25 May 1984, Volume 224, Number 4651

SCIENCE

The Formation of Stellar Systems from Interstellar Molecular Clouds

Robert D. Gehrz, David C. Black, Philip M. Solomon

Summary. Star formation, a crucial link in the chain of events that led from the early expansion of the universe to the formation of the solar system, continues to play a major role in the evolution of many galaxies. Observational and theoretical studies of regions of ongoing star formation provide insight into the physical conditions and events that must have attended the formation of the solar system. Such investigations also elucidate the role played by star formation in the evolutionary cycle which appears to dominate the chemical processing of interstellar material by successive generations of stars in spiral galaxies like our own. New astronomical facilities planned for development during the 1980's could lead to significant advances in our understanding of the star formation process. Efforts to identify and examine both the elusive protostellar collapse phase of star formation and planetary systems around nearby stars will be especially significant.

Perhaps the greatest fascination in man's age-old quest to understand the forces that order the cosmos has centered around the origin of the stars, sun, planets, and life itself. What complex physical processes have conspired to produce life and the solar system? How many of the countless stellar systems in our own galaxy and the universe have experienced a similar evolutionary process? Such questions, which challenge the limits of understanding, have intrigued generations of scientists, philosophers, and laymen. Never before has astronomical science had such great potential to provide answers. Observational and theoretical results of modern astronomical research have given insight into the chain of events that led from the early expansion of the universe to life on the planet Earth. Star formation, a crucial link in the chain, is a continuous process in the disk of our galaxy. Studies of regions where star formation is occurring provide us with an opportunity to observe firsthand the physical conditions and events that must have attended the formation of the solar system.

From Primordial Material to Stellar Systems

The process of star formation can be placed in the context of our current understanding of cosmic evolution (*1, 2*). As the Big Bang fireball expanded at nearly the speed of light, matter cooled from $\geq 10^{12}$ to 10^8 K within ~ 1000 seconds. Nearly all primordial nucleosynthesis must have occurred during this brief interval. Theory suggests that nuclei heavier than ^{4}He did not form in significant quantities before the cessation of Big Bang nucleosynthesis (*3*), so that the expanding primordial medium consisted almost entirely of isotopes of hydrogen and helium (≈ 90 and 10 percent, respectively, by number). Elements basic to life, such as carbon, nitrogen, and oxygen, were highly deficient in the primordial material as compared to their abundance in the solar system. Very heavy elements were virtually nonexistent.

As the expanding universe cooled, localized fragments of the primordial medium collapsed by self-gravitation to form protogalaxies. Spiral galaxies such as our own are thought to have condensed from relatively rapidly rotating protogalaxies which fragmented into stars, clusters, and interstellar clouds. A halo of stars and globular clusters was left behind the contracting protogalaxy, but most of the material collapsed into a thin rotating disk containing newly formed stars and interstellar matter (*4*). Although galaxy formation appears to have been confined to an era about (10 to 15) $\times 10^9$ years ago, star formation in active regions of the interstellar medium (ISM) in the disks of spiral galaxies is a continuing process during which the by-products of nucleosynthesis in massive short-lived stars are incorporated into successive stellar generations. This stellar processing of primordial material in evolving galaxies has produced all the other elements in the periodic table.

During the 1950's, progress in our understanding of stellar evolution and nuclear reaction rates led to a theory of nucleosynthesis that successfully accounts for the production of heavy elements from primordial hydrogen and helium inside evolving massive stars (*5, 6*). These massive stars return some of their processed matter back into the interstellar medium. Several different ejection mechanisms seem required to account for all the elements found in the solar system. Injection of processed material from aging massive stars into the ISM was documented during the past decade by infrared astronomers (*7*). Red giant and supergiant stars have extended circumstellar shells containing dust grains

R. D. Gehrz, Professor of Physics and Astronomy at the University of Wyoming, Laramie 82071, chaired the Galactic Astronomy Working Group of the National Academy of Sciences Astronomy Survey Committee. D. C. Black, Astrophysicist in the Space Science Division at NASA Ames Research Center, Moffett Field, California 94035, and P. M. Solomon, professor of Astronomy at the State University of New York, Stony Brook 11794, were members of the Working Group. This article is a review of the status of research in the field of star formation and interstellar matter based in part upon the deliberations of the Working Group.

composed of heavy elements. The dust is probably silicates (for example, $MgSiO_3$) in the shells of oxygen-rich stars (*8*), while carbon and silicon carbide (SiC) grains form in the shells of carbon-rich stars (*9*). Circumstellar dust grains are driven into the ISM by pulsations and stellar radiation pressure, carrying the shell gas with them by momentum coupling (*7*). This steady-state process alone does not satisfactorily account for the presence of elements heavier than iron in the interstellar medium since such elements cannot form in the interiors of even the most massive stars. These elements appear to be formed mainly by rapid neutron capture in the shells ejected in supernova eruptions of very massive [$\approx$ 30 to 100 times the mass of the sun ($M_\odot$)] stars (*10*). Thus, the presence of elements heavier than iron in the solar system implies that supernova ejecta were at some time mixed into the presolar nebula (*10a*).

The ISM is, then, the crucible in which primordial material and heavy elements ejected from generations of massive short-lived stars are mixed. Star formation is the critical process that incorporates this new mixture, vastly different in chemical composition from protogalactic material, into later generations of stars like the sun. Existing observational knowledge about star formation is confined to the interstellar and early post-protostellar collapse configurations. New astronomical facilities proposed for the 1980's (*11*) may enable astronomers to examine the elusive protostellar collapse phase.

Molecular Clouds in the Interstellar Medium

Early 21-cm radio observations of atomic hydrogen (HI) traced the diffuse component of the ISM in our galaxy (*12*). High-density regions of the nearby ISM were originally recognized because they obscured visible radiation from stars in the galactic plane, appearing as dark structures against the bright background of the Milky Way. Although numerous nearby dark clouds were identified by star counting, quantitative measurements of their composition, density, mass, and galactic distribution were not possible with optical astronomical techniques because these regions emit no visible light. The advent of millimeter-wave detection techniques enabled astronomers to observe emission from dozens of interstellar molecules and to identify the chemical composition and structure of the dense interstellar clouds (*13*).

Millimeter-wavelength spectral line surveys of the emission from the carbon monoxide (CO) molecule have substantially revised our view of the density and distribution of interstellar matter in the galaxy (*14, 15*). The CO fundamental rotational emission at 2.6 mm traces the more abundant hydrogen molecule (H_2), which has no permanent electric dipole moment and no radio or millimeter transitions. Although H_2 emission at 28.2 μm is believed to be an efficient cooling mechanism for clouds hotter than 100 K (*16*), the line is blocked by atmospheric water vapor. Moreover, most of the matter in interstellar molecular clouds is at much lower temperatures (*15*). Thus, CO emission reveals the spatial morphology of the higher density regions of the ISM where almost all the hydrogen is molecular.

