FORMATION OF SMALL AND LARGE STELLAR SYSTEMS

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ABSTRACT

Current evidence indicates that stars form in a hierarchy of groupings of various sizes, within which binary systems stand out as distinct tightly bound units. The distribution of separations of binaries resembles the internal spatial distributions of stars in larger systems, including massive young star clusters and elliptical galaxies, and this suggests that similar mechanisms may be involved in structuring stellar systems on a wide range of scales. Gravitational drag or dynamical friction effects are almost certainly important in all cases, and may account for the characteristic very broad, almost uniform logarithmic distribution of stars in separation or distance from the center that is observed in systems ranging in size from binary and multiple systems to elliptical galaxies.

1. Introduction

Stars are observed to be distributed in systems with an enormous range of sizes, extending from binary and multiple systems through clusters and associations to galaxies, galaxy clusters, and cosmological large-scale structure. As our understanding of the formation of systems of various sizes has increased, it has become increasingly clear that the origin of structure on any one scale cannot be fully understood without understanding the influence of structure on other scales. This is especially clear in the case of galaxies, since they originate as parts of larger-scale cosmological structures, and interactions with close neighbors can strongly influence their formation and evolution. More recently, it has become clear that stars, too, form in a hierarchy of groupings of various sizes; for example, most stars are located in binary or multiple systems, and the frequency of close companions is even higher among the youngest stars, suggesting that nearly all stars are formed in such systems (Abt 1983; Mathieu 1994; Larson 1995). Therefore star formation cannot be properly understood without understanding the formation of binary and multiple systems. Young stars are also typically distributed in larger groupings of various sizes (Blaauw 1964, 1991; Larson 1982; Gomez et al. 1993), and it appears that most stars form not only in binaries but also in clusters like those containing most of the newly formed stars in nearby regions of star formation (Lada & Lada 1991; Lada, Strom, & Myers 1993; Zinnecker, McCaughrean, & Wilking 1993). Thus, the evidence suggests that star formation is intrinsically a hierarchical process that forms groupings on a wide range of scales.

The fact that galaxies typically form in close proximity to other galaxies means that tidal interactions and mergers can play an important role in determining their structures. The formation of elliptical galaxies, in particular, almost certainly involves the merging of smaller systems of some kind (Toomre 1977; Larson 1990b, 1992), and this process appears to account well for the characteristic light profiles of these galaxies (White 1978; Villumsen 1982, 1983; Barnes 1990, 1992; Katz 1991). Similarly, if stars form in close groupings with other stars, protostellar interactions can play an important role by transferring angular momentum away from the condensing protostars and dissipating their orbital energy, causing them to form tighter groupings and perhaps even accounting for the formation of binaries (Larson 1982, 1984, 1990a). Thus it is important to study the clustering properties of newly formed stars, just as it is important to study the clustering of galaxies. Some results of recent studies of the clustering of young stars will be summarized below in Section 2. An important result is that binary systems stand out as distinct tightly bound structures that can be regarded as the basic units from which the larger groupings are built. The data also show that binary systems are formed with a well-defined, very broad distribution of separations that resembles the extended spatial distribution of stars in elliptical galaxies. Some dynamical effects that may play a role in producing this broad distribution of separations are discussed in Section 3, and the analogous mechanisms that are thought to be involved in structuring elliptical galaxies will be discussed further in Section 4.

2. Clustering Properties of Young Stars

In the nearby Taurus-Auriga region of star formation, nearly all of the known young stellar objects are optically visible T Tauri stars, and the existing sample of these stars appears to be almost complete. The clustering properties of these stars can therefore be analyzed in a statistically meaningful way, and the first effort in this direction has been made by Gomez et al. (1993) using the two-point angular correlation function which has been much used in studying the clustering of galaxies. The result is that, as for galaxies, the correlation function of the young stars in the Taurus-Auriga region can be approximated roughly by a declining power-law function of separation, suggesting that these stars are clustered hierarchically in a roughly self-similar way. However, Gomez et al. (1993) also noted that there is marginal evidence for a change in the slope of this correlation function at an angular separation of about 0.02 degrees, corresponding to a linear separation of about 0.04 parsecs. To establish more definitely whether the clustering of the Taurus-Auriga stars is really self-similar or whether there is a departure from self-similarity at some scale, more data are needed for systems with very small separations.

