Hierarchical Star Formation

Richard B. Larson

Yale Astronomy Department, New Haven, CT 06520-8101

Abstract.

The evidence is briefly reviewed that stars often form in groups and clusters of various sizes, and that star clusters often form in clouds that have been strongly disturbed by the effects of prior episodes of star formation. Evidence is also presented that the newly formed stars in Taurus are clustered in a self-similar fashion on scales larger than 0.04 pc, but that this self-similarity does not extend into the regime of binary and multiple systems on smaller scales. This suggests that binary and multiple systems are not formed by the same mechanism that produces the clustering observed on larger scales, but by the fragmentation of protostellar clumps with a characteristic size of ~ 0.04 pc. These clumps appear to constitute the basic units of star formation, and therefore it seems very significant that their inferred size is essentially equal to the Jeans length in typical molecular cloud cores.

1. The Formation of Star Clusters

Most of our present theoretical understanding of star formation is based on models of stars forming in isolation, but it has become increasingly clear that most stars do not form in isolation. Most stars are members of binary or multiple systems (Abt 1983; Duquennoy & Mayor 1991), and the likelihood that nearly all stars are formed in such systems is strengthened by the fact that the T Tauri stars in nearby regions of star formation have even more close binary companions than do main-sequence field stars (Mathieu 1994). Most of the newly formed stars in well-studied regions of star formation are also found to be in groups and clusters of various sizes (Lada, Strom, & Myers 1993; Zinnecker, McCaughrean, & Wilking 1993); even in the relatively sparse Taurus region, most of the young stars are in small groups (Larson 1982; Myers 1987; Gomez et al. 1993), while in the Ophiuchus region most of the young stars are concentrated in a single cluster embedded in the core of the ρ Oph cloud (Wilking, Lada, & Young 1989; Wilking 1992). In the Orion region, which has much larger clouds and many more young stars, the majority of the newly formed stars are located in several compact clusters, including the Trapezium cluster, which are closely associated with the most massive cloud cores (Lada et al. 1993; Zinnecker et al. 1993). Many young clusters also appear to contain subclusters (Elson 1991; Piché 1993), so that star formation may generally be a hierarchical process that involves clustering on a wide range of scales.

Star formation in clusters is clearly a much more complex process than the formation of stars in isolation, and little is yet understood about it theoretically. However, a large body of relevant observational information has been accumulated in recent years, providing the basis for a phenomenological approach to understanding this subject, which is probably the most fruitful approach to follow at present. Some observed features of cluster formation that may be relevant to the origin of the hierarchical structure to be discussed below are summarized here; more extensive reviews of the phenomenology of cluster formation and of its possible theoretical implications have been given by Larson (1993, 1994).

Observations of the dense molecular gas associated with young or still forming star clusters have shown that the regions of ongoing star formation in these clusters are typically very localized and occupy only a small fraction of the cluster volume. In all of the cases mentioned above, stars are currently observed to be forming only in very dense clumps arranged along filaments; a well-known example is the dense 'ridge' of molecular gas in the Orion A cloud which passes almost through the middle of the Trapezium cluster, and which contains three currently active sites of star formation (Sargent & Mundy 1988; Genzel & Stutzki 1989). A similar situation is seen in NGC 2024, the most prominent young cluster in the Orion B cloud; it too contains a molecular filament, embedded in which are several very dense and cold clumps that appear to be at a very early stage of star formation (Mezger et al. 1992; Mezger 1994). Even the ρ Oph embedded cluster contains a chain of dense cold clumps which are apparently just beginning to form stars (André, Ward-Thompson, & Barsony 1993). The origin of these molecular filaments is not yet understood, but it is clear that any simple spherically symmetric model of cluster formation would fail badly to represent the observations; the data instead suggest that cluster formation involves complex dynamical phenomena that often create filamentary structures in star-forming clouds.

