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PROCESSES IN COLLAPSING INTERSTELLAR CLOUDS

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Richard B. Larson
Yale University Observatory, New Haven, Connecticut

1. INTRODUCTION

The study of dense interstellar clouds that collapse gravitationally to form stars is still an embryonic field of astrophysics, but one that seems likely to play an increasingly important role in improving our understanding of many of the properties of stars and stellar systems. As our understanding of various astronomical objects and systems has increased, it has become more and more apparent that some of their most fundamental properties can be explained only through an understanding of the way in which they were formed. For example, the masses of the stars and the frequent occurrence of binary and multiple systems clearly depend on the details of the star formation process. In addition, the structure and evolution of star clusters and galaxies depend to a large extent on the details of the collapse and star-formation processes by which they were formed. Even such phenomena as spiral structure and nuclear activity in galaxies probably cannot be completely understood without reference to collapse and star-formation processes, since for both types of phenomena most of the observed energy output probably comes from very young objects which have recently been formed by the collapse of dense gas clouds.

Recent years have seen substantial progress in the development of theoretical models for collapsing clouds, and at the same time the study of collapsing clouds and protostars has become a subject of active observational interest. Infrared and microwave techniques have provided new tools for studying the physical conditions inside the dense dark clouds in which star formation is thought to be going on, and have led to the discovery of a number of infrared and molecular line sources which appear to be associated with collapsing clouds or protostars. While the theoretical models are of necessity still quite idealized, the resemblance between them and some of the observed objects thought to be collapsing clouds or protostars is sufficient to encourage a belief that at least some of the basic qualitative characteristics of collapsing clouds can be understood on the basis of present theoretical concepts and models. In the present article we attempt to provide a brief summary of our current understanding of the processes occurring in collapsing interstellar clouds, but not to give an exhaustive or completely impartial account of all the work that has been done in this rapidly developing field.

2. THE FORMATION OF DENSE CLOUDS AND THE ONSET OF GRAVITATIONAL COLLAPSE

If interstellar matter is to condense into stars, it must first be compressed into clouds massive and dense enough to be gravitationally bound. Such clouds are in fact observed, since many of the dense dark clouds observed around the Milky Way appear to be gravitationally bound (Heiles 1971), and many of them may even be collapsing gravitationally. The origin of these dense clouds is, however, not yet completely understood, although a number of mechanisms for producing dense interstellar clouds have been proposed, and at least some of them seem likely to play a role. It has been shown, for example, that a medium that is partially supported by a magnetic field is susceptible to a Rayleigh-Taylor-like instability which tends to concentrate the gas into large condensations or clouds (Parker 1966). It has also been shown that in the presence of heating by cosmic rays or X-rays, the interstellar medium can become thermally unstable and separate into a dense cool phase, identified with interstellar clouds, and a hot tenuous intercloud medium (Field 1970b). Both these mechanisms may play a role in forming clouds or in maintaining their existence once they have formed.

If a cloud is to collapse gravitationally, its mass, density, and temperature must satisfy the Jeans criterion, which requires in essence that the gravitational binding energy of the cloud must exceed the thermal kinetic energy (plus the energy of rotation and magnetic fields, if present). For the temperatures and densities found in typical interstellar clouds (not the dense dark clouds referred to above), the Jeans criterion indicates that a cloud can collapse gravitationally only if its mass is of the order of $10^3\ M_\odot$ or larger. Since most interstellar clouds are less massive than this, only the most massive clouds can collapse to form stars; most clouds are not gravitationally bound and will not collapse unless their masses are somehow increased, or unless they are compressed to sufficiently high densities that they become gravitationally bound.

A possible mechanism whereby most of the matter in interstellar clouds might eventually condense into stars, originally suggested by Oort (1954) and developed into a quantitative model by Field & Saslaw (1965) and others, assumes that small clouds collide with each other and coalesce into larger clouds until a massive gravitationally bound cloud is formed, whereupon collapse and star formation occur. More recently, interest has centered on attempting to explain the fact that star formation occurs predominantly in spiral arms; this indicates that collapse and star-formation processes are somehow triggered by the large-scale dynamical phenomena responsible for galactic spiral structure. In the currently popular density-wave theory of spiral structure, it is predicted that a spiral density wave will be accompanied by a shock front in the interstellar medium, and the compression produced by such a shock front could be instrumental in causing interstellar clouds to collapse into stars. In the model of Shu et al (1972), the critical cloud mass required for gravitational collapse decreases from about 3000 $M_\odot$ between the spiral arms to only about 120 $M_\odot$ in the compressed region following the shock front; thus clouds with masses greater than $\sim$120 $M_\odot$ may be squeezed into collapse as they pass through a density-wave shock front.

Since an interstellar cloud can collapse gravitationally only if its mass exceeds about 10^3 $M_\odot$ (or at least $\sim$120 $M_\odot$ in the model of Shu et al 1972), it is clear that stars of ordinary mass cannot be formed by the direct collapse of interstellar clouds. If a protostar or condensation of normal stellar mass is to form and collapse to a star, the Jeans criterion indicates that it must have an initial density of at least 10^3 to 10^6 cm^{-3}, depending on its mass. These densities are several orders of magnitude higher than those of typical interstellar clouds, but they are attained in the interiors of clouds that have begun to collapse. It is therefore generally believed that star formation proceeds via the fragmentation of a massive collapsing cloud into smaller subcondensations or protostars as it collapses and the Jeans mass within it decreases. Some of the dense dark clouds in which star formation seems likely to occur do in fact appear to contain internal structures or subcondensations similar to what might be expected in a cloud that is collapsing and fragmenting into protostars; thus there seems to be little doubt that fragmentation does indeed occur in collapsing clouds and that it can lead to the formation of small collapsing "fragments" or protostars with a wide range of masses.

Since the dynamics of collapse and fragmentation processes is sensitive to the thermal behavior of the collapsing cloud, we briefly summarize the thermal properties of dense collapsing clouds before continuing to discuss the dynamics in more detail.