High-spatial-resolution CO maps of the inner portion of our galaxy show that the ISM is dominated by large massive clouds (*15*) (giant molecular clouds or GMC's), which are the primary sites of current star formation in the galaxy. Relatively nearby (to the sun) GMC's such as the one associated with the Orion Nebula (*17*) are invariably found near associations of young stars and ionized gas. Figure 1 is a CO map of the galaxy between 290° and 90° longitude, and Fig. 2 shows CO emission in a cross section of part of the galactic plane. Clumping of the emission in both spatial and velocity coordinates is characteristic of discrete clouds rather than of a diffuse medium. The strongest emission comes from clouds or cloud complexes associated with HII regions (ionized gas surrounding recently formed massive stars). Most of the clouds producing the emission in Figs. 1 and 2 are at distances between 3 and 13 kiloparsecs (kpc) (9,000 to 39,000 light-years) from the sun in the highly flattened disk of the galaxy.

Contours of CO emission (Fig. 1) can be used to measure the size and number of molecular clouds (*15*). Cloud size along the galactic plane is determined from knowledge of the distance (inferred from rotation models of the galaxy) and angular extent. Internal gas velocities implied by CO line widths show that large-scale motions within these clouds are highly supersonic. GMC's are relatively dense, having 10^2 to 10^3 H_2 per cubic centimeter, as compared to 1 to 10 hydrogen atoms per cubic centimeter in atomic hydrogen clouds and much less than 1 atom per cubic centimeter between clouds. Although there are numerous small molecular clouds, the mass in the ISM of the inner galaxy is dominated by a few thousand GMC's. In addition, these clouds tend to cluster into complexes. Figure 2 shows a complex about 150 pc (450 light-years) at galactic longitude ~ 35°. A typical GMC is 20 to 60 pc in diameter with an average density of 300 H_2 per cubic centimeter (*15, 18*) and a mass of 10^5 to 10^6 $M_\odot$ (1 $M_\odot = 2 \times 10^{33}$ g). GMC's are the most massive objects in the galaxy. The molecular mass throughout the galaxy is about 3×10^9 $M_\odot$. The ringlike nature of the distribution (*14*), which peaks at a distance of 5.5 kpc from the galactic center (the sun is 10 kpc from the center), is the most obvious large-scale morphological feature. The tendency for emission to occur approximately along lines in Fig. 1 suggests the presence of enhanced emission from spiral arms or segments of spiral arms, but there is currently no general agreement about the degree of confinement of molecular clouds to spiral arms. The research group at the Goddard Institute for Space Studies maintains (*19*) that virtually all CO-emitting molecular clouds are in two or three spiral arms in the inner galaxy. The Stony Brook–Massachusetts group finds (*15, 20*) that, although the hottest and the largest GMC's are in spiral-like patterns, similar to the patterns of ionized hydrogen, a substantial fraction of molecular clouds including giant clouds exists between spiral arms (*15, 20*) indicating that star formation is widespread in the galactic disk.

Physical conditions within the clouds are apparently favorable for promoting chemical reactions required to form complex molecules. More than 50 different molecules have been identified in the gas phase of GMC's, primarily by millimeter-wave observations (*21*). These include such exotic organic molecules as ethyl cyanide (CH_3CH_2CN), methyl cyanide (CH_3CN), methyl mercaptan (CH_3SH), acetaldehyde (CH_3CHO), and ethyl alcohol (CH_3CH_2OH). Clearly, the chemistry of the galaxy is much richer than originally expected. Some investigators have argued that the infrared spectrum of interstellar dust shows evidence for the presence of organic or even biological particles (*22*). It is apparent that a very complex chemical broth is incorporated into protostellar condensations within molecular clouds.

Several fascinating problems have emerged from our study of GMC's. Densities and temperatures derived from CO spectra show that thermal gas pressure in clouds is insufficient to oppose their gravitational collapse (*23*). However, the current star formation rate in our galaxy is much lower than would be predicted if molecular clouds were freely collapsing, even if we were to assume a star formation efficiency of less than 1 percent (*24*). Comparison of the gravitational potential energy with the internal pressure derived from the velocities of large-scale nonthermal internal motions (deduced from Doppler-velocity broadening of molecular lines in the clouds) shows that the clouds are in or near equilibrium. It is difficult, however, to understand how such motions are maintained. Turbulence would be highly supersonic and should rapidly dissipate by shock heating.

Highly energetic outflows recently observed in the star-forming cores of many molecular clouds may bear on this problem. For example, millimeter and infrared CO and H_2 observations (*25*) reveal a shock front propagating away from a central source in the core of the Orion Molecular Cloud (OMC). The speed of the shock (30 to 50 km/sec) and its distance (0.3 pc) from the central source suggest that the events that precipitated the shock occurred only 1000 to 3000 years ago. The energy in the outflow exceeds 10^{47} ergs. Presumably, the source of the outflow is a highly luminous newborn star that is driving material away from its outer envelope or protocloud. Although there is no general agreement on the specific dynamical mechanism responsible for such outflows, they appear to be a normal occurrence accompanying star formation. Sufficient amounts of kinetic energy may be deposited into the molecular cloud by many young stars to oppose gravitational collapse. An intriguing possibility is that star formation in a given molecular cloud is a self-regulating process. The fact that interstellar matter is still plentiful (not all transformed to stars) in our galaxy is due to this inefficiency or self-regulation of the star formation process. By contrast, star formation may have been much more efficient in the early stages of the evolution of elliptical galaxies or in globular clusters that are left with no interstellar matter (*26*).

Star Formation in Molecular Cloud Cores

A typical GMC is more massive by four orders of magnitude than individual massive stars and more massive by two orders of magnitude than an entire galactic cluster. Thus, star formation must proceed in fragments or core regions of the GMC's (*27*). Processes within a molecular cloud that cause the high-density cores to form and that subsequently lead to the condensation of protostars are not well understood. Compression of matter by shocks may induce gravitational collapse. Mechanisms proposed to date include supernova shocks (*28*), ionization fronts (*29*), cloud-cloud collisions (*30*), and, on a larger scale, galactic density waves (*31*). It is not clear from the observations whether kinetic energy input by the shocks observed around young stars on the average disrupts or encourages star formation.

High-density molecular cloud cores form when portions of a GMC fragment and condense by self-gravitation. A typical cloud core may contain 10^2 to 10^3 $M_\odot$ of material at densities of 10^4 to 10^5 H_2 per cubic centimeter and temperatures of 50 to 100 K in a region less than 1 pc in diameter. A small molecular cloud might develop only a single core near its geometric center, whereas GMC's containing roughly 100 to 1000 cloud core masses might be expected to form a number of core regions throughout their volume, some of them relatively near the GMC boundaries (*32*). Astronomers have observationally identified core regions of molecular clouds and recently formed stars embedded within them. The actual protostellar collapse phase, discussed below, is predicted to be exceedingly short-lived and has thus far escaped observation.