Even more drastic departures from spherical symmetry, and more compelling evidence for complex and even violent dynamical phenomena, are seen when the larger-scale environments of young clusters are examined. The dense ρ Oph cloud core and its embedded cluster are located in the head of a comet-shaped cloud whose tail points away from the center of the adjacent Upper Scorpius OB association; several other molecular clouds in its vicinity also have a windblown appearance suggesting that they have been shaped and compressed by outflows from the OB association, which have also created large shell structures in the surrounding region (de Geus, Bronfman, & Thaddeus 1990; de Geus 1991; Blaauw 1991). Similar phenomena are apparently occurring on an even larger scale in the Orion star-forming region, where the Trapezium cluster is found near the head of the strikingly comet-like Orion A cloud whose tail points away from the center of the Orion OB association (Bally et al. 1991; Blaauw 1991). The Orion B cloud and a number of smaller nearby molecular clouds also show evidence of being ablated by outflows from the OB association, and the fact that the densest parts of these clouds are located on the edges facing the center of the OB association suggests that these outflows may also have compressed the gas in the dense regions where the clusters have recently formed (Bally et al. 1991). This and other evidence suggest that the formation of star clusters is associated with energetic dynamical phenomena that both ablate and compress star-forming clouds, and probably also generate strong turbulence in them (Larson 1993, 1994). Chaotic and turbulent gas dynamics might then play an important role in the formation star clusters, and it would not be surprising if this were to result in complex and perhaps hierarchical structures for the star-forming clouds, and equally complex spatial distributions for the stars that form in them. Evidence for hierarchical structure in systems of young stars and some of its possible implications are discussed further below.

2. Hierarchies and Scales in Star Formation

As was noted above, observations of regions of star formation suggest that stars often form in a hierarchy of groupings of various sizes. Numerical simulations of cloud collapse and fragmentation have also suggested that hierarchical systems are often formed (Larson 1978; Bonnell et al. 1991; Boss 1993b). In the Taurus region of star formation, hierarchical clustering appears to extend over a considerable range of scales, as may be seen in Fig. 1 of Gomez et al. (1993), which shows the distribution on the sky of all the known visible young stars in this region; many small stellar groupings are seen, and they are clustered into larger groupings on a range of scales. The clustering of these stars has been analyzed quantitatively by Gomez et al. using the two-point angular correlation function, which has been widely used to study the clustering of galaxies; these authors have found that, as is the case for galaxies, the correlation function for the Taurus young stars can be approximated as a declining power-law function of separation, although there is marginal evidence for a change in the slope of this function at an angular separation of about 0.16 deg or 0.04 pc.

If the correlation function of the Taurus stars can be represented by a single power law at all separations, this would imply that these stars are clustered in a scale-free fashion, and this in turn would suggest that similar mechanisms may have operated on all scales to produce the observed clustering. If such scale-free clustering extends into the regime of binary and multiple systems, this would suggest in particular that these systems were formed by processes similar to those that produced the clustering observed on larger scales. If, on the other hand, the correlation function departs clearly from a power law at some scale, this would imply that the clustering of the Taurus young stars is not self-similar, and would suggest that different processes are important on different scales. Such a departure from self-similarity might be expected if an intrinsic length scale plays an important role in the star formation process; an example of such a length scale is the Jeans length, which separates two physical regimes such that thermal pressure provides the dominant support against gravity on smaller scales, while turbulent and magnetic pressures dominate on larger scales.

To establish more definitely whether a single power law can adequately represent the clustering of the Taurus stars on all scales, more data are needed for systems with very small separations, and such data are now available thanks to the searches for close binary companions to many of these stars conducted by Leinert et al. (1993), Ghez, Neugebauer, & Matthews (1993), and Simon (1992). Since all of these studies and that of Gomez et al. (1993) are based on similar and to a large extent overlapping samples of stars, their results can be directly compared. In order to present all of the results in a homogeneous and physically significant way, the data from each study have been used independently to

Figure 1. The average surface density of companions per star Σ_c in stars per square degree is plotted as a function of the angular separation θ in degrees for the four indicated studies of the young stars in the Taurus-Auriga region. The power-law fits shown for small and large separations are proportional to $\theta^{-2.15}$ and $\theta^{-0.62}$ respectively, and they intersect at a separation of about 0.017 degrees or 0.04 pc.

calculate the surface density of companions on the sky as a function of angular distance from each star, averaged over all of the stars observed in each study (including the newly discovered ones). The average surface density of companions per star has been used in preference to the two-point angular correlation function, which essentially measures the excess surface density of companions above that expected for a uniform stellar distribution, because the actual surface density is the more physically relevant quantity to examine in looking for possible scaling relations or fractal clustering.

The correlation function plotted in Fig. 2 of Gomez et al. (1993) has therefore been converted into the average surface density of companions per star as a function of separation, using for this conversion the average stellar surface density in the region for which the correlation function was derived. The result is indicated in Fig. 1 by the solid dots with statistical error bars; this function is very similar in its general appearance to the correlation function of Gomez et al., except at the largest separations where the actual surface density declines less rapidly than does its excess above a uniform distribution. The tabulations given by Leinert et al. (1993) and Ghez et al. (1993) of all of the known close companions of the stars observed by them, including previously known as well as newly discovered ones, have also been used to calculate the average surface density of companions per star as a function of separation, binning the listed pairs in intervals of a factor of 2 in separation and counting each pair as containing two companions, and the results are indicated in Fig. 1 by the crosses (Leinert et al.) and the open circles (Ghez et al.). The results of these two surveys are seen to be in excellent agreement, as would be expected since many of the same stars were observed and many of the same companions were detected in both cases. To extend this plot to separations even smaller than the limit of about 0.1 arcsec attained by these surveys, an additional point (the open square) has been added in Fig. 1 at a separation of 0.04 arcsec, based on results from the lunar occultation survey of Simon (1992).

