Theoretical Aspects of Star Formation

Richard B. Larson

Yale Astronomy Department, Box 208101, New Haven, CT 06520-8101, U.S.A.

1. Introduction

Star formation is probably the most fundamental of all astrophysical processes: not only do the properties of stellar systems of all types depend on how their stars were formed, but the properties of the interstellar medium in galaxies are controlled to a large extent by various feedback effects of star formation. Thus there are many reasons why it is important to understand how stars form, and a comprehensive 'theory' of star formation that would be able to predict such things as the stellar initial mass function would be extremely useful. However, such a theory does not now exist, and it may be that a fully deductive theory capable of predicting everything that one would like to know about star formation from a few basic principles will never exist because the phenomena involved are just too numerous and too complex: star formation depends on many processes and many variables, all interrelated in complex ways that make the subject difficult to treat in a deterministic way in the tradition of classical physics. Analogies with meteorology or even with biological ecosystems may be more apt, and it has indeed been realized for many decades that star formation is just one of a cycle of processes whereby matter and energy are continually being exchanged between stars and the various parts of the interstellar medium. The feedback effects of star formation quickly destroy star forming clouds and recycle their matter back into the more diffuse phases of the ISM, thereby replenishing the diffuse ISM and largely determining its properties; a new cycle of star forming activity begins when gravity reassembles this dispersed matter back into new star-forming clouds, and the cycle is repeated many times during the evolution of a galaxy (Oort 1954; Larson 1988; Tenorio-Tagle & Bodenheimer 1988). Many processes participate in this cycle, each depending on the others, and there are many feedback effects that make star formation a strongly self-regulating process (Larson 1996).

Because of the complexity of the problem, and because of the great progress that has been made in recent years in observational studies of star formation, we now have a situation where the observations have far outstripped the ability of theory to explain what is being observed. Therefore, I believe that theoretical efforts to understand star formation will have to focus increasingly on the phenomenology of the subject and work toward building up an understanding of it bit by bit. In this overview of some of the theoretical ideas that may be relevant, I shall therefore place strong emphasis on observed phenomena and on efforts to understand various observational aspects of star formation, with particular attention to the properties of the Orion complex, the nearest region where stars with a large range of masses are currently forming.

2. Large-Scale Aspects: Formation of Large Cloud Complexes

For purposes of discussion, it will be convenient to consider the various processes of star formation in order of the scales on which they operate, proceeding from larger to smaller: on the largest scales, there are the processes that generate spiral structure and create large star-forming cloud complexes in galaxies; on intermediate scales, there are the many complex processes involved in the formation and evolution of individual molecular clouds; and on the smallest scales, there is the problem of understanding how the dense cores of these clouds eventually collapse to form stars or groups of stars.

The overall evolution of galaxies depends on the rate at which their interstellar gas is converted into stars, and this is correlated empirically with global galactic properties such as Hubble type. The star formation rate depends on the rate at which diffuse interstellar matter is collected into dense star-forming molecular clouds, and this process is probably driven mainly by the large scale self-gravity of the gas layer in a galaxy (Larson 1988, 1992b). It may also be assisted by a stellar density wave, if one is present, but the role of the density wave may mainly be one of determining where, rather than whether, star formation occurs. The most important controlling parameter is then the surface density μ of the gas layer, which together with the velocity dispersion c and the epicyclic frequency κ determines the value of the Toomre stability parameter $Q = c\kappa/\pi G\mu$. The gas layer is gravitationally unstable if $Q < 1$, and finite 'swing amplification' of shearing disturbances can occur for values of Q up to about 2 (Toomre 1981). Most spiral galaxies appear to be marginally stable by this criterion, and they have estimated values of Q that are typically between 1 and 2. If c and κ are given, a minimum gas surface density is required in order for Q to be small enough for these self-gravitational effects to be important, and the prediction that a threshold gas surface density is required for star formation to occur is supported by observations showing that conspicuous star formation activity is present only in those parts of galaxies where Q is less than about 2 (Kennicutt 1989), as would be expected if swing amplification were the effect primarily responsible for driving star formation.

In addition to the self-gravity of the galactic gas layer, feedback effects of star formation may sometimes contribute to the formation or restructuring of star-forming cloud complexes by creating large expanding shell structures in the ISM; in this way star formation may sometimes trigger further star formation (Elmegreen 1992). The Orion complex itself might belong to a large expanding shell or ring structure called the 'Lindblad Ring' or the 'Gould Belt System' that has been proposed to exist, centered on the extinct Cas-Tau association and containing in addition to the Orion complex several other prominent nearby regions of star formation (Blaauw 1991; Elmegreen 1992). If this expanding ring structure is real, the Orion complex could owe its existence to the sweeping up of interstellar matter by the effects of previous episodes of star formation centered in the Cas-Tau region. However, as Blaauw notes, the observed kinematics of the proposed expanding ring are complex and do not fit any simple expansion model. Another complication is that the Gould Belt is tilted with respect to the Galactic plane, and this property has no obvious explanation in terms of the effects of previous episodes of star formation (or, for that matter, the effects of the self-gravity of the ISM.) Possibly an external disturbance caused by an infalling high-velocity cloud has played a role (Franco et al. 1988). In any case, it is quite possible that several different phenomena have contributed to the origin of the Orion complex, and it is not clear that any one simple model can provide an adequate description of this process.

3. Intermediate-Scale Aspects: Evolution of Molecular Clouds

The formation and evolution of individual giant molecular clouds clearly involves many complex processes, and this is perhaps the most poorly understood aspect of star formation. Molecular clouds are highly irregular in their structure, and they have fractal-like shapes resembling those of many wispy terrestrial clouds; they also have supersonic internal 'turbulent' motions that are believed to consist partly of magnetohydrodynamic waves. The formation of these clouds is not presently well understood, but it probably involves the accumulation of more diffuse forms of interstellar matter into massive concentrations in large complexes, driven mostly by the large-scale self-gravity of the ISM as discussed above. The atomic component of the ISM from which the molecular clouds are probably mostly assembled is itself extremely complex and chaotic in its structure (Hartmann & Burton 1996), and the formation of massive molecular clouds from this highly nonuniform medium must therefore involve the agglomeration of many smaller clouds (Elmegreen 1993; Larson 1994). Much of the irregularity in the structure and internal motions of molecular clouds could result from such a chaotic and turbulent accumulation process. The ram pressure generated by this process will also produce a high pressure in molecular clouds, and this high pressure may play an important role in the small-scale aspects of star formation to be discussed further in Sections 4 and 5.