The morphology of and physical conditions in cloud cores vary enormously, depending upon the degree to which star formation has progressed. Very young cloud cores in which stars have not yet formed appear merely as hot spots in the CO emission from the parent molecular cloud and emit no significant optical,

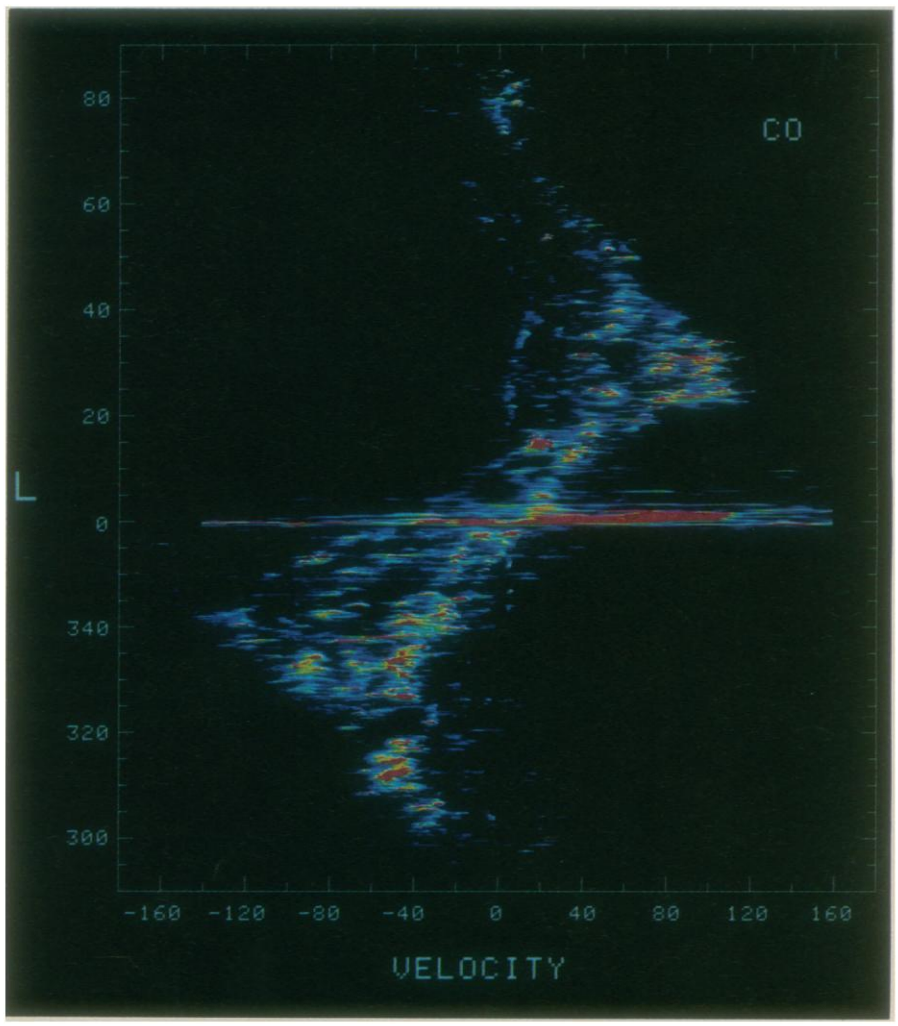


Fig. 1. A representation of the intensity of millimeter-wave emission from CO at a wavelength of 2.6 mm along the inner galactic plane between 290° and +90° longitude (*L*). The velocity of the emission indicates the distance from the galactic center, with the highest velocity at each longitude (or lowest velocity at negative longitude) corresponding to the closest approach of that line of sight to the galactic center. The strongest emission arising from giant molecular clouds (GMC's) and clusters of GMC's is apparent in the yellow and red structures. For example, at longitude = 15°, velocity = 15 km/sec (M17) and longitude 30.5°, velocity = 90 km/sec (W43), two well known GMC's associated with active star formation and ionized gas (from hot stars) are very prominent. The strong emission near longitude 0 is from the galactic center region. This picture is a composite of data from two surveys. The southern data are from the Australian survey by B. J. Robinson, R. N. Manchester, J. B. Whiteoak, and W. H. McCutcheon. The northern data are from the Massachusetts–Stony Brook survey by D. B. Sanders *et al.* (*53*).

near-infrared, or radio-continuum radiation (*32*). Several cool young cloud cores have also recently been identified in the OMC by their far-infrared ammonia (NH_3) line emission (*33*). On the other hand, cloud cores containing recently evolved young stars become observable throughout the electromagnetic spectrum. The youngest stars are still embedded in dense cocoons of gas and dust that are remnants of the protostellar collapse phase (*34*). Such objects, like the Becklin-Neugebauer (BN) star in Orion, appear as compact infrared hot spots within the cloud core. The inner regions of these cocoons may be as hot as 300 to 1000 K, and therefore they emit strongly in the 2- to 30-μm spectral region. Infrared spectroscopy has shown that dust, similar in composition to the material being ejected from aging massive stars, is a major constituent of these cocoons, and the associated gas phase contains such molecules as H_2O, CO, and H_2. Another signpost of dense fragments, maser emission from H_2O, SiO, and OH, has been observed in the immediate vicinity of many molecular cloud cores.

As hot young stars (OB stars) in cloud cores evolve toward the main sequence (hydrogen burning) phase, they can dissipate their cocoons by heating, radiation pressure, and stellar winds. The initial stages of such a process may account for the high-velocity CO outflows. During the dissipation of the remnant protostellar cocoon, the circumstellar material can become optically thin to ionizing radiation from the central star; this causes a compact ionized hydrogen (HII) region to propagate outward through the molecular cloud core material surrounding the young star (*35*). At this point, the cloud core emits both a rich optical recombination spectrum and thermal bremsstrahlung radio-continuum radiation from the ionized gas and thus becomes identifiable by a wide variety of

