1989, shortly after the Exxon *Valdez* spill, while 80% agreed with it 2 months later. The *Times* concluded that "Public support for greater environmental efforts regardless of cost has soared since the Exxon *Valdez* oil spill in Alaska" ["Concern for environment," *New York Times*, 2 July 1989, p. 18].
37. W. K. Viscusi, *Risk by Choice* (Harvard Univ. Press, Cambridge, MA, 1983).
38. Little heed has been paid to innovative suggestions, such as the proposal of M. O'Hare, L. Bacow, and D. Sanderson [*Facility Siting and Public Opposition* (Van Nostrand Reinhold, New York, 1983)] that communities submit negative bids for accepting noxious facilities.
39. Support from the Decision, Risk, and Management Science Division of the National Science Foundation is gratefully acknowledged.

The Formation of Sunlike Stars

CHARLES J. LADA AND FRANK H. SHU

Understanding how stars like the sun formed constitutes one of the principal challenges confronting modern astrophysics. In recent years, advances in observational technology, particularly at infrared and millimeter wavelengths, have produced an avalanche of critical data and unexpected discoveries about the process of star formation, which is blocked from external view at optical and shorter wavelengths by an obscuring blanket of interstellar dust. Fueled by this new knowledge, a comprehensive empirical picture of stellar genesis is beginning to emerge, laying the foundations for a coherent theory of the birth of sunlike stars.

THE ORIGIN OF STARS REPRESENTS ONE OF THE MOST fundamental unsolved problems of contemporary astrophysics. Stars are the basic objects of the universe. Indeed, the discovery of the nature of most stars as hydrogen-burning thermonuclear reactors and the subsequent development of the theory of stellar evolution rank among the greatest triumphs of 20th-century science. Deciphering stellar genesis, on the other hand, has proven to be a formidable challenge for astronomers. Until a quarter of a century ago, only a rudimentary understanding of the subject existed. This state of comparative ignorance prevailed because no substantive body of empirical data existed that could be used to critically test even the most basic hypotheses concerning stellar origins.

In our galaxy, stars form within the dust-enshrouded dense cores of molecular clouds [for example, (*1–3*)]. The obscuration provided by the solid grains that permeate the clouds renders newly forming stars (protostars) completely invisible at optical and shorter wavelengths. Moreover, the molecular gas that gives birth to young stars is itself extremely cold (10 to 20 K) and, with a few exceptions, can only be observed in emission in the submillimeter and millimeter regime, a spectral window opened by radio astronomers only in the 1970s. As a result, the classical tools of optical and radio astronomy do not effectively probe the regions where stars are born. Although the dust effectively absorbs visual and ultraviolet light emitted by buried young stellar objects (YSOs), this light heats the initially very cold dust and is eventually reradiated at mid- and far-infrared wavelengths.

During the last two decades, impressive advances in technology have provided astronomers with the ability to observe star-forming regions in considerable detail at infrared, millimeter, and submillimeter wavelengths. With this new instrumental capability, a direct assault on the star-formation problem became possible. Indeed, over the last few years, observations with filled-aperture telescopes and interferometric arrays have produced a series of remarkable, exciting, and unexpected discoveries that have begun to remove the veil of mystery that surrounds the star-formation process in our galaxy. As a result of these discoveries, we are beginning to understand the processes of star formation and early stellar evolution and are developing the foundation for a coherent theory of star formation.

Modern star-formation research has as an objective the elucidation of the physical process by which a giant molecular cloud transforms a small fraction of its mass into numerous self-gravitating balls of gas that have just the right range of masses—roughly, 10^{-1} to 10^{2} times the mass of the sun ($1\ M_\odot = 2 \times 10^{33}$ g)—to fuse the primary product of the Big Bang, hydrogen, into heavier elements by way of nuclear reactions. In this article, we review some of the remarkable progress recently made in the endeavor to achieve this objective.

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Sites of Star Formation

The vast majority of stars in our galaxy form in giant molecular clouds (GMCs). With spatial extents on the order of 100 pc (3×10^{20} cm) and masses often in excess of $10^5\ M_\odot$, GMCs rival globular clusters as the largest and most massive objects in the Milky Way system. Discovered less than 20 years ago, GMCs number among the coldest objects in the universe, with gas temperatures seldom exceeding 10 K. Composed mostly of molecular hydrogen (H_2), they also contain significant amounts of interstellar dust and are permeated by magnetic fields. When observed in the trace molecule CO, they have inferred H_2 densities equal, in the mean, to about 100 to 300 molecules per cubic centimeter. Their molecular emission features often have linewidths on the order of a few kilometers per second, considerably greater than the thermal motion (≈ 0.2 km s^{-1} for H_2, 0.04 km s^{-1} for CO) expected for a very cold gas. Supersonic differential motions therefore characterize the overall dynamical state of a GMC. If this motion has a turbulent nature, it should be highly dissipative, yet GMCs maintain their supersonic dynamical states throughout their supposed lifetimes, 10^7 to 10^8 years. Because GMCs survive for times comparable to or longer than the dynamical time scales that characterize the gas motions within them, the existence of their supersonic velocity fields poses quite a puzzle (*4, 5*). Moreover, being strongly bound, molecular clouds receive too little support from thermal pressure alone to prevent overall gravitational collapse. Yet GMCs cannot suffer free-fall contraction, or star formation would proceed in the galaxy at a rate two to three orders of magnitude faster than its measured value (*6*). Some agent of mechanical support other than thermal pressure must exist inside molecular clouds.

Increasingly, astronomers believe magnetic fields provide the missing ingredient necessary to solve these outstanding problems. Zeeman measurements show that magnetic field strengths on the order of 10 to 1000 μG exist in the envelopes and cores of GMCs (*7*), with the largest values found in very dense regions exhibiting OH maser emission near newly formed stars. For a typical gas density $\rho = 10^{-21}$ g cm^{-3} and field strength $B = 30\ \mu$G, the Alfven speed $v_A = B/(4\pi\rho)^{1/2}$ has a value equal to about 3 km s^{-1}. Thus, although clouds may exist in a highly supersonic dynamical state, the fluid motions may remain sub-Alfvenic and less dissipative than one might otherwise suppose (*5*). Moreover, field strengths of the measured magnitude can provide the support needed to sustain clouds against gravitational collapse (*8, 9*). However, if such fields were to remain frozen to the molecular gas as it increased in density by 20 orders of magnitude in the collapse to form a star, B would increase (in three-dimensional compression) as $\rho^{2/3}$ and have values at the stellar surface of $\sim 10^9$ G, a million times greater than those ($\sim 10^2$ to 10^3 G) indirectly suggested by observations of pre–main-sequence stars. Before a star can form in a GMC, the contracting gas must lose a tremendous amount of magnetic flux.