Star-forming molecular clouds are massive and dense enough to be significantly self-gravitating, and they contain even denser cores that are observed to be the sites of star formation. The early evolution of these clouds therefore presumably involves the gravitational contraction of subregions, accompanied by the dissipation of turbulent motions, to produce the observed dense star-forming cores. However, as soon as massive stars begin to form, stellar feedback effects clearly begin to play a major role in the subsequent evolution of large molecular clouds, and the Orion complex provides a striking example. The influence of the massive stars in the Orion OB association on the structure of the remaining molecular clouds is apparent in the frequently reproduced Figure 7 of Blaauw (1991), which shows the distribution of molecular gas in the Orion A and B clouds plotted together with the distribution of massive stars in the neighboring OB association; both clouds have a windblown appearance that strongly suggests that they are being ablated by energetic outflows from the OB association. The Orion A cloud, in particular, has an elongated comet-like shape with a long tail that points away from the center of the association. Even though star formation is continuing vigorously in both clouds, the dominant phenomenon presently occurring in this region is almost certainly the destruction of the Orion molecular clouds by ionization and energetic wind- and supernova-driven outflows from the OB association. This process has apparently already been going on for some time, and has produced features such as Barnard's Loop and a large partially evacuated cavity that contains many smaller comet-shaped clouds that also point away from the center of the OB association (Bally et al. 1991).

Similar phenomena are seen in other regions of star formation, such as the Ophiuchus-Scorpius-Centaurus region, where the smaller Ophiuchus molecular clouds also have filamentary or comet-like shapes that point away from the center of the adjacent Upper Scorpius OB association. In this case it is clear that these clouds are being shaped and ablated by interaction with a large expanding atomic hydrogen shell centered on the Upper Scorpius association (de Geus 1991; Blaauw 1991). The Orion clouds might represent a somewhat later stage of such a process after an expanding shell has mostly passed over them, and remnants of this shell might now be observable in features such as Barnard's Loop. More complicated phenomena can also occur; for example, multiple episodes of star formation can produce multiple shells, as is again clear from observations of the young stars and atomic gas in the Ophiuchus-Scorpius-Centaurus region (Blaauw 1991).

The most conspicuous recent star formation activity in the Orion complex has occurred in a string of compact clusters closely associated with a number of massive dense molecular clumps located along the edges of the Orion A and B clouds closest to the OB association. The fact that these massive clumps are located in the parts of the clouds closest to the OB association suggests that the formation of these clumps and of their associated compact clusters might have been triggered by external compression caused by the effects of previous massive star formation in the OB association. However, it is difficult to be certain that the star formation observed in these clumps has actually been triggered, rather than just uncovered by the sweeping away of surrounding gas, since the Orion clouds might have formed such dense clumps and star clusters anyway as a result of internal gravitational contraction without the need for any external triggering mechanism. Perhaps both types of processes have played a role, and even though stars might have continued to form anyway in the Orion clouds, external disturbances have influenced the way in which this has occurred; external compression may have helped to produce the exceptionally high gas densities observed in the cluster-forming clumps, and this may have favored the efficient formation of compact clusters of stars in them, perhaps as the culmination of star formation activity in the region (Larson 1993).

While the internal evolution of molecular clouds remains poorly understood theoretically, it is an observed fact that these clouds are extremely ragged and filamentary in their structure, even on very small scales, and this is well illustrated by the detailed CO maps of the Orion A cloud of Bally et al. (1987, 1991). It is obvious from their highly irregular structure that most molecular clouds cannot be in anything like an equilibrium configuration, and this invalidates many theoretical models that begin with this assumption. The small-scale filamentary structure of molecular clouds does however seem to play an important role in star formation, since most star formation is observed to occur in clumpy filaments. For example, most of the T Tauri stars scattered along the length of the Orion A cloud (Larson 1982, Figure 4) are closely associated with filamentary features seen in the CO map of Bally et al. (1987). The largest concentration of young stars in Orion is centered on the Trapezium cluster located in the dense 'head' region of the cometary Orion A cloud, and much small-scale filamentary structure is seen in this region (e.g., Wiseman & Ho 1996). The most prominent feature is the well-known 'Orion ridge' which lies directly behind the Trapezium cluster and which contains several dense molecular clumps that are all sites of ongoing star formation (Sargent & Mundy 1988). Thus, star formation seems to be occurring in clumpy filaments everywhere in the Orion A cloud, both in the Trapezium region and elsewhere, and there is no apparent distinction in this regard between 'clustered' and 'distributed' modes of star formation. There is also no clear evidence that star formation in the Orion A cloud has been 'sequential', i.e. that it has occurred first in one place and then in another, and it seems at present to be occurring simultaneously throughout the cloud.

What does seem clear is that star-forming clouds like the Orion clouds are in a chaotic and turbulent dynamical state, and their small-scale structure must therefore be transient and rapidly changing. Not only do molecular clouds contain a hierarchy of chaotic internal motions suggestive of turbulence, but their fractal-like shapes (e.g., Herbertz, Ungerechts, & Winnewisser 1991) resemble those of structures seen in laboratory turbulent flows (Falgarone 1989, 1996; Falgarone & Phillips 1991). In the present context, the term 'turbulence' is to be understood broadly, since magnetic fields are believed to play an important role and the observed motions are believed to be partly wave-like. Numerical simulations are needed to gain insight into the complex interplay of physical effects involved, and with this problem in mind, several groups have begun to present the results of detailed simulations of supersonic turbulence in magnetized self-gravitating media (Gammie & Ostriker 1996; Ostriker 1997; Vázquez-Semadeni, Passot, & Pouquet 1996, 1997; Balsara, Crutcher, & Pouquet 1997; MacLow, this conference). These simulations all show that, even when magnetic fields are important, shocks are ubiquitous and generate large density fluctuations. The simulations also show a tendency toward equipartition between the kinetic energy of turbulent motions and the energy in magnetic field fluctuations, implying a tendency toward pressure balance between the fluctuating dynamical and magnetic pressures. Filamentary structures resembling those seen in molecular clouds are frequently produced in the simulations, and when self-gravity is included, these filaments may also contain dense bound clumps. The filaments are typically formed at the interfaces between supersonically colliding flows (e.g., Vázquez-Semadeni et al. 1995). Although such numerical studies are only beginning and few quantitative results are yet available, they already show much promise for improving our understanding of the dynamics and evolution of molecular clouds, which clearly is a crucial step in understanding star formation.