Many new close companions to the T Tauri stars in the Taurus-Auriga region have been found in surveys using lunar occultations and near-infrared speckle interferometry (Ghez, Neugebauer, & Matthews 1993; Leinert et al. 1993; Simon et al. 1995), and these results have been used by Larson (1995) to extend the clustering analysis to smaller separations. Instead of using the two-point angular correlation function, Larson (1995) derived the average surface density of companions on the sky as a function of angular separation; this is equivalent to but more physically meaningful than the correlation function, which is proportional to the excess surface density of companions above that expected for a uniform distribution. The resulting plot is similar in general appearance to the correlation function shown by Gomez et al. (1993), but the addition of the new data for smaller separations now confirms beyond question the existence of a marked change in slope at an angular separation of about 0.02 degrees. Thus, groupings of T Tauri stars of all sizes including binaries clearly do not form a single self-similar clustering hierarchy. Instead, two clustering regimes are found, each characterized by a different power-law dependence of average companion surface density on separation: (1) a regime of self-similar hierarchical clustering at large separations where the average surface density of companions varies as about the -0.6 power of angular separation, and (2) a regime of (typically) binary systems at small separations where the companion surface density falls off much more steeply as about the -2.1 power of separation. The two power laws intersect at an angular separation of 0.017 degrees, which corresponds to a linear separation of 0.04 parsecs; this scale therefore appears to be an important intrinsic length scale in the star formation process.

On scales larger than that of the break in slope at 0.04 pc, the observed power-law dependence of average companion surface density on separation implies that the stars are distributed in a self-similar clustering hierarchy that can be described as a fractal point distribution with a dimension of about 1.4 (Larson 1995). The fact that this behavior extends only down to a minimum scale of 0.04 pc means that the clustering hierarchy can be regarded as being built of basic units of about this size that have a much more spatially concentrated internal mass distribution. The average number of companions per star at all separations smaller than 0.04 pc is found to be slightly more than one, implying that these basic units of star formation are typically binary systems (Larson 1995). Binary systems can thus perhaps be regarded as the small-scale analogs of galaxies, since galaxies also stand out as distinct tightly bound structures that have a much more spatially concentrated internal distribution of stars than would be predicted by an extension to smaller scales of the self-similar clustering seen on larger scales.

The basic star-forming units suggested by the clustering analysis can be identified with the well-studied 'ammonia cores' of the Taurus-Auriga clouds, which have typical diameters of the order of 0.1 pc and typical masses of the order of 1 $M_\odot$ (Myers 1985, 1987). Since a star-forming region of this size forms on the average slightly more than two stars, as noted above, a typical stellar mass should then be of the order of 0.5 $M_\odot$, in good agreement with the typical masses of the observed T Tauri stars. The sizes and masses of these inferred star-forming units are also very similar to the Jeans size and mass predicted for an isothermal gas sphere forming in equilibrium with the ambient pressure in a typical molecular cloud; adopting, for example, a temperature of 10 K and a pressure of 3×10^5 cm^{-3} K, the radius and mass of a critically stable 'Bonnor-Ebert sphere' are predicted to be about 0.03 pc and 0.7 $M_\odot$, respectively. The results of the clustering analysis therefore support the view that the star formation process has an intrinsic scale that is determined by the Jeans criterion, and that this scale is what basically determines typical stellar masses (Larson 1995, 1996).

3. The Formation of Binary Systems

In addition to the evidence noted above for fractal-like clustering of young stars on large scales, another remarkable feature of the spatial distribution of these stars is the much steeper, but still approximately power-law, dependence of average companion surface density on separation that is seen in the regime of binary systems; this behavior extends over three orders of magnitude in separation from less than 10 AU to about 8000 AU. Since the average star in the Taurus-Auriga region has just one companion in this range of separations, the power-law behavior in this regime does not imply self-similar clustering, but instead implies a scale-free distribution of binary separations. Expressed in the usual way in terms of the number of systems per unit logarithmic separation interval, the resulting distribution is almost flat and varies only as the -0.1 power of separation. This is similar to the distribution of separations of field main-sequence binaries, which is very broadly peaked and is flat or only slightly declining in the same range of separations (Duquennoy & Mayor 1991; Simon et al. 1995). Even the small departure from a power law that is shown by the pre-main sequence binaries follows closely the shape of the distribution for main-sequence binaries, but with a systematic offset of about a factor of 2 which implies that the Taurus-Auriga stars have about twice as many close companions as do the field main-sequence stars. The higher frequency of close companions among T Tauri stars had already been noted by Ghez et al. (1993), Leinert et al. (1993), and Reipurth & Zinnecker (1993), and it suggests that almost all stars are formed in binary systems. The fact that the field main-sequence stars have a lower frequency of binaries is probably a consequence of the destruction of some of the initially formed binaries by dynamical interactions in the dense clusters in which most stars are formed (Larson 1995; Kroupa 1995).