Radio observations show that GMCs contain appreciable substructure, consisting of numerous filaments and dense clumps or cores (*10*) (see Fig. 1). Between 1 and 10% of the mass in a GMC exists in relatively dense ($\gtrsim 10^4$ cm^{-3}) cores (*3, 10*). Only within such cores do stars actually condense (*2, 3*). The cores within a GMC have a spectrum of sizes and masses. They range from small cores, with radii r (measured in the NH_3 molecule) on the order of 0.05 pc and masses between 1 and 10 $M_\odot$, to cores that are 100 to 1000 times as massive and have dimensions of a few parsecs (*2, 10*). The size and mass spectra of cloud cores seem to satisfy a power law, with small, low-mass cores being more numerous than large, high-mass cores. However, most of the dense gas and star formation activity within a GMC occurs within a few massive cores (*3*). If observed at all, the rotational velocities of cores in clouds are found to be low (*11*). Small cores, which form individual stars similar in mass to the sun, have typical angular velocities $\Omega \leq 3 \times 10^{-14}$ rad s^{-1}. The angular momentum per unit mass $r^2\Omega$ of the slowly rotating core gas is therefore on the order of 10^{21} cm^2 s^{-1}, considerably in excess of that of the sun ($\sim 10^{15}$ cm^2 s^{-1}) but not much more than that of the outer planets of the solar system ($\sim 10^{20}$ cm^2 s^{-1}). The smooth distribution of angular momentum with mass in a molecular cloud core, however, differs considerably from that which prevails in the current solar system (with 99.9% of the mass having only 2% of the total angular momentum), so appreciable redistribution of mass and angular momentum must occur before a molecular cloud core can successfully form a solar system (*12*).

Fig. 1. An image of the Orion A giant molecular cloud in the $J = 1 \rightarrow 0$ emission line of ^{13}CO. Roughly 60 pc in extent, this active star-forming cloud complex contains about $10^5\ M_\odot$ of cold molecular gas. The cloud complex is clearly clumpy and filamentary in structure. This particular image shows emission in the velocity range 4.5 to 6.5 km s^{-1} and is color-coded by velocity such that blue represents emission at velocities between 4.5 and 5.0 km s^{-1} and red represents emission at velocities between 6.0 and 6.5 km s^{-1}. The full velocity extent of CO emission from this cloud is about 10 km s^{-1} (*68*). [Courtesy of John Bally and Bell Laboratories]

Differences Between YSOs of Low and High Mass

Stars that form from molecular clouds have, both individually and collectively, considerably less mass than the cores that produce them. Indeed, astronomers have estimated the efficiency with which a GMC, over its lifetime, converts its mass into stars as only a few percent (*1, 6, 13, 14*). The number of stars born with masses between m and $m + dm$ is given by

$$f(m)dm \propto m^{-2.35}dm \tag{1}$$

for stars with m between 0.4 and 10 $M_\odot$ (*15*). Great uncertainty attaches to the form of the mass spectrum outside these limits, but recent studies suggest a turnover or peak in the spectrum at about 0.3 $M_\odot$. Apparently, most stars formed from molecular clouds are less massive than the sun.

High- and low-mass stars have quite different modes of formation and life histories. For most of their lives, during the so-called main-sequence phase of stellar evolution, stars generate energy by hydrogen-burning nuclear reactions that take place at their centers. The rate of energy generation is quite sensitive to the central temperature, and a 50-$M_\odot$ main-sequence star produces 10^6 times as much luminosity L_* as the sun, whereas a 0.1-$M_\odot$ main-sequence star produces 10^{-3} times as much. Because massive stars spend their fuel reserves so prodigiously, their evolution is rapid and their careers are short. Indeed, for a star's radius R_* to contract to the main-sequence value and for the star to commence hydrogen burning takes a Kelvin-Helmholtz time, GM_*^2/R_*L_*, where G is the gravitational constant, on the order of 3×10^7 years for a 1-$M_\odot$ star but only about 10^4 years for a 50-$M_\odot$ star. In comparison, the free-fall time for the dynamical collapse of a self-gravitating sphere of uniform density ρ is given by $t_{ff} = (3\pi/32G\rho)^{1/2} \approx 4 \times 10^5$ years if the density corresponds to average core values, $n_{H_2} = 10^4$ cm^{-3} (*16*). Thus, high-mass stars begin burning hydrogen before they finish their formative stage, that is, while still gaining mass from the collapsing molecular cloud core. On the other hand, low-mass stars ($M \leq 1$ to $2\ M_\odot$) emerge from their dusty cocoons before they begin to burn ordinary hydrogen [but perhaps after they have ignited the trace amounts of heavy hydrogen in the form of deuterium (*9*)]. As a consequence, young stars of low mass (known as T Tauri stars) have outward characteristics (principally a relatively large size and cool stellar surface) that allow astronomers to identify them as pre–main-sequence objects and to approximately date their ages.

Moreover, low-mass stars can form in relative isolation and are much less destructive of their natal environments than massive stars. Consequently, regions of low-mass star formation provide unique and important laboratories for the study of star formation and early stellar evolution. Unfortunately, because low-mass stars are much fainter than high-mass stars, they can only be practically studied in nearby molecular clouds with the most sensitive instruments.

YSOs of Low Mass: Observations

Because varying amounts of gas and dust surround YSOs embedded in molecular clouds, we expect them to radiate a significant fraction of their luminous energy at infrared wavelengths. Moreover, the large spatial extent of this circumstellar material compared to the radius of the stellar photosphere yields material with a wide range of temperatures, and the emission that emerges will have a spectral distribution much broader than that of a single blackbody. To detect the bulk of the luminous energy radiated by an embedded YSO therefore requires observations over a broad range of infrared wavelengths, typically between 1 and 100 μm. The shape of the emergent infrared spectrum of a YSO will depend on both the nature and the distribution of the surrounding material. Clearly then, we expect the shape of the spectrum to depend on the state of evolution of a YSO. The earliest (protostellar) stages, during which large amounts of infalling circumstellar material still envelop an embryonic star, should have a very different infrared signature from the more advanced stages, in which most of the original star-forming material has already been incorporated into the young star itself.

