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Star formation in groups

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ABSTRACT

In order to study the relation between clustering and binary formation, the analysis by Gomez et al. of the clustering of young stars in the Taurus region has been extended to smaller separations by using data from recent searches for close companions to these stars. The Taurus young stars are found to exhibit self-similar or fractal clustering on the largest scales, but there is a clear break from self-similarity at a scale of about 0.04 pc which divides the regime of binary and multiple systems on smaller scales from that of true clustering on larger scales. This break provides clear evidence for the existence of an intrinsic scale in the star formation process, and this scale is found to be essentially equal to the Jeans length in typical molecular cloud cores. The associated mass is of the order of one solar mass, supporting the hypothesis that typical stellar masses are determined by the Jeans mass. Both the self-similar clustering of the Taurus stars on the larger scales and the power-law form of the upper stellar IMF may have their origin in hierarchical, and perhaps fractal-like, cloud structure. The very different distribution of stellar separations that is observed in the regime of binary and multiple systems strongly suggests that these systems are not formed in the same way as the hierarchical clustering, but by a distinct mechanism which is probably the fragmentation of collapsing clumps of about the Jeans size. The evidence suggests that nearly all stars are formed in binary or multiple systems, and that some of these systems are subsequently disrupted by interactions in the denser star-forming environments to produce the observed mixture of single, binary and multiple stars.

Key words: binaries: general – stars: formation – ISM: clouds – open clusters and associations: general.

1 INTRODUCTION

Much evidence indicates that stars prefer to form in groups of various sizes rather than singly. On the smallest scales, most stars belong to 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 youngest visible stars, the T Tauri stars, appear to have an even higher frequency of close companions than do main-sequence stars (Ghez, Neugebauer & Matthews 1993; Leinert et al. 1993; Reipurth & Zinnecker 1993; Mathieu 1994). On larger scales, most of the newly formed stars in nearby well-studied regions of star formation are observed to be in groups or clusters; even in the relatively sparse Taurus region, most of the newly formed stars are located in small groups (Larson 1982; Myers 1985; Gomez et al. 1993), while in the Ophiuchus and Orion regions, most of the newly formed stars are in compact clusters associated with the most massive molecular cloud cores (Lada & Lada 1991; Lada, Strom & Myers 1993; Zinnecker, McCaughrean & Wilking 1993). Thus, in addition to being formed in binary or multiple systems, most stars are also formed as members of larger groups or clusters. Many young star clusters even contain subclusters (Elson 1991; Piché 1993), so that star formation may generally be a hierarchical process that involves clustering on a range of scales. A well-known example of hierarchical star formation is provided by the Trapezium cluster (Zinnecker et al. 1993), which contains two subgroups of newly formed massive stars, one of which is embedded in the Kleinmann–Low infrared nebula and the other of which, the Trapezium itself, is a hierarchical multiple system, most of whose members are close binaries.

A number of questions are raised by this evidence that star formation is a hierarchical process. An obvious one is whether stellar groupings of all sizes, including binary and multiple systems, belong to a single self-similar clustering hierarchy; if so, this would suggest that all of these groupings might have a common origin. One possible mechanism for

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forming them would be the self-similar hierarchical fragmentation of a star-forming cloud, as has been postulated to account both for the formation of binaries (Bodenheimer 1978) and for the origin of the stellar initial mass function (IMF) (Elmegreen 1985). Another possibility is that turbulence might generate the required hierarchical structure in star-forming clouds (Larson 1981; Scalo 1987, 1988; Falgarone 1989). On the other hand, it is possible that star formation processes are not similar on different scales because of the existence of preferred length and mass scales; in this case a departure from self-similarity in the clustering properties of young stars might be expected. A well-known example of such a preferred scale is the Jeans length, which may play an important role in determining stellar masses (Larson 1985, 1991); the Jeans length separates two physical regimes such that thermal pressure provides the dominant support against gravity on smaller scales, whereas turbulent and magnetic pressures predominate on larger scales.

A related question concerns the relation, if any, that may exist between the hierarchical clustering of newly formed stars and the hierarchical structure often observed in molecular clouds (Scalo 1985, 1988, 1990). Several indications suggest that the hierarchical structure of molecular clouds may be roughly self-similar; a number of studies have found, for example, that the boundary shapes of these clouds have a fractal character (Scalo 1990; Falgarone, Phillips & Walker 1991; Falgarone 1992; Zimmermann & Stutzki 1992). Also of interest is the question of what relation may exist between hierarchical cloud structure and the approximate scaling laws that have been found relating the linewidths, sizes and densities of molecular clouds (Larson 1981; Myers 1985; Falgarone, Puget & Pérault 1992).