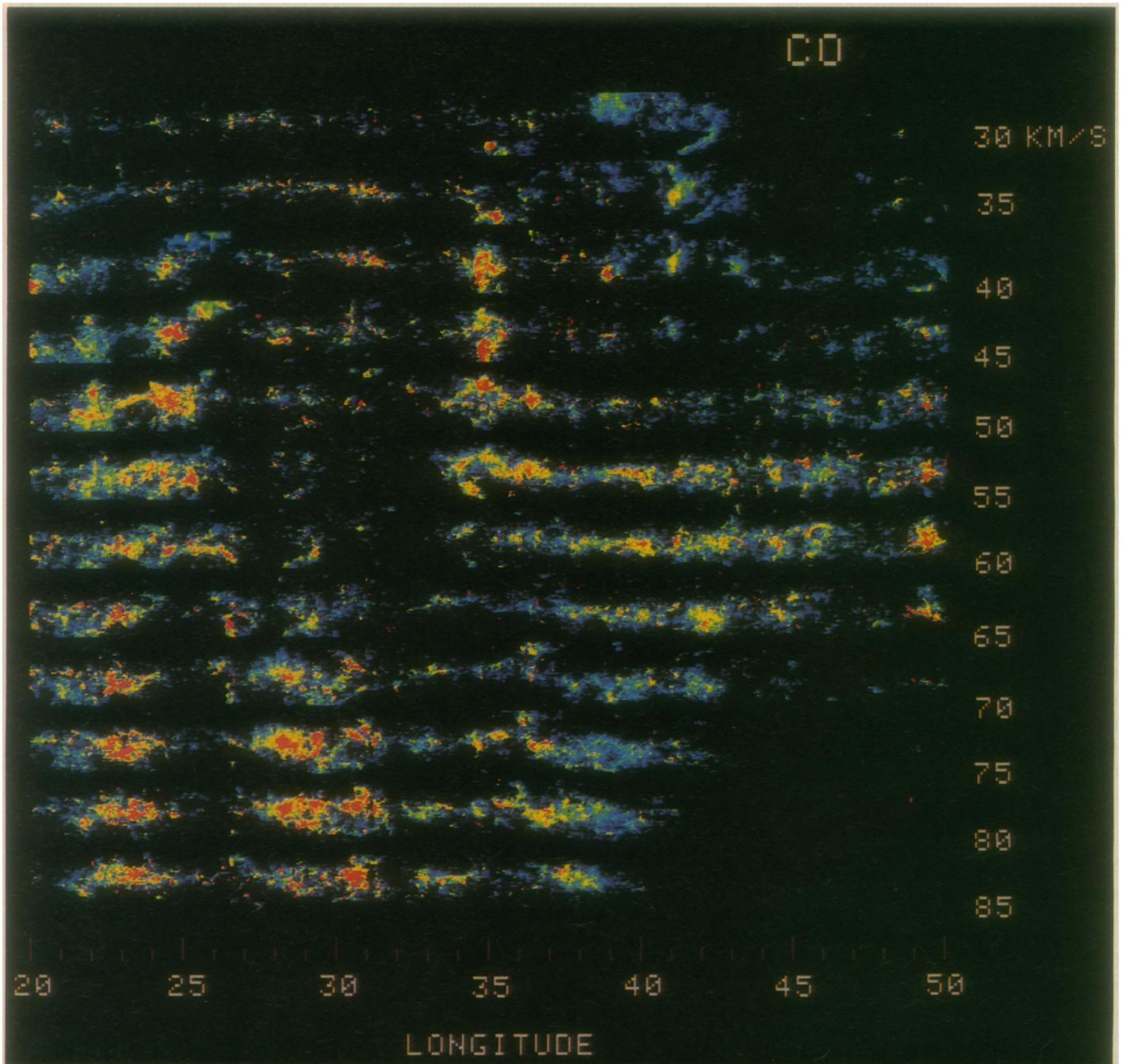
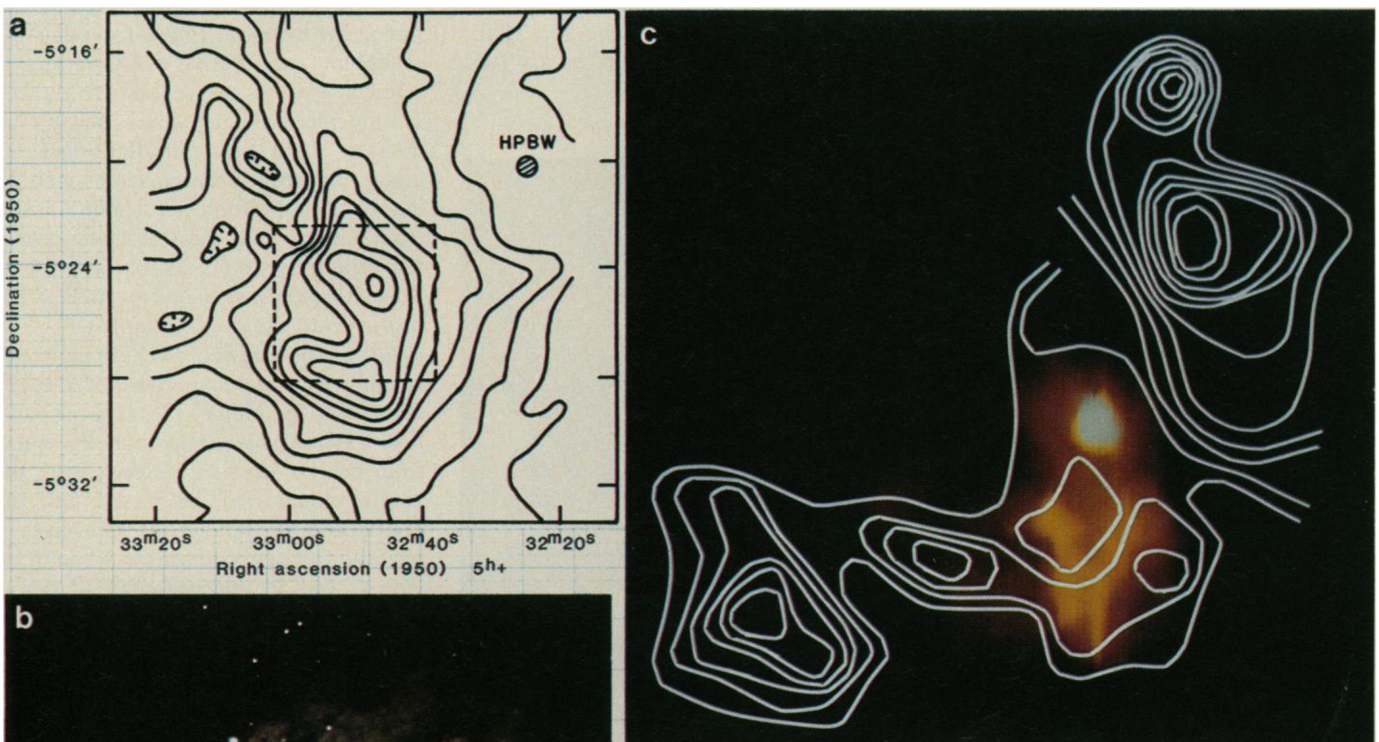


Fig. 2. A map showing the location and intensity of CO emission from interstellar molecular clouds. Each strip is a view of the galactic plane from longitude 20° to 50° and latitude −1° to +1.0°, at a fixed velocity (Doppler shift); the map consists of a composite of 24,600 observations at 0.05° intervals. Individual GMC's as well as clusters of molecular clouds, which are the most massive objects in the galaxy, dominate the emission. The clouds in this picture are at a distance of from 6,000 to 36,000 light-years from the sun. The data are from the Massachusetts–Stony Brook survey of the galaxy.

detection techniques. An evolving young OB star may eventually vaporize and blow away nearly all the remnant material. It can then be observed as an optical object surrounded by a large HII region. OB stars that form near the edge of a molecular cloud appear able to break out of the cloud, sweeping away the surrounding molecular medium by radiation pressure and stellar winds (*36*), and are observed to be in relatively low-density regions of the ISM just outside the molecular cloud boundary. Because highly evolved cloud cores emit most of their radiation at optical and near-infrared wavelengths, they are most readily identified when they lie near the GMC boundaries facing the sun. More deeply embedded cores suffer large amounts of extinction at short wavelengths. Thus, far-infrared, millimeter, and radio observations are necessary to delineate the distribution of cores within GMC's.