The formation of stars in a given molecular cloud probably occurs throughout the lifetime of the cloud. In any given cloud and at any given time, therefore, one expects to find YSOs of roughly similar mass in different stages of formation and early evolution. The infrared spectra of a population of YSOs within a given molecular cloud should display, therefore, systematic variations in shape. Recent observations of embedded populations of YSOs within (and between) molecular clouds have largely confirmed these expectations (*17, 18*). Such observations have shown that the broad-band infrared spectra or energy distributions of YSOs within a cloud exhibit well-defined structure (*1*). Moreover, systematic variations in source-to-source spectral shapes are observed. Indeed, one can meaningfully classify YSO infrared spectra into broad but distinct morphological groups, which appear to represent different phases in an evolutionary sequence from protostar to main-sequence star (*19*).

If one defines a spectral index $\alpha = d\log\lambda F_\lambda / d\log\lambda$ to be evaluated at infrared wavelengths, then the spectral energy distributions (that is, $\log\lambda F_\lambda$ versus $\log\lambda$) of most known YSOs fall into three distinct classes (see Fig. 2). Class I sources have positive values of α and energy distributions broader than that of a single blackbody or stellar photosphere. Radiation at far-infrared wavelengths dominates their spectra. Class I sources derive their steep positive spectral slopes from the presence of large amounts of circumstellar dust. These sources usually lie deeply embedded in molecular gas and rarely exhibit detectable emission in the optical band of the spectrum. They have long been suspected, largely on the basis of theoretical arguments (*9*), of having a protostellar nature. That is, through the accretion of surrounding cloud material, they may still be in the process of assembling the bulk of the mass that they will ultimately contain as hydrogen-burning (main-sequence) stars. However, despite numerous attempts to detect infall motions in the gas surrounding such sources, little direct evidence exists to support this interpretation.

Class II sources also have energy distributions broader than a single-temperature blackbody, but their values of α are negative. This indicates that they are surrounded by considerably less dust than class I sources. As a result, nearly all known class II sources can be observed in the optical as well as the infrared portions of the spectrum. When studied optically, class II sources usually have the emission-line characteristics of T Tauri stars, the classically known pre–main-sequence objects of low mass. Moreover, the optical portion of their spectrum is blackbody-like and similar in shape to that of a cool stellar photosphere. On the other hand, the infrared portion of their spectrum has a power-law form and departs from a blackbody shape, indicating the presence of some luminous circumstellar material around these stars (see Fig. 3). Theoretical considerations suggest that stars can produce such power-law infrared energy distributions if the luminous circumstellar material associated with them is contained within an optically thin and spatially flat disk. If such an optically thin and spatially flat disk has a power-law

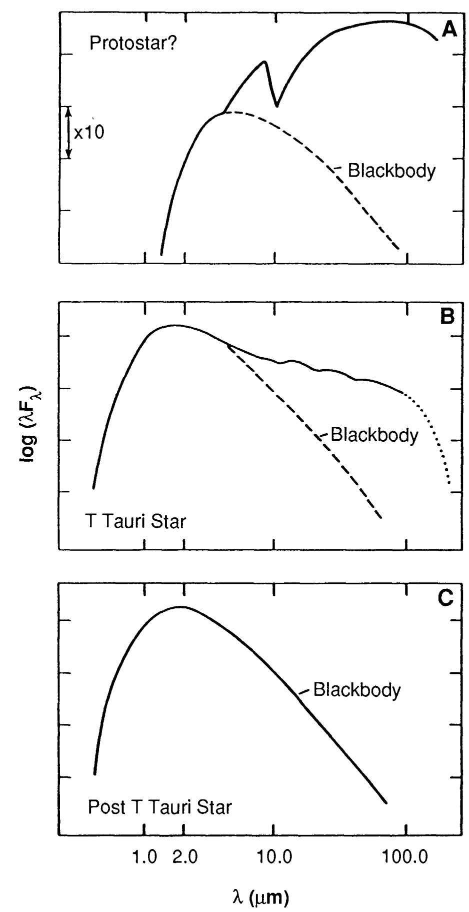

Fig. 2. Characteristic spectral energy distributions observed for YSOs embedded in molecular clouds and ordered by shape (F = flux density). Class I distributions (**A**) deviate strongly from that of a single-temperature blackbody and are characterized by slopes that are generally positive at wavelengths longer than a few micrometers. This indicates the presence of large amounts of luminous circumstellar dust around an embedded object. The departure of the spectrum from the blackbody shape at infrared wavelengths is referred to as the "infrared excess." Class II distributions (**B**) also exhibit infrared excess emission but have negative slopes longward of a few micrometers, suggesting relatively smaller amounts of circumstellar material around these objects. Class III distributions (**C**) are similar in shape to single blackbody functions and characterize YSOs surrounded by very little (if any) circumstellar material (*1*).

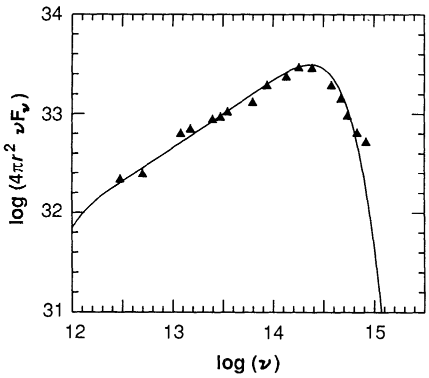

Fig. 3. Composite spectral energy distribution of seven class II sources. The dereddened and averaged data points are shown by the solid triangles. The solid curve shows the theoretical spectrum for a star surrounded by a disk with a power-law radial temperature gradient of index $n = 0.6$. In the infrared portion of the spectrum ($\log \nu \leq 14.5$) the shape is well modeled by a power-law form (*69*).

radial temperature gradient, $T_{disk} \propto r^{-n}$, it will radiate a power-law spectrum characterized by

$$\alpha = \frac{2}{n} - 4 \qquad (2)$$

Early theoretical work indicated that a luminous accretion disk, which derives luminosity in steady state from the local frictional heating of disk material in a field of differential motion characterized by Keplerian rotation, would have a temperature gradient with $n = 3/4$ (*20*). These workers proposed that such viscous accretion disks encircle T Tauri stars, predicting thereby that they have power-law infrared energy distributions with $\alpha = -4/3$. More recent work has shown that a flat passive disk, which derives all its luminosity solely from the reprocessing and reradiation of light it has absorbed from the central star, also has an equilibrium temperature gradient characterized by $n = 3/4$ (*21*) and produces a spectrum similar in shape to that of a viscous accretion or active disk. Moreover, most class II sources have spectral slopes that are less steep than those predicted for either a passive flat disk or a classical viscous accretion disk (see Fig. 3). Shallower temperature gradients and flatter spectral slopes may result if the disk either has a flared shape or owes its accretion mechanism to gravitational instability rather than to a viscous process (*22*). At present, it is not possible for observations to decisively distinguish between these various disk models. Nonetheless, circumstellar disks appear to be the most promising explanation for the power-law shapes of infrared spectra of most class II sources.