New data relevant to these questions have been provided by recent studies of the spatial distribution of the young stars in the Taurus region, and by recent searches for additional close companions to these stars. Gomez et al. (1993) have derived the two-point angular correlation function for the young stars in the Taurus region, and they have found that it can be roughly approximated by a power law on all scales between ~ 0.005 and 5 pc, suggesting that these stars are clustered in a self-similar fashion over a wide range of scales. They also note, however, that there is marginal evidence for a change in the slope of the correlation function at a separation of ~ 0.04 pc; more data for systems with small separations are therefore needed to establish whether a single power law is an adequate approximation at all separations, and whether the apparent self-similarity of clustering extends into the regime of binary and multiple systems. Such data are now available from the searches for close companions to these stars conducted by Simon (1992), Ghez et al. (1993) and Leinert et al. (1993), and these data can be used to extend the clustering analysis to smaller separations and address more definitively the question of the relation between clustering and binary formation. The results presented in Section 2 clearly confirm the existence of a break in the slope of the correlation function at a separation of 0.04 pc, and thus provide evidence for the existence of an intrinsic scale of this order in the star formation process. The clustering of the Taurus young stars appears to be self-similar on scales larger than this, and the relation between this clustering and the scaling properties of molecular clouds is discussed in Section 3. The implications of these results for our understanding of the stellar IMF are discussed in Section 4, and implications for the formation of binary and multiple systems are discussed in Section 5.

2 CLUSTERING AND CLOSE COMPANIONS OF T TAURI STARS

As Gomez et al. (1993) have noted, the presently available sample of optically visible young stars in the Taurus–Auriga region includes nearly all of the known pre-main-sequence stars in this region, since only a few additional optically invisible objects have been found in infrared surveys. This sample of stars also appears to be essentially complete to a V magnitude of 15.5, since recent searches have found very few new stars brighter than this. It therefore appears that the available sample of visible young stars in the Taurus region is sufficiently complete to warrant a quantitative analysis of their clustering properties. Most of these stars are so young that they cannot have moved very far from their birthplaces, and therefore their present spatial distribution must closely reflect that with which they were formed.

A plot of the distribution on the sky of the visible young stars in the Taurus region is shown in fig. 1 of Gomez et al. (1993), where it can be seen that these stars are clustered hierarchically, with smaller groupings within larger ones over a considerable range of scales. Gomez et al. have analysed this clustering using the two-point angular correlation function, which has been widely used for studying the clustering of galaxies, and they have found that, as is the case for galaxies, the correlation function of the Taurus young stars can be roughly approximated as a declining power-law function of separation. They also note, however, that there is a 'very marginal indication' of a change in the logarithmic slope of this function at an angular separation of about $0\overset{\circ}{.}016$, which corresponds to a linear separation of about 0.04 pc. The correlation function derived by these authors does not extend to separations smaller than 6 arcsec, and therefore it does not include most binary and multiple systems, which have separations smaller than this. The recent searches for close companions to the T Tauri stars in this region conducted by Simon (1992), Ghez et al. (1993) and Leinert et al. (1993) have yielded many new data for companions with separations as small as ~ 0.1 arcsec, and these data can be used to extend the clustering analysis to much smaller separations.

In order to present the results of all of these studies in a homogeneous and physically meaningful way, the data from each survey have been used to calculate the average surface density of companions on the sky as a function of angular distance from each star, the average being taken over all of the stars observed in each survey, including the newly discovered ones. The average companion surface density has been used in preference to the two-point angular correlation function, which is proportional to the excess surface density of companions above that expected for a uniform stellar distribution, because the actual surface density is the more relevant quantity to examine in looking for possible scaling relations or fractal clustering. The correlation function presented 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 resulting average companion surface density is plotted as a function of angular separation in Fig. 1, and is indicated by the solid dots with statistical error bars. This function is very similar in its general appearance to the correlation function plotted by Gomez et al., except at the largest separations where the actual surface density declines less rapidly with separation than does its excess above a uniform distribution.