The OMC is an excellent example of a GMC that has fragmented into several cloud cores containing recently formed stars in various stages of evolution (*35, 37*). Nearly all the cloud core and post-protostellar configurations described above are represented. In Fig. 3, a, b, and c, we show three views of the OMC that describe active cloud cores and young stellar stages of the star formation process. The central 0.3° (3 pc) of the OMC, shown in ^{12}CO (Fig. 3a), is fragmented into several smaller cloud core regions each $\sim$ 0.5 pc in diameter. The active star formation region centered on the Trapezium, a small cluster of optically visible OB stars (Fig. 3b), contains $\approx 10^3\ M_\odot$ of material at densities of 10^4 to 10^6 H_2 per cubic centimeter. The Trapezium stars and the OB stars to the southeast are examples of recently formed stars that have substantially dissipated most of their remnant protostellar clouds. They provide the ionizing photons that cause the fluorescence and radio-continuum emission from the well-developed HII region and are driving HII shock fronts into the surrounding medium. The Becklin-Neugebauer-Kleinmann-Low (BNKL) object in the cloud core (Fig. 3c) is a very young star or cluster of stars still enveloped by post-protostellar material (*25*). Thus, the OMC complex shows fragmentation on several scales, the largest representing cloud cores and the smallest representing individual stellar masses.

Current observational knowledge about extremely young stellar systems comes from infrared observations of the compact condensations in molecular cloud cores, but it is highly unlikely that any of the objects observed thus far are in the state of protostellar collapse. They probably represent the immediate post-protostellar contraction phases during



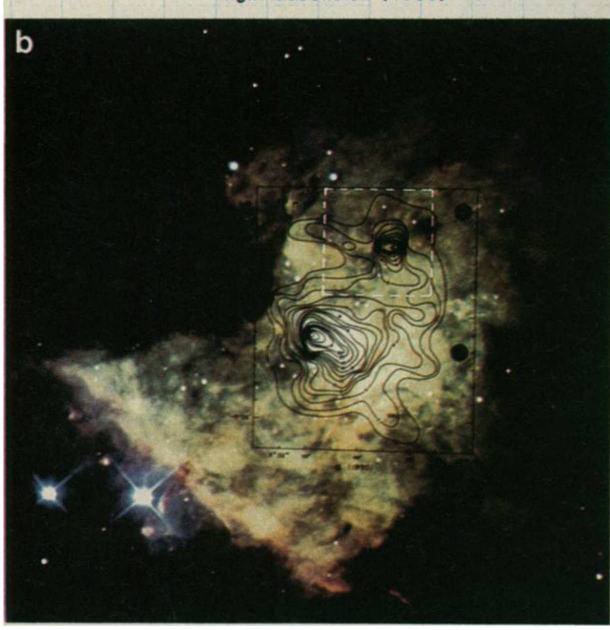


Fig. 3. (a) The brightness temperature distribution of CO ($J = 1 \rightarrow 0$) emission from the central 0.3° of the Orion Molecular Cloud (OMC) (*49*). The black dashed box indicates the area covered by (b); *HPBW*, half-power beam width. North is at the top, east is to the left. (b) A 5′ square optical photograph of M42, the active star formation region in the OMC, with 10-μm dust emission contours superimposed (*50*). Stars of several ages are represented. The white dashed box indicates the area covered by (c). North is at the top, east is to the left. (c) The core region (1′ square) of M42 showing infrared emission (color) from the BNKL complex and H_2 emission (white contours) from a shock front in the vicinity (*51*). BN is possibly the youngest stellar object to have been observed to date. Its formation may be associated with the shock front. The infrared image was produced by displaying 11-, 12-, and 20-μm images on the blue, green, and red guns of a cathode-ray tube (*52*). North is at the top, east is to the left.

which the initial stages of nuclear fusion have begun. The high-energy outflows might be expected for young stars beginning to dissipate their protoclouds. There is as yet no conclusive evidence for the presence of infalling material that would indicate a collapse phase. However, observations of infrared sources embedded in molecular clouds are crucial since they may provide indirect evidence about the physical processes that occurred in the immediately preceding but less easily observable phases of rapid protostellar collapse.

Recent high-resolution spatial maps acquired using new infrared imaging techniques on objects such as Sharpless 106 (S106) and W3 (see Fig. 4) are providing insight into the geometric morphology of the immediate postprotostellar collapse phase (*38*). Images of S106 show that the central source is surrounded by a flattened ring of dense gas and dust similar to that expected to form in the collapse of a rotating protostellar cloud (*39*). The resulting biconical nebula contains a number of dense subcondensations that may be formation sites for companion stars. The outflow observed optically in the biconical lobes of S106 (*40*) suggests that the newly formed star is beginning to dissipate the remnant cocoon.

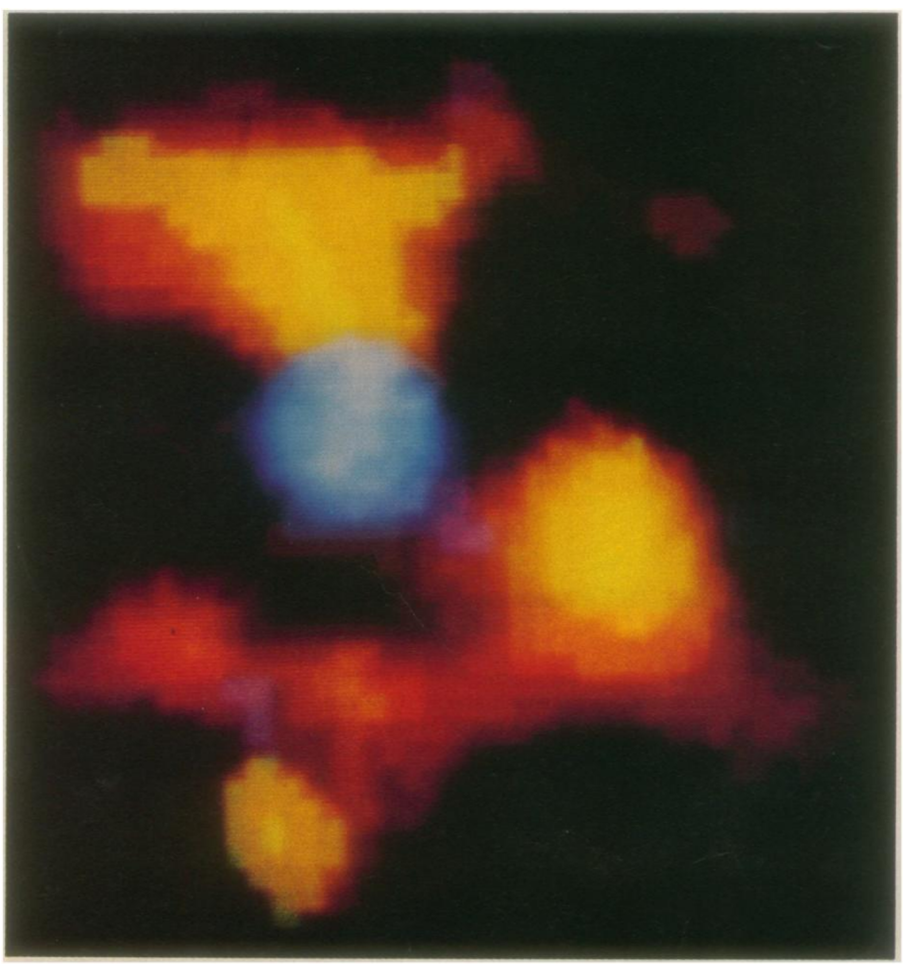


Fig. 4. False-color image of Sharpless 106 produced by displaying 3-, 10-, and 20-μm images on the blue, green, and red guns of a cathode-ray tube (*38*). The young star is the blue spot in the center. An outflow is observed in the orange biconical lobes. North is at the top, east is to the left.

