Hierarchical Formation of Galactic Clusters

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Young stellar groupings and clusters have hierarchical patterns ranging from flocculent spiral arms and star complexes on the largest scale to OB associations, OB subgroups, small loose groups, clusters and cluster subclumps on the smallest scales. There is no obvious transition in morphology at the cluster boundary, suggesting that clusters are only the inner parts of the hierarchy where stars have had enough time to mix. The power-law cluster mass function follows from this hierarchical structure: $n(M_{cl}) \propto M_{cl}^{-\beta}$ for $\beta \sim 2$. This value of $\beta$ is independently required by the observation that the summed IMFs from many clusters in a galaxy equals approximately the IMF of each cluster.

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1 Introduction

One way to study the origin of clusters is to observe the general morphology of star formation, how it fits with the surrounding gas distribution, and how it responds to various energy sources like other star formation or galactic-scale processes like spiral waves. A startling revelation in ISM structure came 20 years ago following Infrared Astronomical Satellite surveys of dust emission and CO and HI surveys of the Galactic plane. These surveys demonstrated that interstellar gas is not a random arrangement of round clouds with a smooth intercloud medium. It is a scale-free continuum of structures with a power-law power spectrum, correlated velocities and densities, and no obvious limits on either large or small scales except those defined by the galaxy itself. This view was present as far back as the 1950s, but dropped from ISM models in the intervening two decades (see review in [29]). Particularly important papers were those by Beech [5], in which fractal structure was found for the
first time in the Lynds dark clouds, Low et al. [48], in which the pervasive and highly structured IR cirrus clouds were discovered, Crovisier & Dickey [5], in which the power-law power spectrum of HI was discovered, and Stutzki et al. [58], in which the power-law power spectrum of CO emission was discovered. All of these followed the influential paper by Larson [47] in which giant molecular cloud (GMC) properties like size, density, and velocity dispersion were shown to be correlated in a manner reminiscent of turbulence. Whole galaxies were eventually found to have correlated properties too [57, 61, 26]. These papers and others led to a change in thinking about the structure, energetics, and evolution of interstellar gas. It did not take long for the theory of star formation to change with it.

Star formation is now seen to follow scale-free patterns like the gas, suggesting that stars form in turbulent gas wherever the density is large, making clusters and loose groups with a power-law distribution of masses. The result is a hierarchy of clouds and young stellar groupings with HI “superclouds” [15] and star complexes [12, 13] on the largest scale, GMCs and OB associations generally clustered together inside of them [23, 24, 57], and molecular cloud cores with galactic clusters inside. An early review is in Scalo [52]. GMCs are not isolated regions of star formation, nor are they the largest scale of cloud structure. GMCs are not ballistic objects, nor long-lived objects, although their pieces may shuffle around and form new clouds after star formation breaks them apart [15]. Self-gravitating clouds more massive than GMCs are observed but they are not molecular. Virialized density decreases with increasing mass at constant pressure, so the largest self-gravitating clouds do not self-shield against dissociative radiation in our Galaxy and are mostly atomic [24]. The largest clouds are more highly molecular in a high-pressure galaxy like M51 [51]. Generally the molecular fraction in a galaxy follows the pressure $P$ and core density $n$: 
$$M_{cl,max} \sim 6 \times 10^3 \left(\frac{P}{3 \times 10^8 \text{ kB}}\right)^{1.5} \left(\frac{n}{10^5 \text{ cm}^{-2}}\right)^{-2}.$$ [25].

GMCs are not special cloud structures, they are only the dense self-shielded parts of the ISM hierarchy [1, 24], and among them, only the most massive tend to be self-gravitating in large-scale surveys [42]. Molecular cores inside GMCs can be self-gravitating too. Density peaks in the diffuse ISM should be viewed as transient, lasting only a few internal turbulent crossing times before shear and random motions from inside and outside change their identities. Even GMCs and their star-forming cores are probably somewhat transient, although perhaps not for the same reasons as diffuse clouds. GMC cores appear to begin star formation very quickly after they form, and the pressure from this star formation disrupts them [18, 21]. Short cloud lifetimes appear to be the norm over a wide range of scales, from individual clusters to whole star complexes, with the actual time scale for formation increasing with size, in proportion to the turbulent crossing time [14].
Hierarchical star formation has been recognized for a long time. In a series of papers in the 1980’s, Feitzinger and collaborators quantified the hierarchical structure and fractal dimension in several nearby galaxies, including the LMC [32, 33, 34]. Other recent studies of the top two levels in the hierarchy, from star complexes to OB associations, were made for the LMC [49, 40, 36, the SMC [4], M31 [4], NGC 300 [50], M51 [3], and M33 [43]. Large surveys of galaxies were in Bresolin [6] and Gusev [39]. These studies found collections of OB stars in OB associations, typically 80 pc in diameter, which are themselves collected into star complexes several hundred pc in diameter. A review of star complexes is in Efremov [13].