3. THERMAL PROPERTIES OF COLLAPSING CLOUDS

The thermal properties of interstellar clouds with densities up to about 10^2 atoms cm^{-3} have been reviewed by Field (1970b). At these relatively low densities, an interstellar cloud is optically thin to cosmic rays and electromagnetic radiation, and its temperature is thought to be determined by a balance between heating by cosmic rays or X-rays and cooling by a variety of atomic and molecular processes, the most important of which involves inelastic collisions of hydrogen atoms or molecules with C^+ ions. The calculated equilibrium temperature decreases with increasing density, and at a density of 10^2 cm^{-3} it may have a value between about 20°K and 60°K, depending on the abundances of the coolants (principally C^+). At the higher densities attained after the cloud has begun to collapse, the cloud becomes opaque to cosmic rays and to visual and ultraviolet radiation, and different heating and cooling mechanisms become important. The temperatures of dense collapsing clouds have been estimated by several authors, including Hattori et al (1969) and Larson (1973c); here we briefly summarize the results of the latter treatment.

As the density of a collapsing cloud rises above 10^2 cm^{-3}, its temperature continues to fall, owing principally to the increased efficiency of cooling by C^+ ions. At densities greater than about 10^3 cm^{-3}, depending on the mass of the cloud, the cloud becomes opaque to cosmic rays and to the stellar ultraviolet radiation which produces the C^+ ions, and both cosmic-ray heating and C^+ cooling become relatively unimportant. For a cloud collapsing approximately in free fall, the most important heating process then becomes compressional heating, and cooling is produced mainly by inelastic collisions of gas molecules with dust grains, which radiate the energy thermally at infrared wavelengths. The resulting temperature continues to drop with increasing density, reaching ~10°K at a density of about 2×10^4 cm^{-3} and ~5°K at a density of the order of 10^6 cm^{-3}. Thereafter the temperature slowly rises again until it reaches ~12°K at a density of about 10^{11} cm^{-3}, at which point the central densest part of the cloud becomes opaque to the infrared radiation emitted by the dust grains. The relatively weak dependence of temperature on density throughout this density range results from the fact that at densities above about 10^5 cm^{-3} the gas temperature becomes closely coupled to the dust temperature, and since the rate of thermal emission from the dust grains depends on a high power of the grain temperature ($\sim T^7$), the temperature is relatively insensitive to the collapse rate or the physical properties of the dust grains.

If the temperature is known as a function of density, the Jeans mass can also be calculated as a function of density. It is found (Larson 1973c) that the Jeans mass is approximately 30 $M_\odot$ at a density of 10^3 cm^{-3}, 4 $M_\odot$ at a density of 10^4 cm^{-3}, 0.5 $M_\odot$ at a density of 10^5 cm^{-3}, and 0.1 $M_\odot$ at a density of 10^6 cm^{-3}. Thus protostars of most masses will fragment out and begin to collapse on their own only at densities high enough that the temperature has already reached a value of ~10°K or less; since the temperature does not change greatly at higher densities, most protostars will therefore collapse roughly isothermally with a temperature of the order of 10°K from the time they are formed to the time the central part of the protostar becomes opaque at a density of $\sim 10^{11}$ cm^{-3}.

The predicted temperatures of dense collapsing clouds are approximately confirmed by radio observations of molecular lines in dense dark clouds (Heiles 1971). The temperatures inferred from these observations range from about 5°K to 20°K, a typical value being about 10°K, in good agreement with the predicted temperatures of collapsing clouds.

4. MAGNETIC FIELDS IN COLLAPSING CLOUDS

Because of the complexities involved, the possible role of magnetic fields in collapsing clouds remains one of the principal unsolved problems in the theory of star formation. In the presence of a frozen-in magnetic field, an interstellar cloud can collapse only if its mass exceeds a critical value proportional to B^3/ρ^2 (Spitzer 1968); however, this critical mass is of the same order as the Jeans mass for a cloud with no magnetic field, i.e. about 10^3 $M_\odot$ (Field 1970a), so that the presence of a magnetic field probably does not greatly affect the Jeans criterion or the onset of gravitational collapse. A frozen-in field may, however, tend to inhibit the fragmentation of a collapsing cloud into smaller and smaller subcondensations as it collapses, although fragmentation can still occur if the collapse is anisotropic, as is probably the case (Spitzer 1968). A better understanding of the effect of magnetic fields on the dynamics of the collapse awaits the performance of detailed numerical calculations, which are not yet available.

It is thought that an initial magnetic field will remain locked into a collapsing cloud during the early stages of its collapse, owing to the ionization produced by high-energy cosmic rays that continue to penetrate the cloud even after the normally more important low-energy cosmic rays have been screened out. However, at densities higher than about 10^9 cm^{-3} even the high-energy cosmic rays are screened out, and the degree of ionization drops to an extremely low value, allowing the magnetic field to decouple from the cloud (Nakano & Tademaru 1972). Thus at densities above about 10^9 cm^{-3}, collapse and fragmentation can proceed freely, uninhibited by magnetic fields, whatever may be the effects of magnetic fields at lower densities.

Observations of magnetic-field strengths in interstellar clouds are for the most part consistent with the hypothesis that the field is frozen into the gas and that the field strength varies as $\rho^{2/3}$, as expected for isotropic compression (Verschuur 1970, 1971). However, some dense clouds have magnetic fields that are much weaker than would be expected on this basis, so that in these clouds the field has apparently decoupled from the gas earlier than expected; possibly this could result from enhanced screening of cosmic rays by inhomogeneities in the magnetic field, as suggested by Nakano & Tademaru (1972). In such clouds the magnetic field may not play a very important role in the collapse. It is perhaps noteworthy that in the dense Taurus dust cloud, a region of active star formation, no magnetic field has yet been detected (Verschuur 1971).