Both Ghez et al. (1993) and Leinert et al. (1993) have tabulated all of the known close companions of the stars observed by them, including both the previously known and the newly discovered ones in each case. Leinert et al. observed a large number of T Tauri stars in the Taurus–Auriga region, including most of those in the sample of Gomez et al., while Ghez et al. also observed many of these same stars and, in addition, observed a smaller number of stars in the Ophiuchus region. Since the Ophiuchus star-forming region is similar in its general properties to the Taurus region and lies at nearly the same distance, the Ophiuchus stars have been included here to increase the statistics, although this makes little difference to the results. Both surveys used *K*-band speckle imaging to detect close companions, and they extended to roughly similar limits in *K* magnitude and separation: the Leinert et al. survey is complete for *K* magnitudes brighter than 9.5 and for separations between 0.13 and 13 arcsec, while Ghez et al. observed a somewhat less complete sample of stars with *K* magnitudes down to 8.5 for the brighter component and 10.5 for any fainter companion, and with separations between 0.07 and 2.5 arcsec. Whenever both surveys observed the same stars, they found the same companions in the overlapping range of separations, and the properties derived for these companions were in good agreement.

The tabulations of Ghez et al. (1993) and Leinert et al. (1993) have been used independently to calculate the average surface density of companions per star as a function of separation, binning the listed companions in intervals of a factor of 2 in angular separation and counting each pair of stars as containing two companions. The results are indicated in Fig. 1 by the open circles (Ghez et al.) and the crosses (Leinert et al.). The results of these two surveys are seen to be in excellent agreement, as would be expected since they included many of the same stars and found many of the same companions. In order to extend these results to even smaller separations, an additional point (the open square) has been added to Fig. 1 at a separation of 10^{-5} deg (about 5 au), based on data from the lunar occultation survey of T Tauri stars in Taurus by Simon (1992).

Although there is little overlap in separation between these binary searches and the clustering study of Gomez et al. (1993), the results of all of these investigations appear to be quite consistent with each other, and they all indicate the same well-defined trend as a function of separation. It is immediately clear from Fig. 1 that, when all of the data are considered, the dependence of average companion surface density on separation cannot be represented by a single power law at all separations; instead, this function has very different slopes at small and large separations, with a clear break at a separation of about 0°.017 or 0.04 pc. This result confirms the tentative suggestion of Gomez et al. (1993) that the correlation function changes slope at about this point. Thus self-similar clustering does not extend over the entire

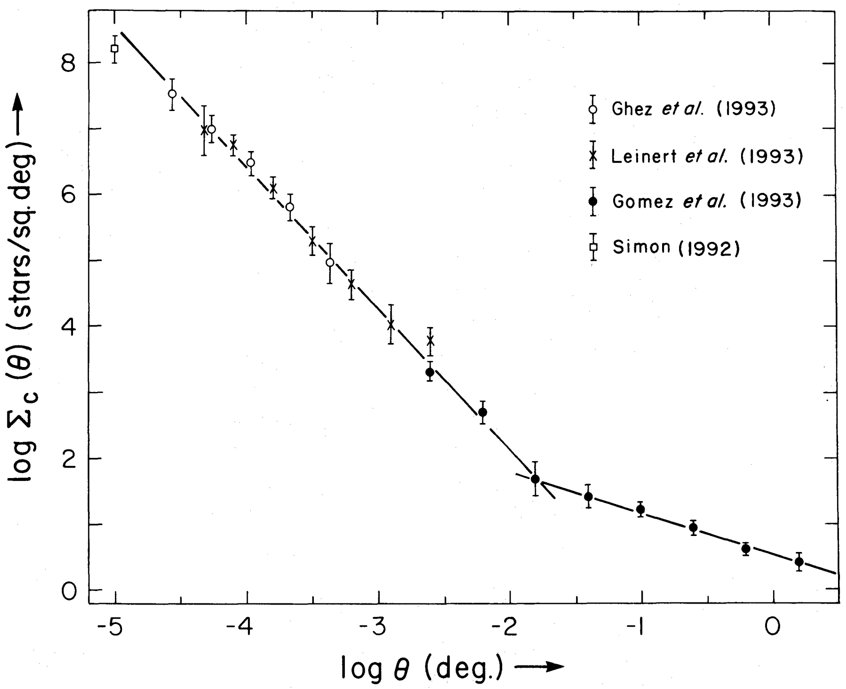

Figure 1. The surface density Σ_c of companions on the sky, averaged over all of the stars observed in each study, is plotted as a function of angular separation θ for the four indicated studies of young stars and their close companions in the Taurus–Auriga region. The power-law fits shown for large and small separations are given by equations (1) and (2), respectively, and they intersect at a separation of about 0°.017 or 0.04 pc.

range of scales illustrated in Fig. 1, and the results instead provide clear evidence for the existence of an intrinsic scale of the order of 0.04 pc in the star formation process.