4. Small-Scale Aspects: The Evolution of Dense Cloud Cores

Evidently, dense star-forming cores are continually being formed amidst all of the chaos in star-forming molecular clouds, and these cores typically collapse rapidly to form stars, since many of the dense cores seen in molecular clouds contain newly-formed T Tauri stars or protostars that are only a million years old or less. The formation of entire clusters of stars must also be a rapid process, since the compact young clusters in Orion are themselves only a million years old or less. The numerical simulations of MHD turbulence mentioned above suggest that the star-forming filaments and clumps in molecular clouds are produced dynamically by turbulent compression, like the corresponding features seen in the simulations. Most of the filamentary structures that appear in the simulations are transient, but the denser and more massive ones may be self-gravitating and may begin to collapse. Thus, if the simulations that have been made so far are a good guide, they suggest that the star-forming clumps in molecular clouds are created by turbulent motions and that they are compressed to their high observed densities by the same fluctuating pressures that pervade molecular clouds and help to support them against gravity on larger scales.

If magnetic fields are important, star-forming clumps may initially be supported against gravity by magnetic forces and may be unable to collapse dynamically until their magnetic flux has been reduced. Many theoretical discussions of star formation have assumed that magnetic support is indeed important and that the required flux loss occurs via slow ambipolar diffusion, during which process a self-gravitating cloud core gradually contracts and becomes more centrally condensed until gravity finally predominates over magnetic forces and a dynamical collapse begins (Shu, Adams, & Lizano 1987). This widely accepted picture has led to the 'standard model' proposed by these authors, in which slow quasi-static contraction is assumed to continue all the way to a configuration closely approximating a singular isothermal sphere supported in hydrostatic equilibrium by thermal pressure with no longer a significant magnetic contribution. This highly unstable configuration is then assumed to collapse dynamically from the inside out in a self-similar fashion that produces a constant rate of accretion onto a central forming star.

Since ambipolar diffusion is a slow process, while real molecular clouds are apparently chaotic and rapidly changing in their structure, the role of ambipolar diffusion and the validity of the idealized 'standard model' are questionable. For purposes of discussion, two limiting possibilities can be imagined for the way in which star-forming cloud cores might evolve to form stars, one being the rapid collapse of a clump that is not initially in a stable equilibrium configuration, and the other being the slow quasi-static contraction postulated by the standard model, followed by an inside-out collapse. Much recent theoretical work on this problem has focused on efforts to find similarity solutions describing the asymptotic evolution of a collapsing cloud core in various cases of interest, and on comparing these solutions with two existing similarity solutions that represent opposite limiting cases: (1) the solution found by Larson (1969) and Penston (1969) describing the asymptotic evolution of the innermost part of an isothermally collapsing spherical cloud and the development of a central density singularity in it, as extended past the singularity by Hunter (1977), and (2) the similarity solution derived by Shu (1977) for the inside-out collapse of an equilibrium singular isothermal sphere that is assumed to have formed by slow quasi-static evolution. A comprehensive discussion of the possible similarity solutions for an isothermally collapsing sphere has been presented by Whitworth & Summers (1985), and they have shown that there is actually an infinite family of such solutions, the Larson-Penston (LP) and the Shu solutions representing opposite limiting cases and all other possibilities being intermediate between them.

In order to check whether the LP solution correctly describes the asymptotic evolution of a collapsing isothermal sphere, Hunter (1977) and Foster & Chevalier (1993) calculated numerically the collapse of a marginally stable Bonnor-Ebert sphere, and both studies found that the late evolution of its central region is well approximated by the LP solution. A useful way of comparing the results obtained in different cases is to give the initial accretion rate onto the central point mass that forms immediately after the development of the singularity; in the Shu (1977) solution the central accretion rate is constant in time and is equal to 0.975 c^3/G, while in the LP solution as extended by Hunter (1977) the initial accretion rate is 47 c^3/G, much higher than the Shu value because in the LP solution the envelope is falling inward at 3.3 times the sound speed rather than at rest, and also because it has a higher density at each radius than a singular isothermal sphere. Hunter (1977) finds numerically an initial accretion rate of about 36 c^3/G, while Foster & Chevalier (1993) state that they find a close approach to the LP value of 47 c^3/G but do not give a precise number. As was shown in the latter study, however, this high initial accretion rate applies only immediately after the formation of the central point mass, and the accretion rate subsequently declines strongly with time and eventually becomes smaller even than the Shu value.

Many authors have recently sought to generalize these results by including the effects of magnetic fields and rotation. The collapse of an unstable magnetized cylinder with conservation of magnetic flux (i.e., with no ambipolar diffusion) has been calculated numerically by Tomisaka (1996a,b), who finds that a flattened disk-like configuration forms and that it becomes increasingly centrally condensed, eventually developing a central singularity in a self-similar way that closely resembles the LP similarity solution for unmagnetized spherical collapse. The subsequent accretion rate onto a central point mass was also calculated by Tomisaka and was found to be larger than 40 c^3/G initially, subsequently declining strongly with time as in the non-magnetic case. The analogous problem of the collapse of an unstable rotating cylinder with conservation of angular momentum has been addressed most recently by Matsumoto, Hanawa, & Nakamura (1997), and they find a very similar result: a disk forms and becomes increasingly centrally condensed, evolving toward a central singularity in an approximately self-similar fashion with superimposed oscillations. The initial accretion rate onto a central point mass was estimated by these authors to be about (15–20) c^3/G, again much higher than the Shu value but within a factor of 3 of the LP value. In both the magnetized and the rotating cases just described, supersonic infall velocities reaching about twice the sound speed were found. These studies show that as long as a cloud core is initially unstable to collapse (that is, as long as gravity predominates over other forces), neither rotation nor a magnetic field qualitatively changes the way in which it collapses toward a central singularity, nor do they alter much the initial accretion rate onto the central point mass; both of these features of the collapse are apparently determined just by the effects of thermal pressure.