Apart from the modeling of spectral energy distributions, independent evidence for circumstellar disks has been obtained from other types of optical and infrared observations. For example, a disk with a size comparable to or somewhat larger than our solar system has been imaged around the pre–main-sequence object HL Tau in scattered near-infrared light as well as in CO emission at millimeter wavelengths (*23*). Optical and infrared spectroscopic observations yield further independent evidence for disks around class II objects. At high spectral resolution, T Tauri stars often have blue (Doppler)-shifted forbidden-line emission (coming toward the observer). Because these lines probably form in stellar winds originating near the surface of the stars, the lack of red-shifted Doppler components suggests the presence of occulting disks close to the stellar surfaces that block from view the receding portion of the flow (*24*).

Direct evidence for a circumstellar disk comes from observations of the class II source FU Ori. Spectroscopic measurements of optical and infrared absorption lines from this object indicate that the emitting material is differentially rotating, as would be expected for a disk in Keplerian motion around a central star (*25*).

Class III sources also have negative spectral indices, but their spectral shapes can be reasonably fitted with a single blackbody, consistent with the spectral distribution expected from reddened (or unreddened) photospheres of young stars, with little or no evidence for circumstellar gas or dust. Class III objects include both young hydrogen-burning (main-sequence) stars and younger pre–main-sequence stars that are no longer surrounded by circumstellar disks (*26*). Studies of embedded populations of YSOs in two of the nearest star-forming regions, Taurus and Ophiuchus, indicate that these clouds contain YSOs with a more or less continuous variation in spectral shapes from class I to class III (*18, 27*). The two clouds have, however, different relative numbers of each type of source. In the Ophiuchi dark cloud, class I and class II sources exist with equal frequency but very few class III objects abound. On the other hand, in Taurus, class II and class III objects have about equal representation, although class I sources are rare.

Although most YSO spectra can be classified into the three classes described above, there exist a small number of sources whose spectra exhibit more complicated structure, with no single value for the spectral index applying throughout the infrared. In most cases, these sources have double-humped spectral shapes and can be classified as subclasses of either class II or class III. These sources probably represent transition objects. In other cases, complex energy distributions may result from confusion arising from the superposition of more than one source in an observer's beam. Such confusion is most likely to occur at long wavelengths and for distant sources where the effective spatial resolution of the observations may be relatively poor.

The continuous variation in spectral shapes from class I to class III suggests a gradual depletion in the distribution and amount of emitting circumstellar dust around an embedded YSO. The hypothesis naturally arises, therefore, that the empirical sequence of spectral classes corresponds to an evolutionary sequence. In this interpretation, class I sources are the youngest and least evolved objects, still intimately associated with the gas and dust from which they formed. Class III sources represent the most evolved objects, and for these sources most of the original star-forming material has been either incorporated into the star or removed from its vicinity. It is likely that the vast majority of low-mass stars in the galaxy pass through these three stages during their formation. However, it is not known if the duration of each of these stages is the same for all stars, including those of the same initial mass. It is possible that differing initial conditions could result in different rates of evolution through the three phases. Certainly, the rate of evolution from class I to class III depends directly on the physics of the clearing process of circumstellar material. In principle, the clearing of circumstellar dust and gas could be accomplished by accreting all surrounding material into the system. This possibility conflicts with the observation that star formation occurs with considerable inefficiency: the cores from which stars form contain much more mass than the stars themselves, and most of the surrounding material cannot end up inside the star. This indicates that at some point in early stellar evolution the cloudy material surrounding a YSO must be physically removed (blown to large distances) by some active agent.

Energetic Molecular Outflows

Ten years ago millimeter-wavelength observations of the molecular gas surrounding YSOs led to the discovery of an unanticipated phenomenon of fundamental importance for understanding star formation (*28*). In addition to their global supersonic velocity fields, molecular clouds were found to contain localized regions (0.1 to 3 pc in size) characterized by hypersonic bulk motion. In these regions the observed widths of molecular emission lines often range between 10 and 100 km s^{-1}. Neither gravity nor magnetic fields can confine these highly supersonic and super-Alfvenic velocities to the localized regions where they occur; they must represent unbound and expanding flows of cold molecular gas within the GMCs (*29*). The regions containing the hypersonic outflows almost always coincide with, if not center on, the position of an embedded YSO. Well over 100 molecular outflows are now known, most within a kiloparsec of the sun, and with properties that have been extensively reviewed in the literature (*30–32*). Briefly, such outflows involve substantial amounts of mass, anywhere between 0.1 and 100 $M_\odot$. Such large masses mean that the outflowing molecular gas consists of swept-up ambient cloud material rather than original ejecta from the driving source. More significantly, the flows have enormous kinetic energies, ranging between 10^{43} and 10^{47} ergs. The dynamical time scales of the flows probably lie between 10^3 and 10^5 years, making their local formation rate roughly comparable to the birthrate for stars of a solar mass or greater.

Perhaps the most intriguing property of the molecular outflows is their tendency to appear spatially bipolar (*28, 29*). In other words, they often consist of two spatially separate lobes of emission, with one lobe containing predominantly blue-shifted gas and the other predominantly red-shifted gas. Furthermore, the two separating lobes often lie on more or less diametrically opposed sides of an embedded infrared source or YSO. About 75% of the known outflows are bipolar; the rest are either single-lobed (one lobe of either predominantly red- or blue-shifted emission), isotropic (one lobe but with both red- and blue-shifted, high-velocity emission spatially coincident), or of complex morphology. Figure 4 shows an example of the prototype bipolar outflow observed in the $J = 1 \rightarrow 0$ rotational transition of CO toward an embedded class I YSO in the dark cloud L1551.