At separations larger than 0.04 pc, each star typically has more than one companion, so this range of separations might be regarded as the regime of true clustering. At these larger separations, the average companion surface density is well approximated by a power-law function of separation, as can be seen in Fig. 1; in fact, it follows a power law more closely than does the correlation function of Gomez et al. (1993). This result suggests that the young stars in the Taurus region are clustered in a self-similar fashion on scales larger than ~0.04 pc. The power-law fit illustrated in Fig. 1 for these larger separations is given by

$$\Sigma_c = 3.4\,\theta^{-0.62}, \tag{1}$$

where Σ_c is the average surface density of companions per star measured in stars per square degree, and θ is the angular separation in deg; this approximation is valid for separations between about 0.017 and 2 deg, or between 0.04 and 5 pc. Equation (1) implies that the number of companions within an angular distance θ of an average star increases as $\theta^{1.38}$, and hence that, over this range of separations, the distribution of these stars on the sky can be described as a fractal point distribution with a dimension of about 1.4. This suggests that the distribution of these stars in space is also a fractal distribution with a dimension of ~1.4, since the projection on a plane of any fractal distribution of points in space whose dimension is less than 2 is also a fractal with the same dimension (Mandelbrot 1982).

At separations less than 0.04 pc, the average star in Taurus has slightly more than one companion (as will shortly be shown), so this range of separations may be regarded as the regime of binary and multiple systems. In this regime the dependence of average companion surface density on separation can again be approximated by a power law, although in this case such a power law does not represent self-similar clustering but corresponds instead to a distribution of binary separations. The power-law fit shown in Fig. 1 for the smaller separations is given by

$$\Sigma_c = 0.0064\,\theta^{-2.15}, \tag{2}$$

where this approximation is valid for angular separations between about 2×10^{-5} and 0.017 deg, or linear separations between 10 and 8000 au. If this approximation for the average companion surface density as a function of separation is integrated with respect to area on the sky, it implies that the average star in Taurus has about 0.9 companions within the above range of separations; if the known companions at smaller separations (Simon 1992) are added, this number increases to about 1.0. Allowing for the fact that a few stars have even closer companions (Mathieu 1994), we conclude that the average T Tauri star in the Taurus region has a little more than one companion within 0.04 pc. If the distribution of binary separations implied by equation (2) is expressed in the usual way as the number of pairs per unit logarithmic separation interval, this distribution varies only as $\theta^{-0.15}$ and so is almost independent of separation; this result is consistent with the known distribution of separations of field main-sequence binaries, which is very broadly peaked and is flat or slowly declining in this range of separations (Duquennoy & Mayor 1991; Ghez et al. 1993).

The main results found above are unlikely to be significantly influenced by sample incompleteness effects. For example, one such effect is the fact that the Gomez et al. (1993) study does not include as many close companions per star as the other data sources used, since it becomes incomplete for companions closer than about 3 arcsec and contains no companions with separations less than 1.5 arcsec. Equation (2) implies that the average T Tauri star in the Taurus region has about 0.5 companions with separations between 0.1 and 3 arcsec; if this number of companions were added to the Gomez et al. sample to make it more comparable to the others, the total number of stars in the sample would be increased by a factor of 1.5, and the average surface density of companions would therefore be increased by this same factor at all separations larger than 3 arcsec. This correction would move the solid dots in Fig. 1 upward by only 0.17 in the logarithm, which is about the typical size of the error bars on these points, and this would decrease slightly the best-fitting slope in the binary regime but would leave unaltered the slope in the clustering regime and the location of the break in slope.

The length scale of ~0.04 pc that has been found to separate the binary regime from the clustering regime is clearly one of fundamental significance for star formation, so it is particularly noteworthy that it is essentially equal to the Jeans length in typical molecular cloud cores, or more precisely to the radius of the smallest clump that can collapse to form a star (Larson 1985, 1991). It also seems significant that the mass of an isothermal sphere with this radius and a temperature of 10 K is about 0.8 $M_\odot$, a typical stellar mass; thus the length-scale found above also appears to be relevant to determining stellar masses. The fact that the Taurus young stars exhibit self-similar clustering only on scales larger than ~0.04 pc suggests that this scale represents the size of the basic units from which the clustering hierarchy is built; as was noted above, these basic units typically form binary systems rather than single stars. The implications of these results for cluster formation, the origin of the IMF, and the origin of binary systems will be discussed further in the following sections.