Since many theoretical discussions of star formation have assumed that the initial state is a *stable* equilibrium configuration supported by a magnetic field and evolving only slowly by ambipolar diffusion, it is of interest also to establish by rigorous calculation whether such a configuration really evolves quasi-statically into something closely resembling a singular isothermal sphere before beginning to collapse from the inside out, as assumed in the standard model. The evolution of a magnetically supported cloud core under the action of ambipolar diffusion, including the effects of rotation, has been studied in a series of papers by Basu & Mouschovias (1994, 1995a,b), and the results of this work have been extended by Basu (1997) who has derived an approximate similarity solution describing the final development of a central singularity. This work shows that a singular isothermal sphere is in fact never closely approached, and thus contradicts the basic assumption of the standard model; instead, it shows that magnetic support becomes insufficient to counteract gravity at a relatively early stage before a high degree of central condensation has been attained, and that the inner part of the cloud core then begins to collapse dynamically in much the same way as in the cases discussed above. The derivation of an approximate similarity solution was simplified by the fact that rotation also becomes dynamically unimportant at an early stage. The resulting solution is again similar to the LP solution, and Basu (1997) shows that the initial accretion rate onto a central point mass must be higher than 13 c^3/G; a plausible extrapolation suggests a value closer to 20 c^3/G.

Safier, McKee, & Stahler (1997) have also calculated analytically the evolution of a pressure-free magnetically supported sphere under the action of ambipolar diffusion, and they confirm the finding of Basu & Mouschovias that magnetic support is lost at an early stage before the cloud has become very centrally condensed. They conclude that most of the mass then begins to collapse dynamically in an 'outside-in' collapse starting from an initial configuration of nearly uniform density. An accretion rate depending on the sound speed cannot be derived from this work because of the neglect of thermal pressure, but the authors expect that when thermal pressure is included, the results will be similar to those previously found for non-magnetic collapse (e.g., Foster & Chevalier 1993). Thus, in all of the cases that have been discussed, the accretion rate onto the central object is expected to be at least an order of magnitude higher initially than in the standard model, and then to decline monotonically to much smaller values. Such a declining accretion rate appears to be in better agreement with observations of protostars than the constant accretion rate of the standard model (Basu 1997). Eventually the accretion rate will decline to very low values because the outermost part of the protostellar envelope is still magnetically supported, but a small residual accretion rate may be allowed by the continuing action of ambipolar diffusion in the envelope (Safier et al. 1997).

The work of Basu (1997) and of Safier et al. (1997) shows that the assumptions of the standard model are not likely to be realized in practice because slow ambipolar diffusion, even if it does play a role, never leads to a configuration closely approximating a singular isothermal sphere. Whitworth et al. (1996) have also given several arguments against accepting the standard model as a good description of star formation, including the fact that it provides no clear way to account for the formation of the binary and multiple systems that are the most common outcome of the star formation process, and these authors too argue for a more dynamic picture of protostellar evolution.

5. Is There a Scale in the Star Formation Process?

The scale-free nature of the singular isothermal sphere and the constant accretion rate of the standard model have led proponents of this model to assert that the star formation process has no intrinsic scale, and in particular that the Jeans mass plays no role in determining stellar masses. However, if thermal pressure is indeed the only real barrier to protostellar collapse, and if its effects become important already at an early stage, as the above results indicate, then the Jeans mass should indeed be relevant. A key question is clearly how much of the mass in a star-forming cloud core eventually collapses and is accreted by the central forming star (or stellar system) before the accretion rate becomes negligible. Safier et al. (1997) suggest that, even in the case of an initially stable magnetically supported cloud core evolving slowly by ambipolar diffusion, the collapsing mass is determined essentially by the Jeans mass at the onset of dynamical evolution. Since the dynamical phase of collapse begins at an early stage, this quantity will not be greatly different from the initial Jeans mass. In the other cases mentioned above where the initial configuration is already unstable to collapse, the Jeans mass is expected to be relevant from the outset, and it depends on the initial cloud properties (Larson 1985). Many numerical simulations of collapse and fragmentation have verified that the Jeans mass or equivalent quantities always play an important role in determining the scale of fragmentation (e.g., Monaghan & Lattanzio 1991).

The Jeans mass can be estimated in a number of ways, but perhaps the most relevant one is to note that if star-forming cloud cores are created by turbulent compression and are confined at least initially by the ambient non-thermal pressure in molecular clouds, the initial state for collapse may resemble a marginally stable Bonnor-Ebert sphere with a boundary pressure given by the ambient non-thermal cloud pressure. The rough scaling relations that are observed to hold for molecular cloud properties imply that these clouds all tend to have similar internal pressures of the order of 3×10^5 cm^{-3} K (Myers & Goodman 1988). The mass of a Bonnor-Ebert sphere with sound speed c and boundary pressure P is given by $M_J = 1.18c^4/G^{3/2}P^{1/2}$, and the radius of such a sphere is $R_J = 0.48c^2/G^{1/2}P^{1/2}$. For a temperature of 10 K and a pressure of 3×10^5 cm^{-3} K, the resulting mass is about 0.7 $M_\odot$ and the corresponding radius is about 0.03 pc. Other ways of estimating a Jeans mass, for example from the critical mass for the fragmentation of a self-gravitating sheet or filament (Larson 1985), are dimensionally equivalent to this result and give similar numbers if the pressure at the center of the sheet or filament is used in the above formula; this central pressure depends only on the surface density of the sheet or filament, and it is equal to the above value if the surface density has a typical molecular cloud value of 100 $M_\odot$ pc^{-2}.

Are these numbers relevant to star formation? Three kinds of evidence suggest that they are, and that the star formation process does indeed exhibit a scale of this order. The first is that the stellar initial mass function (IMF), which has approximately a power-law form above one solar mass, does not continue to follow such a power law down to masses much below a solar mass, but instead flattens out at masses below about 0.5 $M_\odot$ and may even fall steeply (in number of stars per unit logarithmic mass interval) at masses below 0.2 $M_\odot$ (Scalo 1986).