Protostellar Collapse

Since the observations described above refer only to the initial and final configurations in star formation, they provide only circumstantial evidence about crucial physical details of the star formation process. The missing observational link is the true "protostar," a gravitationally bound collapsing cloud fragment whose dynamical evolution and luminosity are driven by gravitational contraction with negligible contribution from nucleosynthesis (*34*). Detailed knowledge about protostellar collapse would be gratifying because the physical events occurring during this stage evidently determine the important morphological characteristics of the final stellar configuration. Formation of binary stars and planets, spatial fractionation of elements within the collapsed disk, and the initial phases of molecular chemistry in the circumstellar material are probably determined during the protostellar phase. Recent theoretical studies of protostellar evolution provide insight into why this crucial evolutionary stage of star formation has escaped direct detection (*41*). The protostellar collapse is believed to progress in three phases: phase I, an initial quiescent contraction; phase II, a rapid near-free-fall collapse; and phase III, an accretion phase at the onset of contraction of the condensed core to the main sequence.

Phase I begins when the molecular cloud core fragments into gravitationally bound stellar mass-sized systems less than a few tenths of a parsec in diameter with densities of 10^3 to 10^4 H_2 per cubic centimeter. Presumably, this phase could be precipitated either by some of the shock mechanisms described above or by gravitational instabilities in the molecular material. Phase I is relatively quiescent, and internal mass motions of a few kilometers per second are typical. During phase I, the cloud density increases about a hundredfold and the cloud temperature decreases as increasing density promotes efficient cooling from far-infrared spectral lines. Cloud temperature may fall as low as ≈ 10 K. Magnetic fields remain frozen into the protostellar gas as it collapses (*42*), so that the magnetic field strength increases roughly as the square root of the gas density in the cloud (*43*). It is possible that external material, such as ejecta from nearby stars or material from the parent cloud, may be mixed into the protostar at this time. Thus, this phase of evolution may represent the point at which considerable amounts of heavy elements were incorporated within the presolar nebula. There is speculation (*10a, 44*), based upon isotopic anomalies in solar system meteorites, that material from supernovae may have been mixed into the presolar nebula. Evidently, detection of phase I clouds requires high spatial resolution and high sensitivity in the far-infrared (wavelength ≥ 100 μm).

After the initial quiescent contraction, the protocloud enters a phase of rapid gravitational collapse (phase II) at a density of $\approx 10^5$ to 10^6 molecules per cubic centimeter (*41*). This rapid infall slows at a density of $\approx 10^{10}$ molecules per cubic centimeter when the central regions of the cloud become optically thick to the radiation released by the material as it gains internal energy during the collapse. Efficient far-infrared cooling mechanisms within the cloud maintain its temperature at around 10 to 20 K. Although the protostar's density increases by a factor of 10^5 during phase II, the evolution time is only 10^4 to 10^5 years. The cloud is cold and small so that it must be observed at high spatial resolution with the use of far-infrared, millimeter, and submillimeter detection techniques. These conditions render the rapid protostellar collapse the most difficult of all the stages of star formation to study observationally. If angular momentum is conserved during the free-fall collapse, strong rotational forces may cause the protostar to fragment into a central ringlike structure that can in turn fragment into several subcondensations orbiting the original center of mass (*45*). Thus, this stage of collapse is crucial to our understanding of the formation of both binary stellar systems and planetary systems. The theoretical prediction of breakup of the cloud during rapid collapse by rotation is encouraging. Perhaps only 30 percent of observed evolved stellar systems are thought to involve single stars; the vast majority are binary or multiple star systems.

The final phase of the protostellar collapse (phase III) begins when the central region of the cloud becomes optically thick to its own radiation, causing the central temperature to increase. Gas pressure is soon sufficient to halt the gravitational free fall, and an equilibrium core (or cores if the system has become a binary star) forms in the center of the protostar (*41*). This core, which may be small if the system's rotation rate is high, appears to accrete material from the outer layers of the protostellar cloud, a process that may lead to the formation of a preplanetary nebula in which additional planet-mass condensations will later fragment (*39*). The central core contracts adiabatically during phase III until the dissociation of H_2 occurs at a temperature of 1800 to 2000 K. The central condensation at this time has a density of $\simeq 10^{20}$ atoms per cubic centimeter and a radius of less than half an astronomical unit (1 A.U. = 1.5×10^{13} cm, the Earth-sun distance). Additional dissociation and atomic ionization barriers are encountered as the density and temperature increase, each acting as an energy reservoir for the nearly isothermal absorption of gravitational energy generated by additional compression. After all ionization barriers have been passed, the core contracts slowly and adiabatically as it accretes mass until its central temperature and density are sufficient for nucleosynthesis to begin (*41*).

Viewed from the distance of the OMC, the 2000 K core would subtend an angle of only 0.8 milliarc second. Dynamical motions are of the order of 10 km/sec. The entire protostellar nebula, with outer regions having temperatures on the order of 100 K, would be smaller than several hundred astronomical units (2 to 5 arc seconds at a distance of 500 pc). Physical conditions during this phase must be studied with near-infrared (10 to 30 μm) and mid-infrared (2 to 5 μm) spectroscopic and photometric techniques that have high spatial and spectral resolution. There are a number of important issues to be addressed regarding the physics of phase III. The angular momentum of the protostar determines to a great extent how much of the material ends up in the central condensation. In the case of our solar system, for example, the angular momentum per unit mass of the sun's rotation is very low compared to that of the planets' orbital motion. Mechanisms such as the transfer of central angular momentum to the outer regions of the protostellar cloud by magnetic braking appear plausible but, to our knowledge, have received no definitive observational or theoretical test. The development of the central condensation may have important consequences for the early nucleosynthetic history of stars.

During the final phases of protostellar collapse, the outer cool regions of the protostar initially contain vast amounts of material condensed in dust grains. The intense radiation field generated as the infall energy of material accreting onto the central condensation may be intense enough to vaporize the dust grains, a process that could alter the chemical composition, structure, and size distribution of the grains and therefore affect the processing of biogenic elements. Unfortunately, there is little observational evidence concerning these processes at present. A final question of great importance concerns the spatial fractionation of the elements within the protostellar nebula during late contraction stages. Here also the theoretical models are severely constrained by the paucity of observational tests.