3 CLUSTERING AND CLOUD STRUCTURE

The clustering of the Taurus young stars presumably originated from pre-existing hierarchical structure in the progenitor clouds. Hierarchical structure consisting of clumps within clumps is, in fact, often observed in molecular clouds (Larson 1981; Scalo 1985, 1988, 1990). A description of this observed structure in terms of a tree hierarchy has been proposed by Houlahan & Scalo (1992), who claim on this basis that there is 'moderate evidence' for hierarchical clumping in the Taurus clouds. The possibility that molecular clouds also possess some degree of self-similarity in their structure is suggested by the existence of approximate scaling laws relating the sizes, densities, and internal velocity dispersions of molecular clumps and clouds of various sizes (Larson 1981; Myers 1985; Scoville & Sanders 1987; Falgarone et al. 1992).

Direct evidence for self-similarity in the structure of molecular clouds is provided by the fact that the boundaries of these clouds on contour maps are fractal curves with dimensions $D_2 \sim 1.4$–1.5 (Falgarone et al. 1991; Falgarone

1992; Zimmermann & Stutzki 1992; Hetem & Lépine 1993). This suggests that the isodensity surfaces of these clouds in three dimensions are fractal surfaces with dimensions $D_3 \simeq D_2 + 1 \sim 2.4$–$2.5$ (Falgarone 1989; Falgarone & Phillips 1991); this relation between the dimension D_3 of the isodensity surfaces of clouds and the dimension D_2 of their projected boundaries is supported by the simple models of Hetem & Lépine (1993) of clouds with fractal isodensity surfaces. Such fractal shapes might be produced by turbulence, since turbulent flows are characterized by fractal interfaces whose typical dimension $D_3 \simeq 2.35$ is similar to the dimensions inferred for the surfaces of molecular clouds (Falgarone 1989; Falgarone & Phillips 1991; Sreenivasan 1991).

The surface shapes of star-forming clouds may not be very relevant, however, to the clustering of the sites of star formation within them, which presumably depends more on the internal mass distributions in these clouds. At present, it is unclear to what extent fractal descriptions may be applicable to the internal mass distributions of molecular clouds, but a possible cloud model having a roughly fractal character on large scales is one in which most of the mass is concentrated in clumps of similar mass that are distributed spatially in a self-similar clustering hierarchy. If this clustering hierarchy has a fractal dimension D, then the amount of mass M contained in a sphere of radius R centred on any object in the hierarchy will be approximately proportional to R^D. Cloud models of this type have been considered by Pfenniger & Combes (1994), who favour dimensions in the range $D \sim 1.5$–2.0 as providing the best representation of real molecular clouds. Dimensions in this range are suggested by the scaling relations noted above: many studies have found that the internal velocity dispersions of clumps and clouds of various sizes increase with size roughly as R^n, where $n \sim 0.3$–0.6 (Larson 1981; Myers 1983, 1985; Scoville & Sanders 1987; Falgarone et al. 1992; Myers & Fuller 1992); if these objects are in virial equilibrium, as appears to be the case at least for the larger ones (Falgarone et al. 1992), their masses must then increase with size as R^D, where $D \sim 1.6$–2.2. These studies also typically find that the average densities of molecular clouds vary with size roughly as R^{-1}, implying a mass–radius relation of the form $M \propto R^2$. Clearly, such a fractal description of the mass distributions in molecular clouds must be highly idealized because not all of the cloud mass is in clumps of the same mass, and also because the observed mass–radius relation must partly reflect smooth density gradients rather than fractal structure, but such a model might nevertheless provide a useful, if rough, way of characterizing how the mass in molecular clouds is distributed on large scales.

It therefore seems at least plausible that the observed hierarchical clustering of the newly formed stars in Taurus could have originated from hierarchical and perhaps fractal-like mass distributions in the parent molecular clouds. If so, the fact that the dimension $D \sim 1.4$ characterizing the clustering of the newly formed stars is smaller than the dimension $D \sim 1.8$ characterizing the mass distributions in typical clouds suggests that the star formation process involves, or is accompanied by, a decrease in the dimensionality of the mass distribution in a star-forming cloud. A decrease in the dimensionality of the mass distribution is, in fact, predicted by nearly all scenarios and calculations of cloud collapse and fragmentation; for example, it is possible that an initially spherical cloud collapses first to a flattened sheet or disc which then breaks up into filaments and finally into clumps (Larson 1985; Miyama, Narita & Hayashi 1987a,b; Monaghan & Lattanzio 1991), each stage of the process involving a decrease in the dimensionality of the mass distribution.