The existence of a steep drop at the low end of the IMF has been confirmed, at least for masses below 0.1 $M_\odot$, by the clear paucity of brown dwarfs (Basri & Marcy 1997; Beckwith, this conference). The IMF in star clusters appears to be similar to that of the field stars, and the best-studied young cluster, the Orion Nebula Cluster, also has an IMF that declines steeply below 0.2 $M_\odot$ (Hillenbrand 1997; this conference). Thus it appears that, at least in the regions accessible to study so far, little mass goes into stars with masses below a few tenths of a solar mass and most of the stellar mass goes into stars with masses of the order of a solar mass or a little less. Stars therefore appear to form with a characteristic mass that is similar to the Jeans mass estimated above. While the lower IMF thus provides evidence for the existence of a mass scale, the power-law form of the upper IMF suggests that the upper IMF is produced in a different and scale-free way, possibly by the accumulation of smaller structures into larger ones in a self-similar manner (Larson 1991, 1992a).

A similar scale also appears in analyses of the spatial distribution of the newly formed T Tauri stars in the Taurus and Ophiuchus regions (Larson 1995; Simon 1997). A plot of average companion surface density versus separation for these stars shows two regimes in which the data can be approximated by power laws: (1) a hierarchical clustering regime on large scales, and (2) a binary regime on small scales, with a clear break at a separation that is about 0.05 pc in Taurus and 0.03 pc in Ophiuchus. If the hierarchical clustering observed on the larger scales is self-similar, as these data suggest (resulting perhaps from cloud structuring by scale-free processes such as turbulence), then this self-similarity clearly cannot extend below the scale of the break, and qualitatively different processes must operate on smaller scales. Larson (1995) interpreted these results as indicating that the clustering hierarchy is built of units of a characteristic size given by the scale of the break, and noted that systems of this size typically contain two stars, suggesting that stars typically form in binary systems. The inference that the scale of the break indicates the size of the basic star-forming (or binary-forming) units is supported by the fact that this scale is comparable to the radii of the star-forming ‘ammonia cores’ in these clouds, which also have typical masses of the order of a solar mass. While such an interpretation may not be correct if the larger-scale clustering is not self-similar, and while it clearly cannot be applied in the dense Trapezium region where evidence of the initial spatial distribution of the stars has been erased (Bate, this conference), the data nevertheless suggest that binary systems form in separate star-forming units that have similar properties everywhere, since the binaries always stand out from the background clustering and have the same distribution of separations in all of the regions studied (Simon 1997). In both the Taurus and the Ophiuchus regions, where evidence of the initial spatial distribution of the stars has not been erased, the scale of the break between the binary and clustering regimes is close to the Jeans radius as estimated above, and the data are therefore consistent with the hypothesis that the basic star-forming units are thermally supported Jeans-mass clumps. Note that the Jeans scale as derived above can be regarded, like the scale of the break, as being the scale at which there is a transition between two different physical regimes, a chaotic regime dominated by turbulent pressures on large scales and a more regular regime dominated by thermal pressure on small scales.

Further evidence for a transition between different dynamical regimes on different scales is provided by detailed studies of the internal kinematics of star-forming molecular cloud cores (Goodman et al. 1998). On scales larger than about 0.1 pc, the non-thermal component of the velocity dispersion in these cores is observed to increase with region size following the general size-linewidth relation for molecular clouds, while on smaller scales this non-thermal velocity dispersion becomes almost constant, i.e. independent of region size, in the central densest parts of these cores. Goodman et al. (1998) interpret these results as indicating a transition from a regime of chaotic motion on scales larger than 0.1 pc to a regime of 'velocity coherence' on smaller scales. They note that this transition occurs at approximately the same scale as the break in the clustering properties of young stars discussed above, and they suggest that these two results are related and that both reflect the existence of the same 'inner scale' of a 'self-similar process', i.e. a scale at which there is a transition from self-similar chaotic behavior on larger scales to regular behavior on smaller scales. Although the physical reason for the onset of 'velocity coherence' on the smaller scales is not entirely clear, since the nature of the non-thermal motions themselves is not yet well understood, it could reflect either a more regular state of motion or a smoother density distribution, or both, on the smallest scales. In either case, the basic cause may simply be the increased importance of thermal pressure on the smallest scales, since thermal pressure would tend to smooth out structural and kinematic irregularities. In this case the 'inner scale' of Goodman et al. (1998) would represent a transition from a chaotic regime dominated by non-thermal pressures on large scales to a more regular regime dominated by thermal pressure on small scales, and it would be identical to the Jeans scale as estimated above.

Thus, three kinds of evidence suggest that the star formation process has a characteristic scale at which there is a transition from self-similar chaotic behavior on large scales to regularity on small scales: (1) the internal motions in star-forming clouds show a transition from 'turbulence' on large scales to 'velocity coherence' on small scales; (2) the spatial distribution of newly formed stars shows a transition from hierarchical clustering on large scales to binary systems with distinct properties on small scales; and (3) the stellar IMF has a power-law form for high masses but shows a peak and a characteristic mass near the low end. In all cases the transition occurs at a length scale of the order of 0.1 pc and a mass scale of the order of 1 $M_\odot$. It would be surprising if these three observations were not all related and if they did not all point to the same intrinsic scale in the star formation process, which as we have seen can be interpreted as the Jeans scale.

6. The Formation of Binary Systems

The studies of the clustering of young stars discussed above show that binary systems always stand out from the background, and that they have the same distribution of separations in all of the regions studied; this suggests that binaries are formed by a separate mechanism that is unrelated to the larger-scale clustering. The distribution of separations of the known pre-main-sequence binaries has the same form as that previously found by Duquennoy & Mayor (1991) for field main-sequence binaries except for its normalization: binary companions appear to be twice as common among the pre-main-sequence stars in several well-studied regions of star formation as they are among field main-sequence stars (Ghez et al. 1997). The form of this apparently universal distribution of binary separations is very broadly peaked, and it is almost flat over several orders of magnitude in separation when expressed in terms of the number of systems per unit logarithmic separation interval.