It is immediately clear from Fig. 1 that, when all of the available data are considered, the dependence of the average companion surface density on separation cannot be represented by a single power law at all separations; instead, this function has very different logarithmic slopes at small and large separations, with a clear break at a separation of about 0.017 deg or 0.04 pc. This result confirms the tentative suggestion of Gomez et al. (1993) that the correlation function of the Taurus stars changes slope at about this point. The clustering of these stars is therefore not self-similar over the entire range of scales considered, and instead shows clear evidence for the existence of an intrinsic length scale of the order of 0.04 pc in the star formation process. On scales smaller and larger than this, the dependence of the average companion surface density on separation can be represented well by power laws with different slopes. The fits illustrated in Fig. 1 are given by $\Sigma_{\rm c} = 0.0064\,\theta^{-2.15}$ for separations smaller than 0.017 deg or 0.04 pc, and $\Sigma_{\rm c} = 3.4\,\theta^{-0.62}$ for separations larger than this, where $\Sigma_{\rm c}$ is the average companion surface density in stars per square degree and θ is the separation in degrees.

If these approximations for the surface density of companions are integrated with respect to area on the sky, they imply that an average young star in Taurus has about one companion within 0.04 pc, and many companions at larger distances. Thus, the break in slope seen in Fig. 1 at a separation of 0.04 pc also marks a division between the regime of binary systems on smaller scales and the regime of true clustering on larger scales. In the binary regime, the above approximation for the surface density of companions as a function of separation corresponds to a distribution of separations which, if expressed in the usual way in terms of the number of pairs per unit logarithmic separation interval, varies only as $\theta^{-0.15}$ and thus is almost independent of separation; this is consistent with the distribution of separations of main-sequence binaries, which is flat or slowly declining over this range of separations (Duquennoy & Mayor 1991; Ghez et al. 1993). Thus an immediate implication of the break in slope in Fig. 1 is that binary and multiple systems do not represent merely an extension to small scales of the hierarchical clustering seen on larger scales; instead, there are clearly many more close binary companions than would be expected from an extrapolation to small scales of the clustering behavior seen at larger separations.

This result constrains theories for the origin of binary systems, and would seem in particular to exclude any mechanism that does not in some way involve a preferred scale of the order of 0.04 pc and favor the formation of systems smaller than this compared with systems of larger separation. For example, it probably excludes the hypothesis that most binaries are formed by captures mediated by interactions with protostellar disks of radius ~ 100 AU (Larson 1990), since this mechanism would not clearly imprint a scale of ~ 0.04 pc on the resulting stellar distribution, and would be important only on much smaller scales. Instead, the above result seems in better accord with the conventional view that binaries are formed by the fragmentation of collapsing protostellar clumps of a characteristic size (Larson 1972; Boss 1992, 1993a; Bodenheimer, Ruzmaikina, & Mathieu 1993; Bonnell, this volume). Captures could still play a role in binary formation if the interacting protostars involved have extended envelopes (Silk 1978), but they would then have to be at an early stage of evolution, in which case it would become difficult to distinguish capture from fragmentation.

Clearly the length scale of ~ 0.04 pc at which the break in slope occurs in Fig. 1 must be one of fundamental significance for star formation. It therefore seems noteworthy that this scale is essentially equal to the Jeans length in typical molecular cloud cores, or more precisely to the radius of the smallest self-gravitating clump that can collapse to form a star (Larson 1985, 1991). It also seems significant that the mass of a marginally stable isothermal sphere with this radius and a temperature of 10 K is about 0.8 $M_\odot$, a typical stellar mass. Thus, the evidence seen in Fig. 1 for the existence of an intrinsic length scale of the order of 0.04 pc in the star formation process supports the relevance of the Jeans length and mass to star formation, and may even provide the most direct evidence yet found for the relevance of these predicted length and mass scales to star formation. The fact that cloud regions of this size typically form binary systems rather than single stars suggests that the basic unit of star formation to be identified with the Jeans mass is actually a binary system rather than a single star; in this case the predicted characteristic mass for a single star is only about one-half of the Jeans mass or ~ 0.4 $M_\odot$, a prediction which is still in reasonable agreement with the typical masses of T Tauri stars.