All of the scaling relations mentioned above might then be related in an evolutionary sense, the fractal dimension of the mass distribution decreasing steadily with time as a cloud collapses and fragments. Turbulent gas dynamics might initially produce a wispy structure with a dimension greater than 2, perhaps qualitatively as illustrated by the simulations of Passot, Pouquet & Woodward (1988). Dissipation of turbulent motions might then allow regions of enhanced density in this fractal structure to condense into a hierarchy of bound clumps (Scalo 1987, 1988; Pouquet, Passot & Léorat 1991; Elmegreen 1993), a process that might be regarded as a type of fragmentation. The formation of such a hierarchy of clumps within clumps in a turbulent compressible medium is illustrated by the numerical simulations of Léorat, Passot & Pouquet (1990) and Vázquez-Semadeni (1994). Since any fragmentation process involves the contraction of the denser parts of a cloud into a progressively smaller fraction of the total volume, it implies a decrease in the dimensionality of the mass distribution. Most molecular clouds are apparently observed when their effective fractal dimensions have decreased to values of the order of 2 or somewhat less. Continuing fragmentation will produce a continuing decrease in this dimension, and the results obtained above suggest that stars eventually form when the cloud substructures from which they form have attained a fractal dimension of only ~ 1.4.

It is plausible that the mass distribution in a star-forming cloud would retain an initial fractal character as the cloud collapses and fragments, as is illustrated by the following example. Mandelbrot (1982) illustrates on pages 306–309 a 'Swiss cheese' fractal whose dimension is continuously decreased by increasing the sizes of the holes; its fractal nature is preserved as long as the sizes of the holes are all increased in the same ratio. Such a model describes qualitatively the evolution of the large-scale structure in the Universe by the growth and overlapping of voids. If molecular clouds are formed with similar sponge-like structures, their evolution might proceed in a qualitatively similar way: as such a cloud contracts under its self-gravity, the empty regions will not shrink as fast as the cloud as a whole since they have relatively little self-gravity, and therefore they will occupy an increasing fraction of the volume and in effect will expand and overlap to an increasing degree. The appearance and growth of nearly empty regions is seen in some numerical simulations of cloud collapse and fragmentation, which show the development of a cell structure similar to that seen in cosmological simulations (Monaghan & Lattanzio 1991). If a sponge-like cloud contracts by a scale factor while the holes in it do not contract, each hole will increase in size relative to the rest of the cloud by this same factor, and therefore the fractal character of the cloud will be preserved as its fractal dimension decreases. Obviously such a model must again be highly idealized, but it may at least add plausibility to the idea that a cloud can retain a fractal character as it collapses and fragments.

4 IMPLICATIONS FOR THE STELLAR INITIAL MASS FUNCTION

As has been reviewed previously by Larson (1986, 1991), there are two basic features of the observed stellar IMF that need to be understood theoretically: (1) the existence of a characteristic stellar mass of the order of one solar mass, possibly depending on environment, and (2) the existence of a high-mass tail on the IMF having an apparently universal power-law form. The results discussed in the preceding sections have implications for our understanding of both of these features of the IMF.

As was noted in Section 2, the fact that the clustering of the Taurus stars departs from self-similarity at a scale comparable to the Jeans length supports the relevance of this theoretically predicted length-scale to star formation. Since the associated mass is about 0.8 $M_\odot$, this result also supports the hypothesis that typical stellar masses are determined basically by the Jeans mass (Larson 1985, 1986, 1991). The exact relation between the Jeans mass and typical stellar masses depends on how much continuing fragmentation may occur in a collapsing Jeans-mass clump, but this question is now answered by the finding in Section 2 that, on the average, slightly more than two stars are formed in a region of this size. The predicted characteristic mass of an individual star is then about half of the Jeans mass, or roughly 0.4 $M_\odot$. This value is similar to the masses inferred for many of the pre-main-sequence stars observed in Taurus and other nearby regions of star formation (Larson 1982, 1986; Zinnecker et al. 1993). Of more fundamental significance than the quantitative details, however, is the fact that the spatial distribution of the Taurus young stars departs markedly from self-similarity at a mass scale of the order of one solar mass, which corresponds to typical stellar masses; this strongly suggests that stellar masses are determined by features of the star formation process itself, rather than by the feedback effects of forming stars on their environment.