5. DYNAMICS OF THE EARLY STAGES OF THE COLLAPSE

Many authors have made numerical calculations of the dynamics of collapsing clouds, adopting a wide variety of different assumptions, and the configurations studied have ranged from very massive clouds with masses of 5×10^5 $M_\odot$ and mean densities of $\sim$15 cm^{-3} (Disney et al 1969) to tiny dense objects of mass 0.05 $M_\odot$ and mean density $\sim2\times10^{13}$ cm^{-3} (Narita et al 1970). In order to keep the calculations tractable, most authors have assumed that the collapsing cloud is spherically symmetric, nonrotating, and nonmagnetic. Much interest has centered on studying the collapse of individual protostars, and the early collapse of protostars of various masses has been calculated, under varying assumptions, by Penston (1966, 1969b), Bodenheimer & Sweigart (1968), Larson (1969a, 1972b), and Appenzeller (1972). These investigations have generally assumed that protostars are formed by the gravitational collapse and fragmentation of interstellar clouds and that the initial conditions are therefore given roughly by the Jeans criterion, although large deviations from the Jeans criterion have also been experimented with. A somewhat different point of view has been adopted in the collapse calculations of Hunter (1969) and of Stein et al (1972), who have shown that under some circumstances the formation of dense protostars from diffuse interstellar material can occur as a result of thermal instabilities in the interstellar medium rather than through purely gravitational collapse and fragmentation processes.

Despite the great differences in the assumptions adopted by various authors, the results of the different collapse calculations are qualitatively strikingly similar. In all cases, the central part of the cloud collapses most rapidly and there is a runaway increase in the central density, so that the density distribution becomes more and more sharply peaked at the center. As the collapse progresses, the rapidly collapsing dense central core of the cloud shrinks to contain a smaller and smaller fraction of the total mass; most of the mass of the cloud is left behind in an extended, more slowly collapsing envelope whose size is still comparable with that of the initial cloud. This highly nonhomologous behavior of the collapse has been found in all of the collapse calculations performed to date, and it appears to be a fundamental property of collapse under gravity.

The reason for the runaway growth of a central density peak is readily understood if the density distribution is centrally peaked to begin with. Since the time scale for gravitational collapse is always approximately equal to the free fall time $t_f = (3\pi/32\ G\rho)^{1/2}$, the collapse proceeds most rapidly where the density is already highest, i.e. at the center of the cloud; consequently the central peaking of the density distribution is enhanced as the cloud collapses. Even if the cloud is initially of uniform density, the density must still fall off at the boundary of the cloud (presumably this is what defines the boundary), and this density gradient will propagate inward as a rarefaction wave at the speed of sound. If the initial state approximately satisfies the Jeans criterion, the rarefaction wave reaches the center of the cloud at an early stage in the collapse; the density then decreases monotonically outward from the center, and the collapse thereafter proceeds nonhomologously as before.

Considerable attention has been paid to the case of an isothermally collapsing cloud, and several investigations have established that in the isothermal case the density distribution approaches the form $\rho \propto r^{-2}$ throughout the cloud. In fact, the density and velocity distributions are approximately described by an asymptotic similarity solution given by Penston (1969a) and Larson (1969a), in which the density and velocity distributions remain unchanged in form except for scale factors which vary with time. The asymptotic similarity solution predicts a density distribution of the form $\rho \propto r^{-2}$, as observed, and predicts in addition that the collapse velocity approaches an asymptotic maximum of 3.3 times the isothermal sound speed, and that the ratio of pressure to gravity forces at the center approaches a value of 0.60; thus the collapse is significantly decelerated from a free fall.

Some preliminary calculations of the collapse of a nonspherical, axisymmetric cloud have been made by Larson (1972a). These calculations have been done only for the case of an isothermal cloud with a fixed spherical boundary, but the principal qualitative results are probably not greatly altered by these restrictions. The results of these calculations suggest that in most cases, both for flattened (oblate) and elongated (prolate) density distributions, moderate initial deviations from spherical symmetry are not amplified during the collapse, contrary to previous results for the pressure-free case (Lin et al 1965); instead, pressure forces, if important initially, tend to maintain rough spherical symmetry throughout the collapse, and the results are very similar to those for the spherical case. This result is important for our understanding of fragmentation, since it suggests that, in the absence of rotation, fragmentation will usually not occur in an isothermally collapsing cloud whose initial state is roughly spherical and approximately satisfies the Jeans criterion; instead, most of the mass may condense into a single central object. The principal exception to this type of behavior is found to occur in the case of an elongated cloud whose mass per unit length exceeds the value corresponding to an equilibrium isothermal cylinder; in this case the cloud collapses toward a thin filament, but at the same time it fragments into several smaller condensations along its length. This result suggests that if a cloud does not collapse roughly spherically, the most likely alternative is for it to collapse toward an elongated or filamentary shape and fragment into a number of smaller condensations along its length. This may explain some of the dark clouds in Taurus and elsewhere that have a filamentary structure and contain a number of dense condensations or "lumps" strung out along their length.

6. EFFECTS OF ROTATION

It has long been realized that a typical collapsing protostellar cloud will almost certainly contain far more angular momentum than can be put into a single star; thus, if angular momentum is conserved during the collapse, its effects must become important long before stellar conditions are reached. It has often been suggested that magnetic braking torques may be able to remove most of the angular momentum from a collapsing cloud; however, the time scale for magnetic transport of angular momentum is probably considerably longer than the free-fall time of the cloud (Spitzer 1968), so that angular momentum should be approximately conserved during the free-fall time. Some preliminary calculations of the collapse of an axisymmetric rotating cloud in which angular momentum is conserved have been carried out by Larson (1972a); although these calculations are fairly crude and refer only to the special case of an initially uniform and uniformly rotating cloud, they suggest some important conclusions which may be of more general validity.