On scales larger than 0.04 pc, the dependence of the average companion surface density on separation is well represented by a power law, and is approximately proportional to $\theta^{-0.6}$; it is notable, in fact, that the average companion surface density plotted in Fig. 1 is more nearly a power-law function of separation than is the correlation function of Gomez et al. (1993). Thus, on these larger scales the Taurus stars do appear to exhibit self-similar clustering. The number of stars within an angular distance θ of a given star increases approximately as $\theta^{1.4}$ in this regime, and therefore the distribution of these stars on the sky can be described as a fractal distribution with a dimension of ~ 1.4. This suggests that the distribution of these stars in space can also be described as a fractal with a dimension of ~ 1.4, since the projection onto a plane of a fractal distribution of points in space is also a fractal with the same dimension (Mandelbrot 1982).

The apparently self-similar clustering of the newly formed stars in Taurus, and hence of the sites of star formation, may be related to other evidence that has been found for hierarchical and possibly fractal structure in star-forming clouds. A number of authors have found, for example, that the boundaries of molecular clouds on contour plots are fractal curves of dimension ~ 1.4–1.5 (Scalo 1990; Falgarone, Phillips, & Walker 1991; Falgarone 1992; Zimmermann

& Stutzki 1992; Hetem & Lépine 1993), which suggests that the isodensity surfaces of these clouds are fractal surfaces of dimension ~ 2.4–2.5. This 'surface dimension' is similar to the dimension of $\simeq 2.35$ that has been found to characterize various interfaces in turbulent flows, and the possibility that the shapes of molecular clouds are due to turbulence has been discussed by Falgarone & Phillips (1991) and Larson (1992). The surface shapes of clouds may not be very relevant, however, to the clustering of the sites of star formation in them, which presumably depends more on the internal mass distribution. It is not yet clear to what extent a fractal description may apply to the internal mass distributions in molecular clouds, but if such a description is applicable, the associated 'mass dimension' must be somewhat smaller than the surface dimension mentioned above. One way to estimate such a mass dimension is to use the empirical scaling laws relating the sizes, linewidths, and densities of molecular clouds; typically they indicate that the linewidth increases as size raised to a power ~ 0.4–0.5, and that the average cloud density is roughly inversely proportional to size. If virial equilibrium holds, these relations imply that the mass of any molecular clump or cloud increases as its size raised to a power ~ 1.8–2.0, suggesting that the dimension best characterizing the mass distribution is about 1.8–2.0.

The dimension characterizing the clustering of the young stars in Taurus is smaller than either of these dimensions, being only about 1.4 as noted above. This suggests that the sites of star formation in molecular clouds are more strongly clustered than the mass distribution, that is, that the cloud substructures from which groups of stars form occupy only a relatively small fraction of the total cloud volume. This property is in fact expected in any picture in which star formation involves the gravitational collapse and fragmentation of the denser parts of star-forming clouds, since these dense subregions contract into progressively smaller volumes as fragmentation proceeds. If the structure of a fragmenting cloud can be described in fractal terms, a progressive decrease in the fractal dimension would be implied. An example of such a progressive decrease in the dimensionality of the mass distribution in a collapsing cloud is provided by scenarios and calculations in which a cloud collapses first to a flattened sheet or disk, which then breaks up into filaments and finally into clumps (Larson 1985; Miyama, Narita, & Hayashi 1987; Monaghan & Lattanzio 1991); in this case the dimensionality of the mass distribution clearly decreases during each stage of the process. In general, collapsing and fragmenting clouds will have a less idealized geometry than in this example, but a description of their evolution in terms of a decreasing fractal dimension might nevertheless provide a useful way of characterizing the fragmentation process.

Clearly, the study of star formation in groups and clusters opens a new realm of complexity in the study of star formation, into which the standard tools of theoretical analysis have as yet made few inroads and where a phenomenological approach is likely to be more useful. Among the techniques that can form an important part of such a phenomenological approach is a quantitative study of the clustering of the newly formed stars in regions of star formation, since as has been discussed here, such a study can yield important new insights and constraints on theory.