Existing millimeter-wavelength telescopes and instrumentation have succeeded in spatially and spectroscopically resolving the important detailed features of many bipolar molecular outflows. Study of the spatial variation in the velocity fields of outflows can provide important information concerning the structure and nature of the outflowing gas. Observations of well-resolved and highly collimated outflows, such as the L1551 source, indicate that the molecular gas in an outflow is largely confined to a relatively thin, outwardly moving shell (*28, 33*). There also exists evidence for the presence of systematic velocity gradients along the axes of the bipolar outflow lobes (*34–38*). Along the projected length ℓ of the bipolar flow axis of well-collimated sources, the component of velocity parallel to the line of sight, $v_\parallel$, often exhibits a linear or "Hubble" law of motion,

$$v_\parallel \propto \ell \qquad (3)$$

Although the systematic increase of gas velocity with distance from the center of the outflow could be interpreted as an acceleration of gas away from the driving source (*33, 36, 37*), such an interpretation would require an unprecedented force that increases with distance from the driving source (*38*). A more plausible scenario holds that the observed velocity field results from the self-sorting of material in some flow. Such sorting occurs, for example, in an explosive event where freely flying shrapnel of different size and mass acquires different initial velocities. With time, the fastest moving shrapnel travels farthest, producing a linear, Hubble-like expansion law when observed at any one instant in time. Alternatively, the effect can also arise if a steady force is applied to a medium consisting of clumps with a range of mass and size or if the steady force that accelerates the swept-up material is angle-dependent (*39*).

The most likely underlying agent pushing the molecular shell is an intense stellar wind emanating from the YSO at the heart of the system (*28–33*). Indeed, it has long been known that T Tauri stars can generate powerful stellar winds (*40*). To have sufficient strength to drive molecular outflows, such stellar winds must be characterized by an appreciable mass-loss rate (for example, 10^{-6} to 10^{-5} $M_\odot$ year^{-1}) and very high velocities (for example, 100 to 400 km s^{-1}). A great deal of observational evidence suggests that very fast stellar winds are generated by YSOs, particularly those in an earlier phase of evolution than T Tauri stars. In particular, measurements of the radial velocities and proper motions of H_2O maser sources and Herbig-Haro objects near YSOs suggest the presence of low-density stellar winds with velocities well in excess of 100 km s^{-1} (*41*). Moreover, optical observations have revealed the presence of jets of ionized gas that appear to emanate from very close to the surface of numerous low-mass YSOs (*42*). These optical jets have considerably more collimation and much higher velocity than the larger scale bipolar molecular flows associated with low-mass YSOs.

Ionized stellar winds, which are relatively easy to detect, have been found around numerous YSOs from both optical and infrared spectral line observations and centimeter-wave radio continuum observations [for example, (*43*)]. However, close examination of these ionized winds has shown that they do not have enough momentum to drive the observed molecular outflows. The conjecture then naturally was proposed that a more massive and harder to detect neutral wind must coexist with the ionized wind (*29, 44*). In particular, models of the hydrogen recombination lines observed in the stellar winds around YSOs strongly suggest that the stellar winds have relatively low fractional ionizations (*45*). Compelling evidence for the presence of high-velocity neutral winds has been found in at least one bipolar outflow source, HH 7-11, in which atomic-hydrogen line emission has been detected at very high velocities (*46*). This neutral wind blows at about 150 km s^{-1}, and it contains enough mass (and momentum) to sweep up and accelerate the bipolar molecular flow. However, the precise nature of the engine that drives the intense neutral wind remains uncertain.

Bipolar molecular outflows are individually energetic enough to disrupt cloud cores (see Fig. 5) and collectively powerful enough to have a significant impact on the dynamics and structure of an entire GMC (*47*). In fact, the molecular outflows generated by a population of embedded YSOs may be able to generate the turbulent pressure that keeps GMCs from global collapse, thereby solving one of the outstanding problems of cloud dynamics. In any event, molecular outflow constitutes the likely agent that removes the bulk

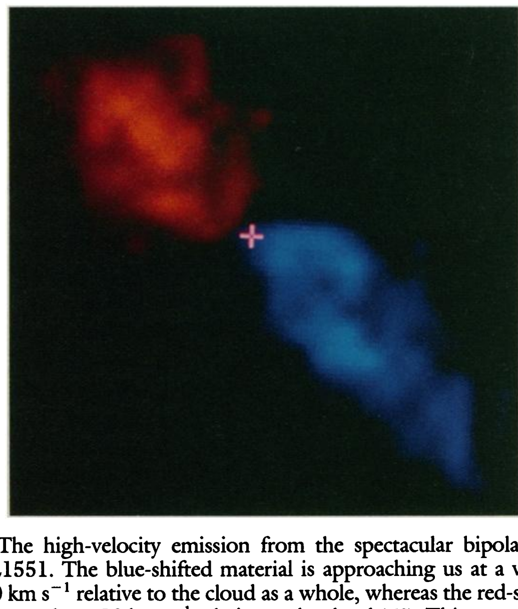

Fig. 4. The high-velocity emission from the spectacular bipolar outflow source L1551. The blue-shifted material is approaching us at a velocity of about 10 km s^{-1} relative to the cloud as a whole, whereas the red-shifted gas is receding at about 10 km s^{-1} relative to the cloud (*69*). This source is one of the most collimated bipolar outflows observed to date. [Courtesy of R. Snell, University of Massachusetts]

of the circumstellar material and drives the evolution of an embedded YSO from the class I to the class II stage. We consider it interesting in this regard to determine by direct observation the nature of the embedded sources that drive cold molecular outflows. A growing body of observational data now clearly shows that molecular outflows are most frequently associated with class I type sources and only rarely with class II or class III objects (*48–51*). In fact, survey observations of both embedded source populations within individual clouds and among all molecular clouds (*49, 51*) indicate that at least half of all studied class I infrared objects drive detectable molecular outflows. In addition, recent studies with more sensitivity and angular resolution than those typical of the surveys have found outflows that would have otherwise escaped detection around additional embedded class I sources (*52*). On the other hand, less than 10% of class II and class III objects have associated molecular outflows, although many of these may still actively have stellar winds (*48*). These observations support the contention that powerful bipolar molecular outflows remove circumstellar material and drive the evolution of a source from class I (protostar) to class II (T Tauri star). The transition of a source from a class II to a class III object results from the removal of its circumstellar disk. Exactly how this occurs is uncertain. The removal of circumstellar disks probably results from the combination of accretion of disk material onto the star, incorporation of disk material into planets, and erosion due to the stellar wind.