As might be expected, the Jeans criterion is found to be somewhat modified by the presence of rotation: a rotating cloud must be compressed to a higher initial density than a nonrotating cloud before gravity can overcome the combined effects of pressure and centrifugal forces and cause the cloud to collapse. Once the collapse begins, however, it proceeds initially in the same nonhomologous fashion as for a nonrotating cloud, and the density distribution again becomes centrally peaked. Infall of material takes place preferentially along the axis of rotation, where the collapse is least inhibited by centrifugal forces, and this causes the central density to rise by a substantial factor before centrifugal forces halt further collapse. Because of the rapid nonhomologous increase in central concentration, centrifugal forces become sufficient to halt the collapse first at the center of the cloud; meanwhile, the material in the outer part of the cloud continues to fall inward and accumulate in a ring-shaped region around the periphery of the central region which has stopped collapsing. In the calculations of Larson (1972a) this leads to the appearance of a ring-shaped region of maximum density somewhat removed from the center of the cloud. However, the formation of such a "ring" is probably not a very realistic result, since the stability criterion of Ostriker & Bodenheimer (1973) for rotating fluid configurations suggests that the inner part of the collapsing cloud will probably become unstable to nonaxisymmetric deformations and fragmentation before a ring is formed; therefore, it seems likely that in many cases the outcome of the collapse of a rotating cloud will be the fragmentation of the cloud into two or more smaller condensations orbiting around each other.

Consequently, while many of the details remain to be clarified, it is appealing to conjecture that a common result of the collapse of a rotating protostellar cloud will be the formation of a binary or multiple system of stars orbiting around each other. If this conjecture (which remains to be verified by detailed three-dimensional calculations) is correct, much of the angular momentum of the initial cloud could go into the orbital motions of the stars formed, and the angular momentum of the cloud would then not pose such a serious problem for star formation as was once believed. In addition, we would obtain an attractive explanation for the fact that most of the stars in the sky are in fact located in binary or multiple systems. Even the single stars might be accounted for as a result of the disintegration of small multiple systems, since such systems are generally very unstable and eject single stars until only a stable binary is left (Standish 1972). Clearly, much theoretical work remains to be done to clarify the final outcome of the collapse of a rotating cloud.

In view of the fact that fragmentation seems less likely to occur in a cloud with no rotation or internal turbulent motions, it appears that the presence of rotation or internal motions in a collapsing cloud is an important factor in determining whether the cloud fragments into smaller condensations as it collapses. The importance of internal motions for fragmentation has also been suggested by Arny (1971). We note that if a rotating cloud fragments into two or more condensations orbiting around each other, the orbital motions of these condensations will keep them separated and prevent them from merging again, as might happen in a nonrotating cloud; this would remove the objection to fragmentation raised by Layzer (1963), who argued that any subcondensations would merge and be obliterated in the continuing overall collapse of the cloud.

7. FRAGMENTATION AND THE STELLAR MASS SPECTRUM

In studies of the structure and evolution of stellar systems, an important role is played by the mass spectrum with which the stars are formed; thus it is of great astrophysical interest to understand how the stellar mass spectrum is produced. It is also important to understand why the stellar mass spectrum appears to differ between different stellar systems; for example, open clusters appear to have fewer low-mass stars than the general field (van den Bergh & Sher 1960). Clearly, the stellar mass spectrum must depend on the complex dynamical processes involved in the fragmentation of collapsing interstellar clouds, but unfortunately our quantitative understanding of these processes is still far from adequate to predict the resulting mass spectrum with any confidence.

Notwithstanding this ignorance, an attempt has been made by Larson (1973b) to predict the stellar mass spectrum on the basis of a simple stochastic model of the fragmentation process in which it is assumed that successive stages of fragmentation can be treated as independent random events. This model predicts a mass spectrum such that the fraction of the total mass per unit logarithmic mass interval is given by a Gaussian function, in approximate agreement with empirical data for the initial mass spectrum in the solar vicinity. The model contains two principal parameters: the mass M of the initial collapsing cloud, which is presumably approximately equal to the Jeans mass, and the probability p of fragmentation during each stage of the collapse. These parameters need not be the same in different circumstances, and variations in these parameters might plausibly account for the apparent differences in the initial mass spectrum between different stellar systems.

8. THE EVOLUTION OF PROTOSTARS

At present, calculations for the evolution of collapsing protostars have been completed only for the special case of spherically symmetric, nonrotating, and nonmagnetic protostars. However, it appears likely that most of the basic qualitative features found in the spherical calculations will also be found in more general circumstances, so it is worthwhile to review the results for the spherical case. The calculations have so far been completed by Larson (1969a,b, 1972b) and, with quite different assumptions, by Narita et al (1970). Here we summarize briefly the results of these calculations; a more complete discussion of the evolution of protostars has been given by Larson (1973c).

After a protostar begins to collapse from an initial state determined approximately by the Jeans criterion, its central concentration increases steadily in the way described in Section 5 until the central density reaches a value of the order of 10^{11} cm^{-3}, at which point the central dense core of the cloud becomes opaque to the thermal infrared radiation from the dust grains. The thermal energy generated by the collapse is then no longer freely radiated away, and the central temperature begins to rise substantially above its initial value of $\sim$10°K. The resulting increase in pressure begins to decelerate and eventually halt the collapse of the opaque core of the cloud, causing it to approach hydrostatic equilibrium. Meanwhile the outer part of the cloud continues to fall inward almost in free fall, and a shock front is formed at the boundary of the hydrostatic core where the infalling material is suddenly stopped. When the core first forms it has a mass of about 5×10^{-3} $M_\odot$ and a radius of about 4 a.u.; its central density and temperature are about 2×10^{-10} g cm^{-3} and 200°K respectively. These results are only weakly dependent on the total mass of the protostar.