Planetary Systems

There is currently firm observational evidence for the existence of only one planetary system: our own. The recent discovery of cold matter associated with the nearby star Vega (*46*), made with the new infrared astronomical satellite (IRAS), will no doubt accelerate the search for other planetary systems. If the accepted theoretical picture of star formation is correct, planetary systems should form in nearly every stellar system. A significant exception to this expectation involves binary stars. It is suspected that the process by which binaries are formed somehow precludes the formation of planetary companions. If so, the fact that at least 70 percent of stars are in binary or multiple star systems would drastically reduce the expected number of planetary systems. Recent studies (*47*) have shown that a wide variety of stable orbits for planets do exist in binary systems if the planets can be formed there. Results from a comprehensive search for other planetary systems would provide an important check on our current theories of star formation (*48*).

Future Research

We have outlined the observationally known properties of regions where star formation is occurring and have presented a theoretical point of view concerning the way in which stars and planetary systems are thought to form. This picture of star formation is only a beginning. Much remains to be learned, both observationally and theoretically.

Observational research during the past decade has been successful in determining the physical and chemical environment of star formation and in identifying very young, recently formed stars. The interstellar molecular clouds and the newly formed stars have been studied primarily at infrared, submillimeter, and millimeter wavelengths. Thus far, these observations have been carried out with instruments that are primitive when compared with those used in optical astronomy and centimeter-meter radio astronomy. In particular, the limits due to lack of high spatial resolution in infrared and millimeter observations and the blanketing of the earth by an absorbing atmosphere in much of the infrared will have to be overcome in order to provide images of star formation comparable in clarity to the optical pictures of normal stars or galaxies now obtained with ordinary medium-sized, ground-based telescopes. For the most part, the spatial resolution of existing far-infrared and millimeter observation is only slightly better than the naked-eye resolution for yellow light. Thus, the universe of molecules, giant molecular clouds, young stars, and interactions between stars and clouds has been revealed, but the picture is still out of focus. A partial remedy has been achieved by the IRAS, but only a beginning. Some basic questions remain. On what scale do GMC's fragment when forming individual stars or star clusters? What are the properties of a true protostellar fragment? What is the energy output from a star or protostar back to the parent cloud? What does star formation look like in other galaxies where we can get a "global" picture? Does the formation of an ordinary star like the sun proceed in a fundamentally different way from that of more massive stars? What does star formation look like in active "star burst" galaxies where the process is faster by one or two orders of magnitude than in our own galaxy?

Several new ground-based and orbiting astronomical facilities that could provide high spatial and spectral resolution appear technologically ready for development during the next several decades. They include the cryogenically cooled shuttle infrared telescope facility, the 15-m ground-based optical-infrared new technology telescope, an orbiting 10-m large deployable reflector for far-infrared–submillimeter measurements, and several ground-based infrared-radio interferometers. Part of a comprehensive plan for the development of new astronomical facilities during the 1980's, these facilities are discussed in detail in the "Report of the Astronomy Survey Committee" (*11*). Another very powerful instrument recently suggested by millimeter-wave astronomers is a high-resolution millimeter-wave synthesis telescope that would resolve giant molecular clouds in other galaxies and that could be used to study nearby cloud cores with a resolution of 0.01 pc. The timely development of these facilities is a basic prerequisite for continued progress in studies of the process of planet and star formation and consequently for understanding the evolution of spiral galaxies, whose beautiful appearance is almost totally determined by recent star formation.

Much of the research that must be done if we are to understand the formation of stars and planetary systems is theoretical. It includes both the modeling of observed phenomena and the calculation of quantities that have not yet been observed. The complexity and diversity of processes involved in star formation, as well as the extreme range of physical parameters, will make it necessary for theoretical studies to rely increasingly upon detailed numerical simulations based on the use of the most advanced computers available (*11*). Although a number of important theoretical questions must be answered, the following are of particular significance: How do relatively small objects (stars) form from massive parent GMC's? During what phases of collapse do fragments form? What are the various ways in which binary systems evolve? What physical conditions and parameters (such as angular momentum and magnetic field strength) have a major influence on the effectiveness of star formation mechanisms? How are planetary systems like our solar system formed? What is their structure, and the range of physical conditions within them? These questions and others will play a central role in our efforts to determine how cosmically insignificant, yet breathtakingly beautiful objects like Earth were formed.

References and Notes

1. A. W. Wolfendale, Ed., *Progress in Cosmology* (Reidel, Dordrecht, Netherlands, 1981).
2. J. Billingham, Ed., *Life in the Universe* (MIT Press, Cambridge, Mass., 1981), and references therein.
3. R. V. Wagoner, *Astrophys. J.* **179**, 343 (1973; ———, W. A. Fowler, F. Hoyle, *ibid.* **148**, 3 (1964).
4. K. O. Thielhelm, in (*1*), p. 305; W. H. McCrea, in (*1*), p. 239; W. W. Roberts and W. B. Burton, in *Topics in Interstellar Matter*, H. Van Woerden, Ed. (Reidel, Dordrecht, Netherlands, 1977), p. 195.
5. F. Hoyle, *Astrophys. J. Suppl. Ser.* **1**, 121 (1954); E. M. Burbidge, G. R. Burbidge, W. A. Fowler, F. Hoyle, *Rev. Mod. Phys.* **29**, 547 (1957).
6. C. A. Barnes, D. D. Clayton, D. N. Schramm, Eds., *Essays in Nuclear Astrophysics* (Cambridge Univ. Press, Cambridge, 1982).
7. R. D. Gehrz and N. J. Woolf, *Astrophys. J.* **165**, 285 (1971).
8. N. J. Woolf and E. P. Ney, *ibid.* **155**, L181 (1969).
9. R. Treffers and M. Cohen, *ibid.* **188**, 545 (1974).
10. W. D. Arnett, *Annu. Rev. Astron. Astrophys.* **11**, 73 (1973); D. N. Schramm, in (*6*), p. 325.

10a. See D. D. Clayton [*Q. J. R. Astron. Soc.* **23**, 174 (1982)] for a stimulating analysis of the scenarios whereby stellar ejecta are mixed into the ISM and presolar nebula.