The high frequency of association between class I infrared sources and molecular outflows poses an apparent paradox. The statistics suggest that a class I object spends a significant fraction of its lifetime in the outflow phase. Yet, if class I sources represent true protostars, their evolution should have been characterized by the infall of surrounding material. How can an object simultaneously undergo both inflow and outflow? Alternatively, how can a star form by losing mass? The answer to this question holds the key to understanding the basic physics of star formation.

Fig. 5. A bipolar outflow in the process of disrupting a dense cloud core in the L43 cloud and revealing the underlying YSO. The solid contours trace the high-velocity CO emission from the blue-shifted lobe, and the dashed contours trace emission from the red-shifted lobe of the bipolar flow. The underlying image is an infrared (I band) charge-coupled device image (*70*). [Courtesy of Robert Mathieu, University of Wisconsin]

Formation of Low-Mass Stars: Theory

As outlined above, the fundamental problems that confront the development of a theory of star formation are (i) to determine what enables a few percent of the otherwise dynamically stable gas and dust in a GMC to collapse and increase in density approximately 20 orders of magnitude to form a star, (ii) to determine how this collapsing gas sheds most of its magnetic field, (iii) to determine how this collapsing gas solves the problem of the redistribution of angular momentum needed to form either a binary star system or a single star plus a planetary system, (iv) to determine the origin and nature of bipolar outflows and how a newly forming star builds up weight despite suffering heavy mass loss, and (v) to understand what determines the final mass of a newly forming star and the form of the initial stellar mass spectrum.

Understanding the formation of a single low-mass star from a small molecular cloud core constitutes a well-defined first step toward the development of a general theory of star formation. Over the last few years, considerable progress has been made in this area. In what follows we outline the general theoretical scenario for low-mass star formation that has emerged as a result of a number of recent theoretical investigations. Much has been learned about the processes of cloud collapse and fragmentation from time-dependent radiation-hydrodynamic calculations carried out in one, two, and three spatial variables by various groups around the world (*53*); however, the most accessible information concerning the formation of star-disk systems from individual molecular cloud cores comes from analytical and semi-analytical studies that trade off some loss of generality of applicability for the convenience and large dynamic range of the resulting physical description.

Numerous studies have suggested that magnetic fields provide the primary agent that supports interstellar clouds against gravitational collapse [for example, (*54*)]. Such support can occur if the mass of a cloud does not exceed a critical value approximately given by:

$$M_{\rm crit} = 0.13\,\frac{\Phi}{G^{1/2}} \approx 10^5 M_\odot \left(\frac{B}{30\ \mu{\rm G}}\right)\left(\frac{R}{20\ {\rm pc}}\right)^2 \tag{4}$$

where Φ is the magnetic flux of the cloud. Thus, a 10^5-$M_\odot$ GMC can be supported by a 30-μG field if it exceeds 20 pc in radius. Such field strengths have been found toward a number of molecular clouds. Moreover, infrared and optical polarization measurements of background stars seen through the clouds indicate that the magnetic field direction is smoothly ordered over the whole of some molecular clouds (*55*), suggesting that the field has sufficient strength to resist tangling by random turbulence of the molecular gas.

The support provided by magnetic fields does not couple directly to neutral molecular gas. However, cosmic rays can penetrate clouds and produce a small amount of fractional ionization. The magnetic fields in a cloud then deflect the trace population of charged particles onto spiral trajectories, and, because the cyclotron frequency of the typical ion much exceeds its mean collision frequency with neutrals, the motion of ions and field are effectively tied to one another. Collisions of ions with the neutrals then exert an opposing frictional force on the latter if they try to contract across field lines under the action of self-gravity. This friction effectively allows the Lorentz force exerted by the magnetic field to help support the bulk matter of the cloud but only at the expense of introducing a steady slip of the neutrals with respect to the ions and magnetic fields—a process that astronomers call ambipolar diffusion (*56*). A lightly ionized cloud, initially in a stable equilibrium, will therefore begin to quasi-statically contract as the supporting field slowly diffuses out. Moreover, because the ionization fraction is a decreasing function of increasing density and because matter remains free to slip along field

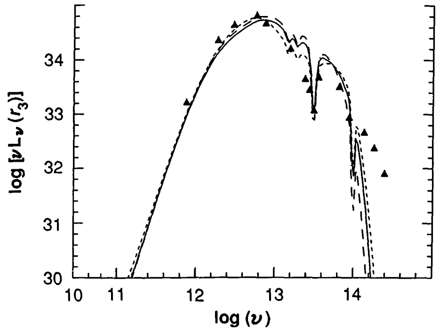

Fig. 6. The spectral energy distribution for the source that drives the L1551 bipolar outflow (which is in the Taurus cloud complex) and is shown in Fig. 4. Triangles denote the observed data. Solid and dashed curves represent the theoretically predicted emergent spectra based on the rotating-collapse solutions described in the text (*19*).

lines, the contraction proceeds in a nonhomologous manner, with an initially dense region becoming ever more dense relative to its surroundings, leading ultimately to the formation of a centrally condensed cloud core. If the ratio of magnetic to thermal pressure starts large enough so that the cloud as a whole is supported primarily by magnetic fields (and turbulence), many small dense cores could condense from the common magnetically stable envelope of the extended cloud (*57*). The same process of ambipolar diffusion probably also solves the magnetic flux problem that we identified earlier for magnetized molecular cloud gas contracting by many orders of magnitude to form a star (*58*).

In regions such as Taurus, ambipolar diffusion probably takes on the order of 10^6 to 10^7 years to produce cores capable of forming stars (*57*). During the last stages of evolution as the core loses more and more magnetic and turbulent support, calculations show that the density profile steepens to a power-law form roughly consistent with that of a singular isothermal sphere:

$$\rho = \frac{a^2}{2\pi G} r^{-2} \tag{5}$$

where $a = (kT/m)^{1/2}$ is the isothermal sound speed, T is the temperature, and m is the mean molecular weight of the gas. When the core acquires such a state, its mass depends only on the radius within which it is measured and otherwise has no special scale.