As was noted above, pre-main-sequence stars typically have one close companion in the binary range of separations, and this suggests that stars typically form in binaries and that the most common outcome of the collapse of a star-forming clump is its fragmentation into two stars (Larson 1995). Fragmentation into two stars would in fact be a plausible outcome of protostellar collapse, because fragmentation is inhibited in centrally condensed clouds (Boss 1987, 1993; Myhill & Kaula 1992), yet rotation will almost certainly cause some fragmentation to occur anyway (Burkert & Bodenheimer 1996; Burkert, Bate, & Bodenheimer 1997). The minimum amount of fragmentation that could occur and still be consistent with retaining any significant angular momentum would be fragmentation into two stars. However, it is also possible that fragmentation often produces more than two objects and that the dynamics of the system then becomes chaotic, causing some of these objects to merge and others to be ejected (Burkert et al. 1997; Burkert, this conference). The final outcome of such complex fragmentation processes has yet to be determined because the calculations have not been carried far enough that most of the mass is in the condensed objects.

A complete understanding of binary formation must of course account not only for the frequent formation of binaries but also for the observed broad distribution of binary separations. So far, most numerical studies of fragmentation have concentrated on following the details of particular cases, but if chaotic effects become important and produce a wide range of outcomes, the details of individual cases may not be very meaningful and it may be necessary to approach the problem statistically, simulating many cases using Monte-Carlo techniques to predict the resulting distributions of properties. To determine the final outcome, it will also be necessary to carry the calculations to the stage where most of the mass has been accreted by the forming objects. Few existing calculations have been carried this far, but techniques capable of following the evolution of a system of accreting objects have been developed by Bate & Bonnell (1997) and Bonnell et al. (1997). Among the few calculations to have been carried (almost) far enough to predict the final outcome were the early and very crude particle simulations of three-dimensional collapse and fragmentation by Larson (1978), which produced results qualitatively resembling the observations in that many binary and multiple systems were formed. The spatial distribution of the objects shown in Figure 6 of that paper can be analyzed in the same way as the spatial distribution of the T Tauri stars discussed above, and the results again resemble the observations in showing the existence of two regimes separated by a break (Larson 1997). What is particularly interesting, although not definitive from these very limited results, is that the distribution of separations of the binaries formed in the simulations is similar to the observed distribution of binary separations in having an approximately constant number of systems per unit logarithmic separation interval. If further work yields similar results, this would suggest that the observed nearly flat distribution of binary separations can be explained by basic features of the dynamics of fragmenting clouds that are included even in crude simulation schemes, such as gravitational drag and chaotic n-body dynamics, both of which are scale-free and capable in principle of yielding a broad distribution of separations with no preferred scale (Larson 1997).

7. Closing the Cycle: Cloud Destruction and ISM Properties

In Section 1, it was noted that star formation is just one of a cycle of processes by which matter and energy are exchanged between stars and the various components of the interstellar medium, and that these processes are interrelated through many feedback effects (Tenorio-Tagle & Bodenheimer 1988; Larson 1996). Therefore, in order to fully understand star formation, it is necessary to understand also the other processes in this galactic ecocycle and their influence on the conditions under which stars form. For example, we have seen in Section 5 that there is evidence for an intrinsic scale in the star formation process, and it was suggested that this scale depends on the typical pressure in star-forming molecular clouds. The internal pressure in molecular clouds is much higher than the general pressure of the interstellar medium, and this suggests that the internal pressure in these clouds is of dynamical origin and results from the cloud formation process. To understand the origin of such cloud properties it is therefore necessary to understand in more detail the cloud formation process and hence the larger-scale structure and dynamics of the ISM, which in turn are largely governed by various feedback effects of star formation.

An obvious feedback effect is the rapid destruction of star-forming clouds by the effects of ionization, stellar winds, and supernovae, and the resulting recycling of dense molecular cloud gas back into more diffuse forms (Larson 1988, 1996). The most important destruction mechanism, in terms of the rate at which matter is converted from one form to another, is ionization, which can evaporate away most of the mass of a star-forming cloud after only a small fraction of it has been turned into stars. The ionized gas so created streams away from the cloud with a velocity of the same order as the sound speed, or about 10 km s^{-1}, although larger speeds can be produced in 'champagne flows' (Tenorio-Tagle 1979, 1982). These ionized flows then replenish the diffuse ionized component of the ISM, and through the subsequent recombination of this gas and by the sweeping up of additional neutral cloud gas, they can replenish the atomic component as well. In this way, most of the mass in star-forming clouds is eventually dispersed in the form of ionized and neutral outflows and cloud debris, all moving with speeds of the order of 10 km s^{-1}. The subsequent explosive effects of stellar winds and supernovae can then further sweep up and accelerate this relatively diffuse gas into large expanding shells, which indeed are common features of the atomic ISM (Hartmann & Burton 1996) and which are often observed in regions of recent star formation (de Geus 1991; Blaauw 1991; Bally et al. 1991; Bally, this conference). A significant fraction of the cloud structure in the atomic ISM may in fact belong to such shells, and the eventual disruption of these shells must be an important source of new interstellar clouds, as was originally suggested by Oort (1954).

To complete the star formation cycle, the diffuse clouds and intercloud gas created by the destruction of old star-forming molecular clouds must be assembled again into new molecular clouds. On large scales, the ISM is collected into large cloud complexes and spiral arm segments primarily by its self-gravity, as was discussed in Section 2, and the building up of new molecular clouds in these regions probably involves the collisional agglomeration of many smaller mostly atomic clouds (Elmegreen 1993; Larson 1994). Such a collisional agglomeration process will generate a dynamical pressure ρv^2, where ρ is the density of the colliding clouds and v is the velocity with which they collide. If the colliding atomic clouds have a typical density of 20 cm^{-3} and a typical velocity of 10 km s^{-1}, the ram pressure produced is about 3×10^5 cm^{-3} K; this is the same as the characteristic non-thermal pressure in molecular clouds (Myers & Goodman 1988), so this process can indeed account for the high internal pressures in molecular clouds. The typical observed velocity of $\sim$ 10 km s^{-1} of the progenitor atomic clouds may be explainable largely as a result of the destruction of star-forming clouds by ionization, as was noted above, in which case the only parameter remaining to be explained is the typical density of $\sim$ 20 cm^{-3} inferred for the atomic clouds (Spitzer 1978).