As the hydrostatic core grows in mass by accreting more material, its central density and temperature rise rapidly and nearly adiabatically until the temperature reaches about 2000°K, at which point hydrogen molecules begin to dissociate. This reduces the ratio of specific heats γ below the critical value 4/3 and causes a second phase of dynamical collapse to begin at the center of the core. Once again the density distribution in the small collapsing region becomes strongly centrally peaked, and the collapse continues until the hydrogen at the center is nearly all in atomic form. A second hydrostatic core is then formed, with an initial mass of about 10^{-3} $M_\odot$ and a radius of about 1 $R_\odot$; its central density and temperature are about 2×10^{-2} g cm^{-3} and 2×10^{4}°K, respectively. The second core, like the first, is bounded by a shock front in which the infalling material is suddenly stopped. Soon after the formation of this second "stellar" core all the material of the first core has fallen into it, so that the first core is quite short-lived and probably not of any interest observationally.

The stellar core grows steadily in mass as the rest of the protostellar cloud falls into it, and this accretion process continues until all the protostellar material has fallen into the core or, if the core becomes sufficiently massive, until the envelope has been dissipated by radiation pressure or other effects. The remnant protostellar envelope then finally becomes optically thin, and the stellar core becomes visible as a pre-main sequence (or main sequence) star. The duration of the infall process and the time scale for the disappearance of the remnant protostellar envelope are comparable with the free-fall time for the initial cloud, which is of the order of 10^5 to 10^6 years if the initial conditions approximately satisfy the Jeans criterion.

After a stellar core or "embryo star" has formed at the center of a collapsing protostar, the protostar begins to emit a substantial amount of infrared radiation. For a protostar with mass $\lesssim 2$ $M_\odot$, the luminosity emitted comes almost entirely from the kinetic energy of the material falling into the shock front at the surface of the core; this kinetic energy is converted into thermal energy in the shock front, and the thermal energy is then mostly radiated away from the hot region just inside the shock front. Since the temperature inside the shock front is of the order of several thousand degrees or higher, the energy is first emitted at visual and ultraviolet wavelengths; this radiation is then absorbed by the dust grains in the opaque infalling envelope and is re-emitted thermally at infrared wavelengths. The luminosity from the shock front heats the infalling cloud to temperatures much higher than the initial temperature of $\sim$10°K, and a temperature distribution roughly of the form $T \propto r^{-1/2}$ is set up, with T varying from several thousand degrees near the surface of the core to only about 10°K at the outer boundary of the cloud. At the point in the cloud where the infrared optical depth is unity, the temperature is typically of the order of several hundred degrees

K, so that a collapsing protostar will typically appear as an infrared object with an apparent temperature of some hundreds of degrees K.

The density distribution in the collapsing envelope, initially of the form $\rho \propto r^{-2}$, later assumes the form $\rho = \rho_0 r^{-3/2}$ in the inner part of the envelope and eventually throughout the whole envelope. The constant ρ_0 is typically about 10^{29} to 10^{30} cm$^{-3/2}$, so that the density in the infalling cloud ranges from values of the order of 10^{11} to 10^{13} cm^{-3} near the stellar core to values of the order of 10^2 to 10^4 cm^{-3} near the outer boundary of the cloud.

As the stellar core grows in mass, the velocity and the kinetic energy of the material falling into it increase steadily, causing the luminosity of the protostar to increase with time. For protostars with masses $\lesssim 2\ M_\odot$, the luminosity reaches a maximum when approximately half the mass has fallen into the core; the kinetic energy influx to the shock front then begins to decrease, owing to the decreasing density of the infalling matter. The maximum luminosity is roughly proportional to the protostellar mass, and is about 30 $L_\odot$ for a protostar of one solar mass. The apparent temperature of the protostar is of the order of 300°K at this time, and it steadily increases with time as the surface of optical depth unity in the infalling cloud recedes inward to smaller radii and higher temperatures. Eventually the mass of the infalling envelope becomes very small and its optical depth drops below unity, so that the stellar core becomes visible from the outside; at about the same time, the kinetic energy influx to the shock front becomes small compared with the luminosity from the interior of the core, so that the core becomes essentially a normal pre-main sequence star. For protostars with masses near 1 $M_\odot$ the resulting newborn star first appears near the lower end of its Hayashi track, with a radius near 2 $R_\odot$; this places it in the region of the H-R diagram occupied by typical T Tauri stars.

For more massive protostars with masses $\gtrsim 3\ M_\odot$, the evolution is qualitatively different from that of less massive protostars, because for a more massive stellar core the time scale for radiative cooling and contraction of the core becomes shorter than the time scale for infall of the remaining protostellar material. As a result, the stellar core begins to contract toward the main sequence along a "radiative track" while still accreting material from an opaque protostellar envelope. For protostars with masses greater than approximately 5 $M_\odot$, the stellar core evolves all the way to the main sequence while still surrounded by its remnant protostellar envelope. Most of the luminosity emitted by a massive protostar comes from the interior of the stellar core, being produced either by pre-main sequence contraction of the core or by hydrogen burning in the core after it has become a main-sequence object; consequently, the luminosity does not pass through a maximum but continues to increase strongly as the core mass increases. In this way very large infrared luminosities can be attained, which cover the whole range of main-sequence stellar luminosities.

The results outlined above have been obtained on the assumption that the initial density of a collapsing protostar is determined approximately by the Jeans criterion; if, however, the initial density is for some reason much higher than is indicated by the Jeans criterion, the collapse time is reduced and the radius and luminosity of the resulting pre-main sequence star are increased. A (probably extreme) example of the results obtained when the initial conditions deviate drastically from the Jeans criterion is provided by the work of Narita et al (1970), who computed the collapse of protostars with initial densities of the order of 10^{-9} g cm^{-3}, some 10 orders of magnitude higher than that given by the Jeans criterion. In these calculations the collapse time is reduced by some 5 orders of magnitude to about 10 years, and the radius of the resulting newly formed star is about $10^2\ R_\odot$ and its luminosity is about $10^3\ L_\odot$. At present, the high initial density assumed in these calculations has not been justified on physical grounds, and it does not seem likely that these results are quantitatively very realistic; nevertheless, the results are qualitatively similar to those outlined above in that they show the same kind of strongly nonhomologous collapse leading to the formation of a stellar core that grows in mass by accretion of the remaining protostellar material.