The main statistical property of binary systems that needs to be explained is then the very broad, almost uniform distribution of logarithmic separations with which they are formed. This type of spatial distribution is not unique to binary systems, and is shared by some larger stellar systems whose stars are also distributed nearly uniformly in the logarithm of separation or distance from the center; in particular, elliptical galaxies have surface brightnesses that fall off approximately inversely as the square of the radius over a considerable range of radii (Hubble 1930, Holmberg 1975), implying that their stars are distributed approximately uniformly in the logarithm of distance from the center (and in the logarithm of separation.) Although current data show that the light profiles of elliptical galaxies are not all the same and tend to become shallower with increasing galaxy luminosity (Schombert 1987), a power law with a slope of -2 remains a representative approximation for galaxies of intermediate luminosity. Some young star clusters also appear to have surface density profiles that vary roughly inversely as the square of radius (Moffat, Drissen, & Shara 1994), so it may be a rather general phenomenon that stellar systems are formed in such a way that their stars tend to be distributed roughly uniformly with respect to the logarithm of separation or distance from the center.

Such a distribution evidently has no preferred length scale over the range of scales in which it applies. In the case of binary systems, the range of possible separations extends all the way from systems that are almost in contact to systems that are so large that they are easily disrupted by encounters with other stars, and the observed separations are distributed over this entire range with only a very broad peak in the middle and no other apparent preference for any particular scale. Thus, it appears that after star-forming clumps with the characteristic size discussed above have formed in a molecular cloud, some mechanism having no preferred scale causes them to form (typically) binary systems with an extremely broad range of separations. Scale-free mechanisms may also be important in structuring larger stellar systems with similar spatial distributions of stars, and the common feature may simply be the dominant role of gravitational forces in the dynamics of systems containing large density fluctuations.

The distribution in separation or period of binary systems is determined physically by their distribution in specific angular momentum j, and a broad distribution in the logarithm of the separation or period implies a broad distribution in $\log j$. The logarithmic period distribution derived by Duquennoy & Mayor (1991) for field main-sequence binaries can be approximated by the gaussian function suggested by these authors, and it implies a gaussian distribution in $\log j$ with a mean of about -3.6 and a width at half maximum of 1.8 if j is measured in $\mathrm{km\,s^{-1}\,pc}$ and logarithms to the base 10 are used. This is a much broader distribution in $\log j$ than would be produced by any simple random process such as the action of turbulence in star-forming clouds, since such a random process would tend to generate a distribution that is gaussian in each of the three components of the specific angular momentum, rather than one that is gaussian in $\log j$. If each of these components has a gaussian distribution with standard deviation σ, the corresponding distribution of $\log j$ is proportional to $j^3 \exp(-j^2/2\sigma^2)$ and has a width at half maximum of only 0.43. The median initial value of $\log j$ suggested by the observed rotational velocities of the Taurus cloud cores studied by Goodman et al. (1993) is about -2.3, so that if these cores are to form binary systems with statistical properties like those discussed above, their initial angular momenta must typically be reduced by more than an order of magnitude (see also Bodenheimer 1995). In addition, if the initial distribution of $\log j$ is like that produced by a simple random process, this distribution must at the same time be broadened by more than a factor of 4 from a width of 0.43 at half maximum to a width of 1.8. Essentially, what is required is that the distribution of $\log j$ must be converted from a narrow one centered around -2.3 to a broad one extending from about this value down to values of -5 or less.