The cool atomic clouds in the ISM appear to be in approximate thermal pressure balance with a warm intercloud medium that has both neutral and ionized components, and that may occupy a large fraction of the volume of interstellar space (Kulkarni & Heiles 1987). Even if magnetic and turbulent pressures generally dominate over thermal pressure throughout most of the ISM, the thermal pressures in the cloud and intercloud phases should still tend to equalize along magnetic field lines. The temperatures and densities of both the clouds and the intercloud medium may then be determined, as in the classical two-phase model of the ISM (Field, Goldsmith, & Habing 1969), by the simultaneous existence of pressure balance and thermal equilibrium, provided that there is an effective radiative heating mechanism. The physics of the two-phase model has been reexamined by Wolfire et al. (1995), and they find that the observed properties of both the cloud and the intercloud phases can be satisfactorily accounted for with such a model in which photoelectric heating takes the place of the cosmic-ray heating originally postulated by Field et al. (1969). As before, pressure balance between the cloud and intercloud phases is possible only for a limited range of pressures depending on several parameters, including in this case the flux of non-ionizing ultraviolet radiation responsible for the photoelectric heating. For typical values of these parameters, Wolfire et al. (1995) find that the maximum pressure for which two phases can coexist in pressure equilibrium is about 3600 cm^{-3} K; pressures any higher than this would cause the intercloud gas to condense into clouds. This predicted maximum pressure is comparable to the thermal pressures inferred from observations for both the cloud and the intercloud phases of the ISM (Kulkarni & Heiles 1987), suggesting that the actual thermal pressure is regulated to remain close to the maximum possible value. This is indeed expected to be the case if star-forming clouds are continually being evaporated by star formation, since this will tend to replenish the intercloud medium and raise its pressure toward the maximum value; the pressure would then be regulated to remain near this value because any further increase would cause the intercloud gas to condense rapidly back into clouds.

If we take, for example, a thermal pressure of 3000 cm^{-3} K and a cloud temperature of 100 K, the predicted cloud density is 30 cm^{-3} and the ram pressure produced by cloud collisions is about 4×10^5 cm^{-3} K, sufficient to account for the typical non-thermal internal pressures in molecular clouds. Thus, the cycling of interstellar matter between condensed and diffuse phases by the effects of star formation, together with the heating of the ISM by ultraviolet radiation that also is a consequence of recent star formation, can account for many of the structural and dynamical properties of the ISM. These properties in turn control how star formation proceeds and what values of the parameters are involved. Star formation is thus clearly a highly self-regulating process; not only are its rate and efficiency strongly limited by the negative feedback effects destruction, but even the quantitative details of how it occurs, such as the mass and length scales involved, are determined by thermal and dynamical properties of the ISM that are themselves largely controlled by the feedback effects of star formation.

Clearly, much remains to be learned about the many processes involved in star formation and the galactic ecocycle, but because of the complexity of the problem, an overall understanding of it will have to be built up bit by bit with careful attention to the phenomenology. A good place to start learning about many of these processes is the Orion complex, the nearest place where a wide range of the relevant phenomena can be studied. When we have understood what is going on in Orion, we shall be in a much better position to understand what is going on elsewhere, although because the Orion complex is rather modest in its activity by Galactic standards, we can surely expect to find much more dramatic versions of these phenomena when we look farther afield.

References

Bally, J., Langer, W. D., Stark, A. A., & Wilson, R. W. 1987, ApJ, 312, L45

Bally, J., Langer, W. D., Wilson, R. W., Stark, A. A., & Pound, M. W. 1991, in Fragmentation of Molecular Clouds and Star Formation, IAU Symp. No. 147, eds. E. Falgarone, F. Boulanger, & G. Duvert (Kluwer, Dordrecht), 11

Balsara, D. S., Crutcher, R. M., & Pouquet, A. 1997, in Star Formation Near and Far, eds. S. S. Holt & L. G. Mundy (AIP, Woodbury), 89

Basri, G., & Marcy, G. W. 1997, in Star Formation Near and Far, eds. S. S. Holt & L. G. Mundy (AIP, Woodbury), 228

Basu, S. 1997, ApJ, 485, 240

Basu, S., & Mouschovias, T. Ch. 1994, ApJ, 432, 720

Basu, S., & Mouschovias, T. Ch. 1995a, ApJ, 452, 386

Basu, S., & Mouschovias, T. Ch. 1995b, ApJ, 453, 271

Bate, M. R., & Bonnell, I. A. 1997, MNRAS, 285, 33

Blaauw, A. 1991, in The Physics of Star Formation and Early Stellar Evolution, eds. C. J. Lada & N. D. Kylafis (Kluwer, Dordrecht), 125

Bonnell, I. A., Bate, M. R., Clarke, C. J., & Pringle, J. E. 1997, MNRAS, 285, 201

Boss, A. P. 1987, ApJ, 319, 149

Boss, A. P. 1993, ApJ, 410, 157

Burkert, A., & Bodenheimer, P. 1996, MNRAS, 280, 1190

Burkert, A., Bate, M. R., & Bodenheimer, P. 1997, MNRAS, 289, 497

de Geus, E. J. 1991, in The Formation and Evolution of Star Clusters, ed. K. Janes (ASP, San Francisco), 40

Duquennoy, A., & Mayor, M. 1991, A&A, 248, 485

Elmegreen, B. G. 1992, in Star Formation in Stellar Systems, eds. G. Tenorio-Tagle, M. Prieto, & F. Sánchez (Cambridge Univ. Press, Cambridge), 381

Elmegreen, B. G. 1993, in Protostars and Planets III, eds. E. H. Levy & J. I. Lunine (Univ. of Arizona Press, Tucson), 97

Falgarone, E. 1989, in Structure and Dynamics of the Interstellar Medium, eds. G. Tenorio-Tagle, M. Moles, & J. Melnick (Springer-Verlag, Berlin), 68

Falgarone, E., & Phillips, T. G. 1991, in Fragmentation of Molecular Clouds and Star Formation, IAU Symp. No. 147, eds. E. Falgarone, F. Boulanger, & G. Duvert (Kluwer, Dordrecht), 119