9. OBSERVATIONS OF COLLAPSING CLOUDS AND PROTOSTARS

Many of the dense dark clouds observed around the Milky Way appear to be sufficiently cool ($\sim$10°K), dense ($\gtrsim 10^3$ cm^{-3}), and massive ($\gtrsim 100\ M_\odot$) to be gravitationally bound (Heiles 1971), and some of them are probably already collapsing gravitationally. The likelihood that some of these clouds are collapsing is supported by the fact that their internal velocity dispersions are typically of the order of 0.5 to 1.0 km s^{-1} (Heiles 1971), comparable with the velocities expected from theoretical collapse calculations. Also, some of the dark clouds have a noticeably centrally condensed or clumpy internal structure, as would be expected for clouds that are collapsing and fragmenting gravitationally. The Southern Coalsack and the dark cloud near ρ Ophiuchi are examples of massive dense clouds containing internal inhomogeneities or condensations, and it seems likely that they are destined to collapse into clusters of stars (Bok et al 1971). Further studies of such clouds with good resolution at both optical and radio wavelengths would be of great value in improving our understanding of how interstellar clouds collapse and fragment into stars.

The dark globules described by Bok et al (1971) have often been thought to be protostars, and while the interpretation of these objects remains a matter of debate, the possibility that at least some of them may be protostars is supported by comparison with theoretical protostar models. The range of masses of the globules coincides approximately with the range of stellar masses, and the sizes and densities of the globules are close to the values predicted by the Jeans criterion for clouds about to collapse gravitationally (Larson 1973c). Some of the dark globules are noticeably centrally condensed, which suggests that they may already have begun to collapse. If the dark globules or the apparently similar dense condensations in larger clouds are indeed protostars, then those that appear completely opaque at the center may already have developed stellar cores. Such objects might emit detectable infrared radiation and perhaps also microwave molecular line emission (Section 12); thus the identification of an infrared source with a dark condensation or globule would provide important confirmatory evidence for current ideas about star formation.

Since protostars emit most of their energy at infrared wavelengths, considerable effort has been devoted to searching for protostars using infrared techniques. While it is now apparent that most infrared sources are not protostars, there remain a number of infrared sources associated with HII regions that seem likely to be protostars (Neugebauer et al 1971). The best known such sources are located in the nearby Orion nebula, but similar sources are also found in association with other HII regions. The apparent association between protostars and HII regions is not unexpected, since the HII regions are very young systems containing recently formed stars and leftover interstellar gas; the densest parts of the gas probably do not become ionized immediately but survive as dense, cool, neutral condensations in the HII region, and it is probable that collapse and star formation continue to occur in these dense un-ionized regions.

The infrared sources detected up to now probably represent only the most luminous and therefore the most massive protostars. The best studied such infrared source is the Becklin–Neugebauer (1967) object in Orion; it has a bolometric luminosity of the order of $10^3\ L_\odot$, and can be interpreted as a protostar with a stellar core of mass $\sim 4\ M_\odot$, which may already have evolved almost to the main sequence (Larson 1972b). This object may be associated with the much more extended and luminous Kleinmann–Low (1967) infrared nebula, which has a total luminosity of the order of $10^5\ L_\odot$ and a large mass of the order of $200\ M_\odot$ (Low 1971). The great luminosity of this infrared nebula can be supplied only by a massive star or group of stars embedded in it, and it seems very likely that these stars have just formed or are still forming by accretion in a dense collapsing cloud that still obscures them from view. The fact that many OH and H_2O maser sources are observed in the region of the infrared nebula (including some that are nearly coincident with the Becklin–Neugebauer object; Raimond & Eliasson 1967) suggests that this nebula may contain many collapsing condensations or protostars; if so, we could be observing here the formation of a new group or cluster of stars near the recently formed Trapezium cluster. If a new cluster of stars is presently forming in the infrared nebula, this region clearly merits further intensive study at both infrared and radio wavelengths because it provides what is probably the closest interstellar "laboratory" in which the processes of collapse and star formation can be observed in progress.

The fact that we observe in the Orion nebula (or behind it) a massive, dense, opaque cloud that is probably collapsing into stars suggests that the cloud that formed the Orion nebula fragmented at an early stage into two or more major condensations, one of which formed the Trapezium cluster and the other of which is still condensing into stars and is presently observed as the infrared nebula. A possible example of the same phenomenon at a later stage of development is provided by the two closely associated young clusters NGC 6530 and NGC 6523

(M8); star formation appears to be completed in the former cluster, whereas the latter still contains much gas (the "Lagoon nebula") which may still be condensing into new stars.

When the infalling envelope of a protostar is no longer completely opaque, the stellar core becomes visible as a pre-main sequence star or, if its mass exceeds roughly 5 $M_\odot$, as a star already on the main sequence. At first such a newborn star will still be surrounded by a dense, murky cloud of gas and dust which dominates its observed properties, but after a time of the order of 10^6 years this circumstellar cloud will disappear and a normal star will be seen. These predictions agree qualitatively quite well with the observed properties of the T Tauri stars and other similar very young objects, many of which show evidence for circumstellar material in varying amounts (Larson 1972b). In particular, Strom et al (1971, 1972a) have found evidence for circumstellar shells around some of the pre-main sequence stars in young clusters; the ages of these stars are of the order of 10^6 years, in agreement with the theoretical prediction that the lifetimes of the remnant circumstellar envelopes around newly formed stars are of the order of 10^6 years.

Since some T Tauri stars are observed to be ejecting material, it is not immediately clear whether the circumstellar material observed around many T Tauri stars is residual protostellar material or matter that has been ejected from the star (or both). However, for certain T Tauri-like stars (the "YY Ori" stars) there is spectroscopic evidence for infall of material at approximately the free-fall velocity (Walker 1972), as is expected from the theoretical collapse calculations; the observations are consistent with the interpretation of the YY Ori stars as extremely young objects still accreting the last remnants of their protostellar envelopes. If this interpretation is correct, these observations are of great importance because they provide the first direct observational evidence for the collapse and accretion processes by which stars form, according to the theoretical calculations. Again, it is clear that further observations of this nature would be of great value in adding to our understanding of star formation.