What kind of mechanism could produce such a large logarithmic dispersion in the specific angular momenta of binary systems? This mechanism must reduce $\log j$ by a highly variable amount, so we can regard the amount by which $\log j$ is reduced as a random variable with a large dispersion. If we define X as the amount by which the natural logarithm $\ln j$ is reduced from its initial value $\ln j_0$, we can then write $j = j_0 e^{-X}$ where X is a random variable with a mean of about 3.0 and a standard deviation of 1.8. This type of exponential dependence of a physical quantity on a negative exponent is suggestive of a damping or decay process; a familiar astronomical example is the effect of interstellar extinction, whereby a variable optical depth τ can lead to a large dispersion in the apparent brightnesses of stars which are proportional to $e^{-\tau}$. To illustrate how such a damping effect might operate on a dynamical variable like j, suppose that the angular momentum of a forming binary system is reduced by a decelerating torque (which might be of gravitational, magnetic, or viscous origin), and that the angular momentum has an associated decay rate A such that $dj/dt = -Aj$; then after any time t we have $j = j_0 e^{-At}$, so that if either the magnitude A of the damping effect or the time t over which it operates varies randomly from one system to another, a large logarithmic dispersion in the specific angular momentum j will result.

Gravitational forces alone can produce such decelerating torques, and their effects have been seen in a number of numerical simulations of cloud collapse and fragmentation; for example, it was noted by Larson (1978, 1984) that the gravitational drag produced by gas trailing behind orbiting mass concentrations can significantly reduce their orbital energy and angular momentum and lead to the formation of more tightly bound systems. Boss (1984) showed with the help of a simple model that in some circumstances these decelerating torques can reduce the angular momentum of a forming binary system by a large factor within an orbital period (see also Boss 1988, 1993; Bodenheimer 1995). This gravitational drag effect is closely analogous to the 'dynamical friction' of stellar dynamics (Binney & Tremaine 1987), and in the simple case of motion through a uniform medium its magnitude can be estimated from classical accretion theory or calculated from detailed numerical simulations (Shima et al. 1985). Similar gravitational drag or dynamical friction effects may play a role not only in the formation of close binary and multiple systems but also in the formation of centrally condensed clusters of stars like the Trapezium cluster, which has at its center the compact and massive Trapezium multiple system (Larson 1990a; Zinnecker et al. 1993). The postulated random variability of the decelerating torque acting in different cases may arise from the chaotic dynamics of fragmenting systems that develop a clumpy structure resembling that of a small n-body system (Larson 1978).

A closely related effect that is important in many types of rotating systems ranging from protostellar disks to galaxies is the outward transport of angular momentum by gravitational torques associated with trailing spiral density fluctuations (Lynden-Bell & Kalnajs 1972; Larson 1984, 1989; Bodenheimer 1995). Numerical simulations of rotating clouds that collapse to flattened disk-like configurations often show such trailing spiral features, and they tend to become more prominent as the spatial resolution of the simulations is increased (e.g., Larson 1978; Miyama, Hayashi, & Narita 1984; Monaghan & Lattanzio 1991; Bonnell & Bate 1994; Bodenheimer 1995). The systems of dense clumps that often form in these simulations tend to lose orbital energy and angular momentum through the associated gravitational torques, causing them to spiral closer together and form more tightly bound systems. These effects have not yet been studied quantitatively in any of these numerical simulations, however, so no quantitative predictions can yet be offered concerning the expected properties of the resulting binary and multiple systems.

The only simulations that have followed the formation of multiple systems far enough that most of the mass is in condensed objects are apparently the early very crude ones of Larson (1978). Although the quantitative reliability of these simulations can easily be questioned, they do include the gravitational drag effect discussed above, and since the magnitude of this effect is not strongly dependent on the nature of the medium producing the drag (for example, it is similar in gaseous and stellar systems), the drag effect may be represented roughly correctly even in these crude simulations. The results presented in Figures 6(a) and 6(b) of Larson (1978) show the formation of numerous binary and multiple systems, which appear to stand out as distinct tightly bound systems, qualitatively as was found for the T Tauri binaries in the Taurus-Auriga region. The same type of clustering analysis can be applied to the simulation results as was previously applied to the T Tauri stars, and the clustering of the simulated objects is found to depart from self-similarity in qualitatively the same way as the clustering of the T Tauri stars: two regimes are again found, in which the dependence of average companion surface density on separation can be approximated by power laws whose slopes are even very similar to those found for the T Tauri stars, being roughly -2.1 at small separations and -0.7 at large separations. Although the slope at large separations is not very well defined in the simulations, the slope at small separations is better defined, and the change in slope is definitely real. It is intriguing that the slope found in the small-separation regime, which again is basically the regime of binary systems, is so similar to that found for the observed T Tauri binaries, since in these simulations the only physical effect that could be responsible for producing this steep slope at small separations is the gravitational drag effect discussed above, acting in regions with about the Jeans size and mass.