Falgarone, E. 1996, in The Interplay Between Massive Star Formation, the ISM, and Galaxy Evolution, eds. D. Kunth, B. Guiderdoni, M. Heydari-Malayeri, & T. X. Thuan (Editions Frontières, Gif sur Yvette), 95

Field, G. B., Goldsmith, D. W., & Habing, H. J. 1969, ApJ, 155, L149

Foster, P. N., & Chevalier, R. A. 1993, ApJ, 416, 303

Franco, J., Tenorio-Tagle, G., Bodenheimer, P., Różyczka, M., & Mirabel, I. F. 1988, ApJ, 333, 826

Gammie, C. F., & Ostriker, E. C. 1996, ApJ, 466, 814

Ghez, A. M., McCarthy, D. W., Patience, J. L., & Beck, T. L. 1997, ApJ, 481, 378

Goodman, A. A., Barranco, J. A., Wilner, D. J., & Heyer, M. H. 1998, ApJ, 504, 223

Hartmann, D., & Burton, W. B. 1996, An Atlas of Galactic Neutral Hydrogen (Cambridge Univ. Press, Cambridge)

Herbertz, R., Ungerechts, H., & Winnewisser, G. 1991, A&A, 249, 483

Hillenbrand, L. A. 1997, AJ, 113, 1733

Hunter, C. 1977, ApJ, 218, 834

Kennicutt, R. C. 1989, ApJ, 344, 685

Kulkarni, S. R., & Heiles, C. 1987, in Interstellar Processes, eds. D. J. Hollenbach & H. A. Thronson (Reidel, Dordrecht), 87

Larson, R. B. 1969, MNRAS, 145, 271

Larson, R. B. 1978, MNRAS, 184, 69

Larson, R. B. 1982, MNRAS, 200, 159

Larson, R. B. 1985, MNRAS, 214, 379

Larson, R. B. 1988, in Galactic and Extragalactic Star Formation, eds. R. E. Pudritz & M. Fich (Kluwer, Dordrecht), 459

Larson, R. B. 1991, in Fragmentation of Molecular Clouds and Star Formation, IAU Symp. No. 147, eds. E. Falgarone, F. Boulanger, & G. Duvert (Editions Frontières, Gif Sur Yvette), 261

Larson, R. B. 1992a, MNRAS, 256, 641

Larson, R. B. 1992b, in Star Formation in Stellar Systems, eds. G. Tenorio-Tagle, M. Prieto, & F. Sánchez (Cambridge Univ. Press, Cambridge), 125

Larson, R. B. 1993, in The Globular Cluster–Galaxy Connection, eds. G. H. Smith & J. P. Brodie (ASP, San Francisco), 675

Larson, R. B. 1994, in The Structure and Content of Molecular Clouds, eds. T. L. Wilson & K. J. Johnston (Springer-Verlag, Berlin), 13

Larson, R. B. 1995, MNRAS, 272, 213

Larson, R. B. 1996, in The Interplay Between Massive Star Formation, the ISM and Galaxy Evolution, eds. D. Kunth, B. Guiderdoni, M. Heydari-Malayeri, & T. X. Thuan (Editions Frontières, Gif sur Yvette), 3

Larson, R. B. 1997, in Structure and Evolution of Stellar Systems, eds. T. A. Agekian, A. A. Mülläri, & V. V. Orlov (St. Petersburg State University, St. Petersburg, Russia), p. 48

Matsumoto, T., Hanawa, T., & Nakamura, F. 1997, ApJ, 478, 569

Monaghan, J. J., & Lattanzio, J. C. 1991, ApJ, 375, 177

Myers, P. C., & Goodman, A. A. 1988, ApJ, 329, 392

Myhill, E., & Kaula, W. M. 1992, ApJ, 386, 578

Oort, J. H. 1954, Bull. Astr. Inst. Netherlands, 12, 177

Ostriker, E. C. 1997, in Star Formation Near and Far, eds. S. S. Holt & L. G. Mundy (AIP, Woodbury), 51

Penston, M. V. 1969, MNRAS, 144, 425

Safier, P. N., McKee, C. F., & Stahler, S. W. 1997, ApJ, 485, 660

Sargent, A. I., & Mundy, L. G. 1988, in Galactic and Extragalactic Star Formation, eds. R. E. Pudritz & M. Fich (Kluwer, Dordrecht), 261

Scalo, J. M. 1986, Fundam. Cosmic Phys., 11, 1

Shu, F. H. 1977, ApJ, 214, 488

Shu, F. H., Adams, F. C., & Lizano, S. 1987, ARA&A, 25, 23

Simon, M. 1997, ApJ, 482, L81

Spitzer, L. 1978, Physical Processes in the Interstellar Medium (Wiley-Interscience, New York)

Tenorio-Tagle, G. 1979, A&A, 71, 59

Tenorio-Tagle, G. 1982, in Regions of Recent Star Formation, eds. R. S. Roger & P. E. Dewdney (Reidel, Dordrecht), 1

Tenorio-Tagle, G., & Bodenheimer, P. 1988, ARA&A, 26, 145

Tomisaka, K. 1996a, PASJ, 48, 701

Tomisaka, K. 1996b, PASJ, 48, L97

Toomre, A. 1981, in The Structure and Evolution of Normal Galaxies, eds. S. M. Fall & D. Lynden-Bell (Cambridge Univ. Press, Cambridge), 111

Vázquez-Semadeni, E., Passot, T., & Pouquet, A. 1995, ApJ, 441, 702

Vázquez-Semadeni, E., Passot, T., & Pouquet, A. 1996, ApJ, 473, 881

Vázquez-Semadeni, E., Passot, T., & Pouquet, A. 1997, in Star Formation Near and Far, eds. S. S. Holt & L. G. Mundy (AIP, Woodbury), 85

Whitworth, A., & Summers, D. 1985, MNRAS, 214, 1

Whitworth, A. P., Bhattal, A. S., Francis, N., & Watkins, S. J. 1996, MNRAS, 283, 1061

Wiseman, J. J., & Ho, P. T. P. 1996, Nature, 382, 139

Wolfire, M. G., Hollenbach, D., McKee, C. F., Tielens, A. G. G. M., & Bakes, E. L. O. 1995, ApJ, 443, 152