10. FORMATION OF PLANETARY SYSTEMS

Nearly everyone believes that the formation of our solar system was connected in some way with the formation of the Sun, but the nature of the formation process remains a matter of speculation and controversy. The model that has been developed in most detail (Cameron & Pine 1973) assumes that a rotating protostellar cloud collapses to a flat disc in centrifugal equilibrium, and proposes that the planets first form by accretion in this disc and that the sun subsequently forms through central condensation of the remaining material. However, a number of objections have been raised to this model: for example, it has been pointed out that the postulated disc is probably unstable to fragmentation (Ostriker 1973); furthermore, dynamical collapse calculations suggest that a rotating cloud probably will not collapse to a disc at all but will instead fragment into a binary or multiple system of stars (Larson 1972a).

Stability considerations suggest that if a flat pre-planetary disc is to form and remain stable long enough for planets to accrete in it, a sufficiently massive central condensation or "embryo sun" must already be present at the time of formation of the disc to stabilize the disc (Ostriker 1973). If such a central condensation or embryo sun forms first, a pre-planetary disc might then form in orbit around it through the accretion of leftover protostellar material that has too much angular momentum to fall directly into the central embryo sun (Larson 1973a). Such a picture would be consistent with our current understanding of gravitational collapse and fragmentation processes: since gravitational collapse always occurs in very nonhomologous fashion, it seems likely that in general star formation proceeds through the formation of a number of dense condensations or embryo stars in a collapsing cloud, surrounded at first by much leftover protostellar material swirling around them and gradually being accreted by them. The material captured by one of these embryo stars will in general have a significant angular momentum with respect to it, in which case the captured matter cannot all fall directly into the embryo star but some of it must form a disc or ring orbiting around it. Strom et al (1972b) have in fact found tentative evidence that some of the "shells" of remnant protostellar material around newly formed stars may be disc-shaped rather than more nearly spherical.

If this picture is correct, the formation of a pre-planetary disc may be a fairly common occurrence during the later stages of the star-formation process, at least in those favorable cases where a circumstellar disc is not disrupted by a close companion star in a multiple system. Some preliminary estimates of the amount of mass and angular momentum that such a pre-planetary disc might be expected to acquire yield a mass of the order of 0.1 $M_\odot$ and an angular momentum of the order of 10^{52} g cm^{-2} s^{-1} (Larson 1973a); while these numbers are very uncertain and probably quite variable in different cases, they are nevertheless encouragingly similar to the values commonly adopted for the "solar nebula" in which the planets are thought to have formed. The formation of such a pre-planetary disc by accretion in a collapsing protostellar cloud will almost certainly involve exceedingly complicated nonaxisymmetric dynamical processes, but at present there exist no adequate calculations or models describing these processes. [However, Dormand & Woolfson (1971) have made calculations for a somewhat similar model whereby protoplanetary material is captured into orbit around the sun from a passing protostar.]

11. FORMATION OF MASSIVE STARS AND HII REGIONS

Although collapse calculations have not yet been carried to completion for protostars more massive than 10 $M_\odot$, it is possible to discuss some of the processes likely to be important for the formation of massive stars. The early evolution of a massive protostar will be qualitatively similar to that of a less massive protostar, but once the stellar core attains a sufficiently large mass and luminosity, the luminosity of the core will begin to have important dynamical effects on the surrounding cloud of infalling material. There are at least four effects that can occur, all of them tending to inhibit the collapse of the outermost layers of the cloud (Larson & Starrfield 1971): (1) For core masses greater than about 10 $M_\odot$, radiative heating of the infalling cloud may raise the pressure to the point where the infall of the outermost layers of the cloud is significantly retarded or prevented. (2) For core masses greater than about 20 $M_\odot$, radiation pressure acting on the inner boundary of the dust-containing "shell" around the stellar core becomes comparable with the dynamical pressure of the infalling material in the shell; this may tend to disrupt the dust shell and impede further infall of material into the core. (3) For core masses greater than roughly 50 $M_\odot$ (with a large uncertainty), the pressure of infrared radiation acting on the outer layers of the collapsing cloud may become sufficient to blow away these outer layers and halt further infall of material. (4) Finally, if other effects do not intervene first, the stellar core in a massive collapsing protostar will become sufficiently massive and luminous to ionize the whole infalling cloud, thereby cutting off further infall of material and forming an HII region throughout the protostellar cloud. Depending on the initial conditions, ionization of the cloud will occur when the core mass reaches a value of the order of 30 to 60 $M_\odot$ (Larson & Starrfield 1971, Larson 1973c).

Clearly, all the above effects will tend to limit the mass the stellar core can attain before further growth in mass is cut off; i.e., they set an upper limit to the mass with which a star can be formed. The most decisive upper limit appears to be set by the ionization of the protostellar cloud; this leads to a maximum attainable stellar mass which under normal circumstances is of the order of 50 or 60 $M_\odot$ (corresponding to a spectral type of about O5 or O4), although this limit is sensitive to the initial conditions and could possibly be as high as 100 $M_\odot$ (Larson 1973c). Within the uncertainties, this theoretical estimate agrees with the observed upper limit of stellar masses, which appears to be of the order of 60 $M_\odot$. The upper mass limit is raised if the temperature of the collapsing cloud is higher than assumed, which could be the case if the abundances of the heavy elements are substantially lower than the typical Population I values; thus it is possible that some of the earliest Population II stars may have formed with masses considerably higher than the largest masses presently observed (Larson & Starrfield 1971).