References

Abt, H. A. 1983, ARA&A, 21, 343

André, P., Ward-Thompson, D., & Barsony, M. 1993, ApJ, 406, 122

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, E. Falgarone, F. Boulanger, & G. Duvert, Dordrecht: Kluwer, 11

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

Bodenheimer, P., Ruzmaikina, T., & Mathieu, R. D. 1993, in Protostars and Planets III, E. H. Levy & J. I. Lunine, Tucson: University of Arizona Press, 367

Bonnell, I., Martel, H., Bastien, P., Arcoragi, J.-P., & Benz, W. 1991, ApJ, 377, 553

Boss, A. P. 1992, in Complementary Approaches to Binary and Multiple Star Research, IAU Colloq. No. 135, H. A. McAlister & W. I. Hartkopf, San Francisco: ASP, 135

Boss, A. P. 1993a, in The Realm of Interacting Binary Stars, J. Sahade & G. E. McCluskey, Dordrecht: Kluwer, 355

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

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

de Geus, E. J., Bronfman, L., & Thaddeus, P. 1990, A&A, 231, 137

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

Elson, R. A. W. 1991, ApJS, 76, 185

Falgarone, E. 1992, in Astrochemistry of Cosmic Phenomena, IAU Symp. No. 150, P. D. Singh, Dordrecht: Kluwer, 159

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

Falgarone, E., Phillips, T. G., & Walker, C. K. 1991, ApJ, 378, 186

Genzel, R., & Stutzki, J. 1989, A&A, 27, 41

Ghez, A. M., Neugebauer, G., & Matthews, K., 1993, AJ, 105, 2005

Gomez, M., Hartmann, L., Kenyon, S. J., & Hewett, R., 1993, AJ, 105, 1927

Hetem, A., & Lépine, J. R. D. 1993, A&A, 270, 451

Lada, E. A., Strom, K. M., & Myers, P. C. 1993, in Protostars and Planets III, E. H. Levy & J. I. Lunine, Tucson: University of Arizona Press, 245

Larson, R. B. 1972, MNRAS, 156, 437

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

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

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

Larson, R. B. 1990, in Physical Processes in Fragmentation and Star Formation, R. Capuzzo-Dolcetta, C. Chiosi, & A Di Fazio, Dordrecht: Kluwer, 389

Larson, R. B. 1991, in Fragmentation of Molecular Clouds and Star Formation, IAU Symp. No. 147, E. Falgarone, F. Boulanger, & G. Duvert, Dordrecht: Kluwer, 261

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

Larson, R. B. 1993, in The Globular Cluster-Galaxy Connection, G. H. Smith & J. P. Brodie, San Francisco: ASP, 675

Larson, R. B. 1994, in The Structure and Content of Molecular Clouds, T. L. Wilson, Berlin: Springer-Verlag, in press

Leinert, Ch., Zinnecker, H., Weitzel, N., Christou, J., Ridgway, S. T., Jameson, R., Haas, M., & Lenzen, R., 1993, A&A, 278, 129

Mandelbrot, B. 1982, The Fractal Geometry of Nature, New York: Freeman

Mathieu, R. D. 1994, ARA&A, 32, in press

Mezger, P., Sievers, A. W., Haslam, C. G. T., Kreysa, E., Lemke, R., Mauersberger, R., & Wilson, T. L. 1992, A&A, 256, 631

Mezger, P., 1994, in The Structure and Content of Molecular Clouds, T. L. Wilson, Berlin: Springer-Verlag, in press

Miyama, S., Narita, S., & Hayashi, C. 1987, Prog.Theor.Phys., 78, 1051 & 1273

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

Myers, P. C. 1987, in Star Forming Regions, IAU Symp. No. 115, M. Peimbert & J. Jugaku, Dordrecht: Reidel, 33

Piché, F. 1993, PASP, 105, 324

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

Scalo, J. 1990, in Physical Processes in Fragmentation and Star Formation, R. Capuzzo-Dolcetta, C. Chiosi, & A. Di Fazio, Dordrecht: Kluwer, 151

Silk, J. 1978, in Protostars & Planets, IAU Colloq. No. 52, T. Gehrels, Tucson: University of Arizona Press, 172

Simon, M., 1992, in Complementary Approaches to Binary and Multiple Star Research, IAU Colloq. No. 135, H. A. McAlister & W. I. Hartkopf, San Francisco: ASP, 41

Wilking, B. A. 1992, in Low Mass Star Formation in Southern Molecular Clouds, ESO Scientific Report No. 11, B. Reipurth, Garching: ESO, 159

Wilking, B. A., Lada, C. J., & Young, E. T. 1989, ApJ, 340, 823

Zimmermann, T., & Stutzki, J. 1992, Physica A, 191, 79

Zinnecker, H., McCaughrean, M. J., & Wilking, B. A. 1993, in Protostars and Planets III, E. H. Levy & J. I. Lunine, Tucson: University of Arizona Press, 429