4. An Analogy With Larger Systems

An analogous problem that has been much more thoroughly studied is the role of dynamical friction in the formation of galaxies, particularly elliptical galaxies which are believed to form by the merging of smaller systems of some sort. As was noted in Section 3, the distribution of the stars in elliptical galaxies with respect to distance from the center is similar to the distribution of the stars in binary systems with respect to separation, in each case being approximately uniform in the logarithm. The essential dynamical effect that causes smaller galaxies to merge into larger ones is dynamical friction, arising in this case partly from interaction with halo dark matter; although the details are obviously different, this process bears some analogy with the formation of binary systems through the gravitational drag effects discussed above. The stars in the merger product acquire a large logarithmic dispersion in distance from the center because the stars in different parts of the precursor systems experience different amounts of frictional drag, and this leads to a large dispersion in their final energies and angular momenta. Several effects can create differences in the amount of drag experienced by different parts of the merging subsystems, including the range in initial conditions and the progressive destruction of the subsystems by tidal forces;

if the amount of drag experienced by different mass elements varies in a quasi-random way, as was suggested above to be the case for different binary systems, an approach to a uniform distribution of stars in the logarithm of separation or distance from the center of mass might again be expected.

Numerical simulations have shown that, regardless of many details, the systems produced by mergers have radial distributions of stars resembling those observed in elliptical galaxies (e.g., White 1978; Villumsen 1982, 1983; Barnes 1990, 1992). Simulations of the formation of elliptical galaxies by the collapse of clumpy or irregular initial configurations yield similar results (e.g., van Albada 1982; Villumsen 1984; Katz 1991). The usual explanation offered for these convergent results is that they are produced by 'violent relaxation', as proposed by Lynden-Bell (1967). However, this explanation has never been very compelling because the amount of relaxation that occurs in mergers is actually rather limited, and because neither the observed structures of elliptical galaxies nor the results of the simulations agree well with the prediction of violent relaxation theory that the final 'relaxed' system should have a structure approaching that of an isothermal sphere; an isothermal sphere has a surface density profile varying approximately as r^{-1}, while the surface brightness profiles of elliptical galaxies are closer to r^{-2}. The structure of elliptical galaxies is therefore not adequately explained by relaxation effects alone, and the fact that the observed profiles are steeper than isothermal suggests that a dissipative effect is also required to produce a more centrally concentrated mass distribution. Dynamical friction is such a dissipative effect, and the numerical simulations show that it can indeed produce a density distribution that is steeper than isothermal, as required.

It has been debated whether elliptical galaxies are structured primarily by the 'dissipationless' processes of stellar dynamics or by the 'dissipative' processes of gas dynamics, but it is now recognized that both kinds of processes are almost certainly involved (Kormendy 1990; Larson 1990b, 1992; Barnes & Hernquist 1992). Evidence favoring dissipative processes includes the very centrally condensed structures of elliptical galaxies and the frequent occurrence of metallicity gradients, both of which can be explained by models involving gas dynamics and the settling of chemically enriched gas toward the center. However, the above discussion suggests that the 'dissipation' required in the formation of elliptical galaxies might be provided mainly by dynamical friction, which can cause the densest and most chemically enriched parts of the precursor systems to sink to the center of the merger remnant. Of course, it is still necessary to start with dense, chemically enriched cores or substructures of some sort in the precursor systems, and this still requires gas dynamics to play a role at an earlier stage. However, the main effect of gas dynamics may just be to form disks, and elliptical galaxies may originate from the merging of compact disk-like systems formed at earlier times. Gravitational torques acting on the residual gas in merging disks can also play an important role in the formation of centrally condensed systems by removing angular momentum from this gas and causing it to become highly concentrated at the center of the resulting system (Barnes & Hernquist 1992; Larson 1994).

In summary, it may be that simple and universal effects of gravity, such as the gravitational drag forces that are unavoidably present in clumpy systems, can account to a large extent for the spatial distributions of stars that are seen in systems ranging in size from binary stars to elliptical galaxies. More complicated effects, such as magnetic or viscous torques in protobinaries and the many possible effects of star formation and gas dynamics in protogalaxies, may of course also be important, but there is clearly still much to be learned about the effects that gravitational forces alone can have in structuring stellar systems of all sizes.

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