11. *Astronomy and Astrophysics for the 1980's*: (report of the Astronomy Survey Committee, National Academy Press, Washington, D.C., 1982), vol. 1.
12. F. J. Kerr and G. Westerhaut, in *Galactic Astronomy*, A. Blaauw and M. Schmidt, Eds. (Univ. of Chicago Press, Chicago, 1965), p. 167.
13. The first few radio-wavelength discoveries of interstellar molecules were actually at centimeter wavelengths prior to the use of millimeter-wave technology [D. M. Rank, C. H. Townes, W. J. Welch, *Science* **174**, 1083 (1971); P. M. Solomon, *Phys. Today* **26**, 32 (1973)].
14. N. Z. Scoville and P. M. Solomon, *Astrophys. J.* **199**, L105 (1975); M. A. Gordon and W. B. Burton, *ibid.* **208**, 346 (1976). For a presentation of the two-dimensional axisymmetric distribution of molecular clouds in the galaxy, see: D. B. Sanders, thesis, State University of New York, Stony Brook (1982); ———, P. M. Solomon, N. Z. Scoville, *Astrophys. J.*, in press.
15. P. M. Solomon, D. B. Sanders, N. Z. Scoville, in *The Large Scale Characteristics of the Galaxy*, W. B. Burton, Ed. (Reidel, Dordrecht, Netherlands, 1979), p. 35; A. A. Stark, thesis, Princeton University (1980).
16. S. Drapatz and K. W. Michel, *Astron. Astrophys.* **36**, 211 (1974).
17. M. Kutner, K. D. Tucker, G. C. Chin, P. Thaddeus, *Astrophy. J.* **215**, 521 (1977); L. Blitz, in *Giant Molecular Clouds in the Galaxy*, P. M. Solomon and M. G. Edmunds, Eds. (Pergamon, New York, 1980), p. 1.
18. H. S. Liszt, D. L. Xiang, W. B. Burton, *Astrophys. J.* **249**, 532 (1981).
19. R. S. Cohen, H. I. Cong, T. M. Dame, P. Thaddeus, *ibid.* **239**, L53 (1980); P. Thaddeus, in *Molecules in Interstellar Space*, A. Carrington, Ed. (Royal Society, London, 1981), p. 3.
20. P. M. Solomon, in *Molecules in Interstellar Space*, A. Carrington, Ed. (Royal Society, London, 1981), p. 16; D. B. Sanders, N. Z. Scoville, P. M. Solomon, *Astrophys. J.*, in press; D. B. Sanders, P. M. Solomon, N. Z. Scoville, D. B. Clemens, IAU Symposium 106, *The Milky Way Galaxy*, H. Van Wouden, Ed. (Reidel, Dordrecht, Netherlands, 1984), for Fig. 2.
21. W. Watson, *Rev. Mod. Phys.* **48**, 513 (1976); E. Herbst, in (*41*), p. 88. Theoretical interstellar ion-molecule chemistry was first introduced by E. Herbst and W. Klemperer, *Astrophys. J.* **185**, 505 (1973).
22. F. Hoyle, M. C. Wickramasinghe, A. H. Olanesen, S. Al-Mafti, D. T. Wickramasinghe, *Astrophys. Space Sci.* **83**, 405 (1982).
23. P. Goldreich and J. Kwan, *Astrophys. J.* **189**, 441 (1974); N. Z. Scoville and P. M. Solomon, *ibid.* **187**, L67 (1974).
24. B. Zuckerman and P. Palmer, *Annu. Rev. Astron. Astrophys.* **12**, 279 (1974); N. Z. Scoville and P. M. Solomon, *Astrophys. J.* **199**, 105 (1975).
25. R. Genzel and D. Downes, in *Regions of Recent Star Formation*, R. S. Roger and P. E. Dewdney, Eds. (Reidel, Dordrecht, Netherlands, 1982), p. 251.
26. K. M. Strom and S. E. Strom, *Science* **216**, 571 (1982), and references therein.
27. A comprehensive reference regarding regions of star formation within molecular clouds is *Proceedings, International Astronomical Union Symposium 92, Infrared Astronomy*, C. G. Wynn-Williams and D. P. Cruileshauk, Eds. (Reidel, Dordrecht, Netherlands, 1981).
28. W. Herbst and G. E. Assousa, in (*41*), p. 368.
29. B. G. Elmegreen and C. J. Lada, *Astrophys. J.* **214**, 725 (1977).
30. J. Smith, *ibid.* **238**, 842 (1980).
31. F. H. Shu *et al.*, *ibid.* **173**, 557 (1972); P. R. Woodward, *ibid.* **207**, 484 (1976).
32. N. J. Evans II, in (*27*), p. 107, and references therein.
33. A. Harris, C. H. Townes, D. N. Matsakis, P. Palmer, *Astrophys. J.* **265**, L63 (1983).
34. C. G. Wynn-Williams [*Annu. Rev. Astron. Astrophys.* **20**, 587 (1982)] has reviewed the properties of objects embedded in molecular cloud cores.
35. G. G. Fazio, in *Infrared Astronomy*, G. Setti and G. G. Fazio, Eds. (Reidel, Dordrecht, Netherlands, 1978), p. 25.
36. A. Whitworth, *Mon. Not. R. Astron. Soc.* **186**, 59 (1979); T. J. Mazurek and G. E. Brown, *Astron. Astrophys.* **81**, 382 (1980).
37. G. L. Grasdalen, R. D. Gehrz, J. A. Hackwell, in (*27*), p. 179; N. Z. Scoville, in (*27*), p. 187.
38. R. D. Gehrz *et al.*, *Astrophys. J.* **254**, 550 (1982).
39. P. Cassen and A. Summers, *Icarus*, in press.
40. H. Hippelein and G. Munch, *Astron. Astrophys.* **99**, 248 (1981).
41. A general review of protostellar processes is contained in *Protostars and Planets*, T. Gehrels, Ed. (Univ. of Arizona Press, Tucson, 1978).
42. J. Nittmann, in (*25*), p. 123.
43. E. H. Scott and D. C. Black, *Astrophys. J.* **239**, 166 (1980); D. C. Black and E. H. Scott, *ibid.* **263**, 686 (1982).
44. A. G. W. Cameron and J. W. Truran, *Icarus* **30**, 447 (1977).
45. D. C. Black and P. Bodenheimer, *Astrophys. J.* **206**, 138 (1976).
46. F. C. Gillett, personal communication; H. H. Aumann, F. C. Gillett, C. A. Beichman, T. de Jong, J. R. Houck, F. Low, G. Neugebauer, R. G. Walker, P. Wesselius, IRAS preprint (1984).
47. D. C. Black, *Astron. J.* **87**, 1333 (1982).
48. ———, *Space Sci. Rev.* **25**, 35 (1980).
49. N. Scoville, R. P. Schloerb, P. Goldsmith, personal communication.
50. Optical photograph by G. Herbig; 10-μm contours from R. D. Gehrz, J. A. Hackwell, J. R. Smith, *Astrophys. J.* **202**, L33 (1976).
51. Infrared data from R. D. Gehrz, G. L. Grasdalen, J. A. Hackwell, unpublished data; H_2 contours from S. Beckwith, S. E. Persson, G. Neugebauer, E. E. Becklin, *Astrophys. J.* **223**, 464 (1978).
52. R. D. Gehrz, G. L. Grasdalen, J. A. Hackwell, unpublished data.
53. D. B. Sanders, N. Z. Scoville, P. M. Solomon, D. Clemens, *Astrophys. J.*, in press.

54. Publication costs for colored images in this article were supported in part by NSF grants to the University of Wyoming and contracts at Stony Brook. This article summarizes only a limited aspect of the great promise and excitement of galactic research in the years to come. We owe a great debt to our fellow members of the Galactic Astronomy Working Group, who contributed in many ways to the material discussed here. They were W. B. Burton, D. F. Carbon, J. G. Cohen, P. DeMarque, F. K. Lamb, B. Margon, S. Van Den Bergh, and P. O. Vandervoort. Consultants to the working group were R. McCray, C. F. McKee, and L. Searle.