Our present understanding of the formation of massive stars also explains the formation of HII regions as a natural byproduct. If a typical massive interstellar cloud with a mass of the order of 10^3 $M_\odot$ and a radius of the order of several parsecs begins to collapse gravitationally, its density distribution will become centrally peaked and stars will begin to form in the dense central region of the cloud; as soon as one or more sufficiently luminous O stars have formed, the whole cloud becomes rapidly ionized (except for any surviving dense condensations) and an HII region with a centrally condensed and roughly spherical structure is formed. The mean density of the resulting newly formed HII region will be of the order of 10^2 cm^{-3}, and the density will increase strongly toward the center following the approximate density law $\rho \propto r^{-2}$ or $\rho \propto r^{-3/2}$ established during the collapse of the cloud. These predictions for the structure of newly formed HII regions closely resemble the observed properties of the Orion nebula, which became ionized only about 10^4 years ago (Vandervoort 1964). The Orion nebula has not had much time to expand since becoming ionized, and therefore its present density distribution should still be similar to that established by the initial collapse process; thus the approximate agreement between the predicted and the observed structure of the Orion nebula provides an important confirmation of our present theoretical understanding of the behavior of collapsing clouds.

In addition to its centrally condensed and roughly spherical structure, the Orion nebula contains many inhomogeneities and condensations of various sizes. These condensations range from the very large and massive Kleinmann–Low infrared nebula to the smaller condensations of approximately stellar mass observed at radio wavelengths (Webster & Altenhoff 1970), as well as the bright condensations and wisps observed visually. The larger and denser of these condensations appear to be so dense that their interiors have been shielded from ionizing radiation and thus still contain cold neutral gas. The sizes and densities of these condensations appear to be roughly consistent with the values given by the Jeans criterion for protostars forming in a collapsing interstellar cloud; this suggests that the condensations were formed by gravitational fragmentation processes in the collapsing cloud which became the Orion nebula. Such condensations might continue to collapse into stars even after the rest of the nebula has become ionized; in fact, this appears to be what is happening in the Kleinmann–Low infrared nebula. If the condensations in the Orion nebula have indeed been formed by gravitational fragmentation in a collapsing cloud, further detailed observational studies of their structures would again contribute importantly to our understanding of fragmentation and star-formation processes.

12. MOLECULAR PROCESSES IN COLLAPSING CLOUDS

In the dense dark clouds where conditions are favorable for collapse and star formation, conditions are also favorable for the formation of many different types of molecules. Most of the molecule formation in dense clouds is thought to occur on the catalytic surfaces of dust grains: atoms of the gas collide with the dust grains and frequently remain adsorbed on the grain surfaces long enough to encounter and react with other adsorbed atoms to form molecules. See Aanestad and Purcell (this volume) for a review of this topic.

The rapidly growing body of observational data on molecules in dense clouds has been reviewed by Heiles (1971), Rank et al (1971), and Snyder (1972); see also Buhl (1973) and Solomon (1973). Observations of molecular emission and absorption lines in dark clouds have yielded valuable information on the composition and physical properties of these clouds and the further development of molecular line observations promises to provide a wealth of detailed information about the properties of dense collapsing clouds and protostars. However, the interpretation of the observations is often complicated by the fact that in many cases non-equilibrium processes are of dominant importance (Litvak 1973). This is particularly true of OH and H_2O maser emission sources, some of which appear to be associated with collapsing clouds or protostars, as is suggested by their association with HII regions and particularly with the infrared sources in HII regions.

While the mechanisms responsible for the population inversions and the strong maser action observed in the OH and H_2O maser emission sources are not yet completely understood, general considerations suggest that the OH emission comes from regions where the density of H_2 molecules is of the order of 10^6 molecules cm^{-3}, while the H_2O emission comes from smaller and denser regions where the density is of the order of 10^8 molecules cm^{-3}; these are approximately the highest densities at which population inversions and maser action are not quenched by collisions (Litvak 1973). At a density of 10^6 molecules cm^{-3} or higher, any cloud or condensation whose mass exceeds about 0.1 $M_\odot$ is unstable to gravitational collapse and is probably already collapsing; this suggests that the OH and H_2O sources associated with HII regions are located in collapsing protostars or protostellar envelopes. In addition, the large radial velocities and the rapid variability observed in these sources, particularly in the H_2O sources, suggest rapid motions such as would be expected in the inner part of a protostellar envelope where the velocities of collapse or orbital motion become quite large.

At present, the OH and H_2O maser emission apparently associated with protostars has not been completely explained by any theoretical models or calculations. Most theoretical discussions (e.g. Litvak 1973, de Jong 1973) envision that the maser amplification occurs in the outer envelope of a collapsing protostar or "cocoon star," but the source of the radiation being amplified and the mechanisms responsible for the population inversions are both uncertain, although there is no lack of possibilities. In the case of the H_2O sources, de Jong (1973) has shown that collisional excitation in the outer layers of a protostellar cloud can plausibly lead to maser action, although simple radial amplification of radiation from a hot stellar core does not seem to account for the observations. However, the large radial velocities of the H_2O maser sources suggest that the H_2O emission originates relatively close to the stellar core, rather than in the outer part of a protostellar envelope. Probably the interpretation of the observations will require more complicated models than have been considered up to now, possibly involving highly inhomogeneous and nonspherical (disc-like?) circumstellar clouds. In any case, it is to be hoped that it will eventually be possible to interpret the OH and H_2O observations in terms of the structure and physical properties of the source regions, since these observations could then potentially yield much information about the conditions existing in protostellar envelopes; such information would be important, for example, for improving our understanding of the conditions under which planetary systems are formed.

NOTE ADDED IN PROOF Gwinn et al (1973) have proposed that the OH maser emission from those OH sources (type I) that seem most likely to be associated with protostars may be produced by collisional dissociation of H_2O molecules sputtered from dust grains, which creates OH molecules in the required excited states. The density required by this mechanism ($\approx 10^8$ cm^{-3}) and the streaming velocity required to produce the sputtering are both found in protostellar envelopes, and this process is able to explain in some detail the observed properties of the type I OH maser sources, including their close association with H_2O sources.

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