The most massive stars must obviously have formed from cloud regions whose masses are much larger than one solar mass, and such regions are likely to have complex internal structures and to contain many Jeans-mass clumps (Larson 1981). Theory and observations both suggest that the most massive stars form by accumulation processes in dense groups or clusters of forming stars (Bastien 1981; Larson 1978, 1982, 1991). If these groups are hierarchically structured as discussed above, then a relation might be expected to exist between the clustering properties of newly formed stars and the form of the IMF, since the larger subgroups can form more massive stars. If the accumulation processes involved are scale-free, then the mass of the most massive star that can form in each subgroup might be expected to increase as some power n of the mass of the subgroup, and, if all stars are formed in a self-similar clustering hierarchy, this implies a power-law IMF with a slope $x = 1/n$ (Larson 1991, 1992). If star-forming clouds have fractal structures, the IMF slope x might be expected to be related to the cloud fractal dimension D; for example, if the mass of the most massive star that can form in each subgroup is proportional to the size of the corresponding cloud region, the predicted relation between x and D is simply $x = D$ (Larson 1992).

Larson (1992) suggested that the relevant value of D in this fractal model for the IMF is approximately the dimension $D_3 \sim 2.3$ of the isodensity surfaces of molecular clouds; however, it now seems likely from the discussion in Section 3 that a more relevant dimension is that characterizing the mass distribution in molecular clouds, and that this 'mass dimension' is smaller than the surface dimension and perhaps only ~ 1.8. If it is assumed again that the mass of the most massive star that can form in each subgroup is proportional to the size of the associated cloud region, the predicted IMF slope then becomes $x \sim 1.8$; this is in better agreement with the range of values $x = 1.7 \pm 0.5$ found from the observations by Scalo (1986), possibly adding support to the idea that the power-law form of the upper IMF is related to self-similar hierarchical structure in star-forming clouds.

5 IMPLICATIONS FOR THE ORIGIN OF BINARY AND SINGLE STARS

The marked difference in slope seen in Fig. 1 between the regime of binary systems and the regime of hierarchical clustering strongly suggests that binary and multiple systems are not formed by the same processes that create the clustering hierarchy discussed above, but by a distinct mechanism that yields a much higher proportion of systems with small separations. The almost flat distribution of logarithmic separations implied by equation (2) is consistent with the known distribution of separations of main-sequence field binaries, which is flat or slowly declining over the same range of separations (Duquennoy & Mayor 1991; Ghez et al. 1993). Unlike the hierarchical clustering discussed above, such a distribution cannot be described in fractal terms with any positive dimension D.

The results found above argue against the formation of binary systems by any process that does not somehow involve a scale of ~ 0.04 pc and favour the formation of systems smaller than this compared with systems of larger separation; in particular, it seems inconsistent with the suggestion of Larson (1990) that many binaries are formed by captures mediated by interaction with protostellar discs of radius ~ 100 au, since such a process would not clearly imprint a scale of ~ 0.04 pc on the resulting stellar distribution, and would operate effectively only on much smaller scales. Random capture processes probably could not in any case account for the observed frequency of close binaries (Larson 1990; Pringle 1991; Clarke 1992; Heller 1994). The above results instead seem more consistent with the conventional view that binary systems are formed by the fragmentation of collapsing clumps of roughly the Jeans size (Larson 1972; Boss 1992, 1993a; Bodenheimer, Ruzmaikina & Mathieu 1993). Capture might still play a role in the formation of binaries if the interacting protostars involved have extended envelopes comparable in size to the Jeans length (Silk 1978), but such protostars would have to be at an early stage of evolution, and it would then be difficult to distinguish capture from fragmentation.

Much recent theoretical work has focused on the possibility that binary and multiple systems are formed by the fragmentation of slowly rotating elongated structures or filaments. Most star-forming cloud cores are observed to be elongated (Myers et al. 1991), and they are also slowly rotating, although their rotation is not dynamically significant and they generally do not rotate about any symmetry axis

(Goodman et al. 1993). Numerical simulations of the collapse and fragmentation of such configurations have shown that they typically fragment into two or more objects, and can form binary and multiple systems with a wide range of properties (Larson 1972; Bastien et al. 1991; Bonnell et al. 1991, 1992; Boss 1993b; Burkert & Bodenheimer 1993; Nelson & Papaloizou 1993). Although no predictions have yet been attempted for the statistical properties of the binaries so formed, the complex and quasi-chaotic dynamics of such systems appears to allow the possibility of producing binaries with a wide range of separations (Pringle 1991; Clarke 1992), in qualitative agreement with what is observed.