At this point the magnetic fields can no longer provide sufficient support for the core to prevent dynamical collapse. The collapse of an isothermal sphere occurs in a self-similar manner (*59*). The solution, which can be found analytically, yields a free-fall density distribution for material in the inner parts of the core,

$$\rho(r) \propto r^{-3/2} \tag{6}$$

with a wave of infall moving from the inside out at the speed of sound a that separates the collapsing and static portions of the core. Well within the infalling regions the flow velocities reach supersonic values. The self-similar collapse solution is characterized by a single important parameter, the mass infall rate, which reads:

$$\dot{M} = 0.975 a^3/G \tag{7}$$

In particular, because of the power-law form of the initial density gradient, no characteristic mass scale enters into the solution.

As long as the infalling material can freely radiate the gravitational potential energy lost during the collapse, the density of the inner collapsing cloud can reach values many orders of magnitude greater than that in the original cloud core (*60*). However, at some point the density becomes so large that the infalling material becomes sufficiently optically thick to trap the internally generated radiation. A hydrostatic star forms shortly thereafter that arrests the infalling material in a strong radiating shock near its surface. The postshock gas then slowly settles into the body of the star, with the protostar growing in mass linearly with time,

$$M(t) = \dot{M}t \tag{8}$$

as matter continues to rain upon it from the molecular cloud core. Moreover, it becomes increasingly luminous as it radiates away the gravitational energy lost by the infalling gas carried into the shock front:

$$L_*(t) = \frac{GM(t)\dot{M}}{R_*} \tag{9}$$

If the molecular cloud core rotates slowly to start with, a modified version of the above collapse solution holds (*61*). The tendency for each fluid element to conserve its angular momentum defines a centrifugal scale size:

$$R_c = \frac{G^3 M^3 \Omega^2}{16a^8} \tag{10}$$

Well outside of R_c, the collapse occurs much as in the nonrotating case, with the trajectories of infalling material defining radial streamlines. However, within R_c, the trajectories are parabolically curved, with material of higher and higher specific angular momentum no longer impacting directly onto the forming star. Instead, this material falls off center onto the equatorial plane and forms a

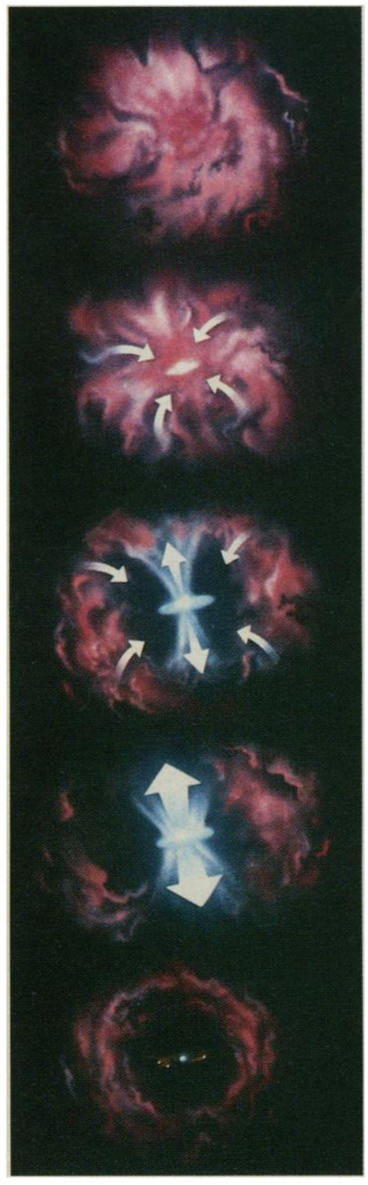

Fig. 7. Artist's conception and schematic diagram representing the stages of formation and early evolution for a low-mass star. First, a relatively dense core forms from a molecular cloud, probably as the result of the loss of the supporting magnetic field. The core becomes dynamically unstable and collapses from the inside out. The rotating collapse produces a disk around the central protostar and eventually a strong bipolar outflow. The outflow allows material of initially high specific angular momentum to accrete onto the star through the disk but simultaneously begins to reverse the infall of the outer envelope onto the central star-disk system. The outflow blows away the surrounding gas and dust, revealing the young object and its circumstellar disk. The material in the circumstellar disk is gradually depleted by accreting onto the star and perhaps by forming planets or a companion star.

flattened disk of radius R_c. At the same time the curved trajectories produce a depletion of density relative to the nonrotating solutions in the volume within R_c, but outside the disk. In any case, we see that the formation of disks around protostellar YSOs arises as the natural consequence of the presence of angular momentum (even in small amounts) in cloud cores.

Given the overlying density distribution, one can calculate the emergent spectral energy distribution of a model protostar as a function of time from the equation of radiative transfer. Apart from the time t (fixed if the mass $M = \dot{M}t$ can be estimated), the problem is essentially completely specified by two parameters, a and Ω, which in principle can be independently determined from the observation of molecular gas. Consequently, modeling the spectra of class I sources in different clouds where the sound speeds (or mass infall rates) and rotation rates differ provides a strong test of the models. It is therefore significant that such rotating-collapse models together with the best available calculation of dust opacities provide good fits for the observed spectra of numerous class I sources in both the Ophiuchus and Taurus molecular clouds (*19, 21*) (see Fig. 6). The ability of this theory to fit the energy distributions of a variety of class I sources appears to lend strong credence to the contention that class I objects are truly protostars. In addition, application of these models to the spectrum of the source HL Tau suggested that it has hints of a class I spectrum and, by inference, an infalling envelope, highly unusual for a T Tauri star. Recently, spectroscopic observations of this star in the infrared resulted in the direct detection of infall motions in the gas surrounding HL Tau (*62*).

For a rotating protostar, most of the mass that ends up on the star must be accreted from the surrounding disk. In order for material to flow through the disk and onto the protostar, the material must lose both energy and angular momentum (*63*). If the mass of the disk is not much larger than that of the central object, the material in the disk should rotate differentially in Keplerian fashion. Gas spiraling in through such a disk will reach the surface of the central star with an orbital velocity and specific angular momentum large compared to that in the star (*64*). If this material is deposited in the star, it will cause the star to spin up. The star will quickly reach breakup equatorial velocities, at which point material can no longer be added past the centrifugal barrier. Thus, the process of star formation can only proceed if the incoming gas somehow can lose additional angular momentum in the process of accreting onto the star or if the star can somehow spin down while accretion takes place.

Angular momentum can be carried away from a star by a stellar wind. Consequently, a protostar may be able to gain mass only if it simultaneously loses mass. If star formation is to continue, the rate of mass loss from the wind should be a fraction of the mass accretion rate:

$$\dot{M}_{\rm wind} = f\dot{M}_{\rm infall} \tag{11}$$

where the physics of the wind-generating mechanism determines the fraction f. The ideal protostellar wind is one that carries away little mass but lots of angular momentum. Recent investigations indicate that centrifugally driven hydromagnetic winds yield a potentially efficient mechanism, whether from a star (*64*) or from a disk (*65*).

One train of thought postulates that star formation from magnetized clouds leads to magnetized protostars (*66*) and disks (*67*); another, that strong stellar fields are internally generated by dynamo action. In either case, the field lines that thread and are anchored to a rotating disk or protostar can be expected to be rigid approximately to a distance R_A, the Alfven radius, the point at which the magnetic field energy is equivalent in importance to the kinetic energy of gas flowing along the field lines ($B^2/8\pi = \rho v^2/2$). If material near the surface of the star or disk can be lifted off the surface, then it will flow along the field lines and be centrifugally accelerated by the nearly rigidly corotating fields until it reaches R_A, past which point it essentially acquires ballistic trajectories. If by this time the material has reached escape speed, it will stream away from the system. The back torque T_b such a wind exerts on the protostellar system is approximately given by

$$T_b \approx \dot{M}_{\rm wind}\Omega_f R_A{}^2 \tag{12}$$

where Ω_f is the angular velocity of the footpoint of the field. Clearly, a wind can generate a large torque and brake the rotation of the protostellar system as long as the product, $\Omega_f R_A{}^2$, is large in comparison with the specific angular momentum of matter at the footpoint, $\Omega_f r^2$.

What are the relative merits and failings of disk winds versus stellar winds? One apparent advantage of the disk winds is that they have a natural tendency to be bipolar because they are driven off both sides of a disk. On the other hand, some ad hoc mechanism must be introduced to start the wind because the same symmetry naturally dictates that the open magnetic field lines, along which a wind might blow, thread vertically through the disk (parallel to the rotation axis). Such an orientation makes the centrifugal mechanism inoperative near the surface of the disk. The thermal pressure available in thin cool disks cannot accomplish the necessary chore of lifting the gas to heights where the open field lines might be expected to bend over enough for centrifugal driving to take place. Moreover, although disk winds can help to remove angular momentum from the disk, they do not help with the problem of continuous spin-up of the star until accretion onto it comes to a halt when the star reaches breakup. Finally, to achieve the energetics of observed molecular flows requires either disk masses that are far larger than inferred from observation or disk winds that originate nearly from the surface of the central protostar in any case.

Stellar winds avoid many of these problems. Because they are generated at the stellar surface, deep in the centrifugal machine, they can easily achieve the relatively high velocities and mass loss rates required to drive the molecular outflows (*64*). The large weight of the overlying gas in stars also makes them more likely to hold onto the high required magnetic fields (which are buoyant in a gravitational field), whose strengths measure as an average at the stellar surface about 100 G. However, for the process to work efficiently (on relatively cool atmospheric gas), the equator of the star must rotate nearly at breakup speeds. In the best developed theory of this class, competition between spin-up by disk accretion and spin-down by stellar mass loss precisely determines the fraction $f = \dot{M}_{\rm wind}/\dot{M}_{\rm infall}$ in the quasi–steady state when the star is kept exactly at breakup. Although the rotational velocities of deeply embedded protostars are not known, T Tauri stars, which also drive appreciable winds, do not spin at breakup. Perhaps winds driven from the boundary layers of such objects provide the desired solution.

In any event, hopeful signs exist that star formation in rotating, magnetic cloud cores results in the formation of protostar-disk systems that can overcome many of the major classical obstacles associated with the subject (collapse to stellar densities, loss of magnetic flux, loss of angular momentum, and simultaneous existence of infall and outflow). In the picture we have described, the generation of an intense stellar wind stands as the central issue. The wind appears necessary both to allow star formation to proceed (by making possible accretion of material through a disk) and to provide a natural mechanism for the ultimate reversal of infall from the surrounding spherical envelope. In this picture the stellar wind and the bipolar molecular flow it generates limit the mass available to be accreted onto the protostar by clearing away the surrounding gas and dust. The wind thus constitutes the agent that drives the evolution of a protostar from a class I to a class II object and determines the final mass of the forming star.

Concluding Remarks

Synthesis of new observational data and theory over the last few years has led to a deeper understanding of the process of star formation in our galaxy. In particular, an overall picture of low-mass star formation in our galaxy is finally beginning to emerge (see Fig. 7). One result of this advance in knowledge is that we are now beginning to appreciate just how rich and complex the physics of stellar creation really is. Indeed, if we have learned anything, it is that star formation is a much more mysterious process than anyone had expected even as late as 15 years ago. Although considerable progress has been made in star-formation research during the last 15 years, we are still far from a solution to this fundamental astrophysical problem. We have discovered and recognized the importance of energetic outflows for the stellar formation process, yet we do not understand how they are generated, when they are ignited, and how long they last. We still have no idea how outflows and other processes actually interact to produce the observed spectrum of stellar masses in the galaxy.

Most disturbing, however, is the fact that, despite numerous efforts, we have yet to directly observe the process of stellar formation. We have not yet been able to unambiguously detect the collapse of a molecular cloud core or the infall of circumstellar material onto an embryonic star. Until such an observation is made, it would probably be prudent to regard our current hypotheses and theoretical scenarios with some degree of suspicion. However, if our current theoretical ideas are even approximately close to the truth, we anticipate that the direct observation of infall-collapse is not far away. The next generation of millimeter- and submillimeter-wave interferometers and near-infrared spectrometers should be able to probe the innermost regions of protostellar cores, the very places where we expect collapse, infall, and accretion to be most manifest. The direct investigation of such inner regions around protostars and young stars will also provide us with knowledge about the physics and evolution of circumstellar disks. It is within such disks that planetary systems are believed to be formed. We now have reason to believe that, as we progress toward a greater understanding of star formation, we will also begin to unlock the secrets of the origin of planetary bodies.

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