Similar processes may have played a role even in the formation of most single stars if these stars were actually formed in binary or multiple systems that were later disrupted by interactions (Larson 1972; Ghez et al. 1993). This type of origin for many single stars is supported by the fact that the pre-main-sequence stars in Taurus have a higher frequency of close companions than do field main-sequence stars (Mathieu 1994), which suggests that nearly all stars are formed in binary or multiple systems, and that some of these systems are later disrupted to produce the combination of single, binary, and multiple systems now observed in the field. Even our Sun may have formed in a dense cluster or multiple system, since the tilt of our planetary system with respect to the solar equatorial plane can plausibly be explained as resulting from a close encounter in a dense system of young stars (Heller 1993). In this respect, the relatively sparsely populated Taurus region may not be a typical star-forming environment, since most stars may actually form in denser regions like the compact young clusters in Orion (Lada & Lada 1991; Lada et al. 1993; Zinnecker et al. 1993). For a typical binary system in Taurus, the median distance to the next nearest star implied by equation (1) is about 0.3 pc, which is probably too far away for multiple interactions to be important in most cases. However, in the Trapezium cluster the stellar density is about three orders of magnitude higher than in the Taurus region, and, if the stars in the Trapezium cluster had formed with a hierarchical distribution similar to that of the Taurus stars but with an appropriately higher density normalization, the nearest companion of a typical binary would have been only about 1000 au away; multiple interactions would then have been important, at least for the wider systems, and would have disrupted some of the binary and multiple systems formed initially. In fact, the Trapezium cluster has a lower frequency of binaries than the Taurus region, and one which is consistent with that of main-sequence field stars (Mathieu 1994; Prosser et al. 1994), as would be expected if the Trapezium cluster is a more typical site of star formation than the Taurus region. The relatively high frequency of binaries in Taurus may then simply reflect the relative lack of disruptive interactions in this relatively low-density environment.

6 SUMMARY AND CONCLUSIONS

Data from several recent studies of the spatial distribution of the newly formed stars in the Taurus region have been used to derive the average surface density of companions as a function of separation, and the results show that this function cannot be represented by a single power law at all separations; instead, it shows a clear break in slope at a separation of about 0.04 pc which divides the regime of binary systems on smaller scales from that of hierarchical clustering on larger scales. This result provides clear evidence for the existence of an intrinsic length-scale in the star formation process, and this length-scale is found to be comparable to the Jeans length in typical molecular cloud cores.

On scales larger than 0.04 pc, the dependence of the average companion surface density on separation is well approximated by a power law, indicating that on these scales the Taurus young stars exhibit self-similar clustering which can be described as a fractal distribution with a dimension of about 1.4. This hierarchical clustering probably originates from pre-existing hierarchical structure in the progenitor molecular clouds, although the mass distributions in molecular clouds are typically characterized by a somewhat larger dimension of about 1.8. The fractal surface shapes of molecular clouds have an even larger dimension of about 2.4. All of these indicators of scaling or fractal structure in star-forming clouds may be related in an evolutionary sense, the dimensionality of the mass distribution decreasing continually with time as a cloud collapses and fragments.

The departure from self-similarity in the clustering of the Taurus young stars at a length-scale of ~ 0.04 pc and a mass scale of $\sim 0.8\ M_\odot$ supports the relevance of the Jeans length and mass to star formation, and in particular their relevance in determining stellar masses. The average young star in Taurus has about one companion within 0.04 pc, so that two stars are typically formed in a region of this size. The predicted characteristic mass of an individual star is then about half of the Jeans mass, or roughly $0.4\ M_\odot$, in reasonable agreement with observations. The power-law form of the upper IMF may originate from the self-similar hierarchical structure of molecular clouds; if the dimension best characterizing this structure is ~ 1.8, rather than 2.3 as suggested earlier by Larson (1992), the IMF slope predicted by the simple model presented in that earlier paper becomes $x \sim 1.8$, in better agreement with observations.

The much steeper dependence of companion surface density on separation that is found in the regime of binary systems suggests that binary systems are not formed in the same way as the hierarchical clustering, but by a distinct process that produces a much larger proportion of systems with small separations. This excludes at least some versions of the capture hypothesis for the origin of binaries, but is consistent with the more conventional view that binaries are formed by the fragmentation of collapsing clumps of about the Jeans size. The fact that the Taurus stars have a higher companion frequency than field main-sequence stars suggests that nearly all stars are formed in binary or multiple systems, and that some of these systems are subsequently disrupted. In this respect, the relatively sparsely populated Taurus region may not be a typical star-forming environment, and most stars may form in denser regions like the Orion compact clusters where disruptive interactions are more important. The relatively high binary frequency in Taurus may then just reflect the relative lack of disruptive interactions in this low-density environment.

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