The top of the hierarchy consists of $10^7 \, M_\odot$ clouds and star complexes that are most likely formed by gravitational instabilities in either the ambient medium, forming flocculent spirals, or in the dense shocks (dust lanes) of spiral arms when a stellar spiral wave is strong. Inside density wave spirals, giant clouds and star complexes are nearly equally spaced with a separation of about 3 times the arm width [31, 32], similar to the relative separation of clumps in other filamentary clouds [55]. This is the characteristic length of the threshold gravitational instability for the tube-like concentration of gas that is a dust lane [17]. The instability also produces feathery clouds that trail off into the interarm region [2, 44]. There might be a characteristic mass for these largest clouds, comparable to the theoretical Jeans mass of $\sim c^4/(\pi^2 G^2 \Sigma)$ for velocity dispersion $c$ and gas mass column density $\Sigma$. Such a peaked mass function is observed in the highly compressed parts of the interacting galaxy IC 2163 [31], but it is not known whether such a peaked function is a general feature of giant spiral arm clouds.

OB associations, loose stellar groupings and star clusters are evidently fragments of these giant clouds. The associations and groups usually cluster inside the giant clouds [37]. On smaller scales, there are universal power-law mass functions, which are presumably the result of scale-free processes such as turbulence and gravitational fragmentation.

The hierarchical structure does not stop at OB subgroups. It continues down to the sub-parsec scale of individual clusters and inside the clusters, which are often hierarchical themselves (e.g., $\rho$ Oph [50], NGC 2264 [5], Serpens [39]). Kiss [45] found 3872 T Tauri stars from 2MASS using colors as a guide. There were 64 possible T associations among these. These groupings have a star-number distribution that continues to increase like a power law from 138 stars down to 4 stars. This distribution implies that hierarchical stellar groupings may continue down to a few stars.

Between the top and bottom of the hierarchy there is a broad range of correlated scales. As just mentioned, there is hierarchical structure in stellar groupings, autocorrelation of clusters [60], power-law power spectra of optical light in galaxies [27, 28, 32]; power-law size distributions of star fields [25, 31], and fractional powers in the run of star-counts versus distance [7]. In general, young star fields are hierarchical, even if the groupings are unbound (e.g. [36]).
for the LMC). Local groupings of low mass x-ray stars (T Tauri stars) in Goulds Belt also have a hierarchical structure [38].

2 Cluster Mass Functions

The power-law mass functions for atomic and molecular clouds and for star clusters and OB associations are most likely the result of the hierarchical nature of the ISM. Clouds like these are not isolated objects but are interconnected by diffuse and molecular gas in a widespread network. The network has a power-law power spectrum, as discussed above, and this means there is no characteristic cloud size or mass. There may be only upper and lower limits. Because clusters form in scale-free gas clouds with about constant efficiency (to within a factor of $\sim 3$), their initial stellar masses are also scale free. The sizes of clusters are apparently not scale-free as there seems to be a characteristic cluster radius [54].

The mass distribution of clusters in spiral galaxy disks is a power law with a negative slope of around $\beta = 2$ on a log-log plot with linear intervals of cluster mass (or a negative slope of 1 on a log-log plot with log intervals of mass). In the Antennae galaxy, $\beta = 1.95 \pm 0.03$ for young clusters and $\beta = 2.00 \pm 0.08$ for old clusters [65]. For the LMC, $\beta = 1.85 \pm 0.05$ [11]. For M51, $\beta = 2$ [35]. For NGC 3310, $\beta = 2.04 \pm 0.23$ and for NGC 6745, $\beta = 1.96 \pm 0.15$ [10]. A mass function with a slope of $\beta = 2$ follows from an ISM that is fractal with a three-dimensional power spectrum slope of $-3.66$ [20, 30], the same as for velocity in 3D Kolmogorov turbulence.

Summed IMFs from clusters can produce a global IMF that is nearly the same as the individual IMFs if the cluster mass function slope is the observed value of $\beta = 2$. Galaxy-wide IMFs are in fact very close to the Salpeter IMF. These IMFs are determined in a variety of ways, including metallicity, colors, H$\alpha$ equivalent widths, and color-magnitude diagram star counts. Cluster IMFs have an average slope comparable to the Salpeter value also [53]. This agreement between galaxy and cluster IMFs implies that the cluster mass function is close to $\beta = 2$. A slightly steeper cluster mass function makes the summed IMF significantly steeper [46, 60], and in clear disagreement with the IMF observations, reviewed in [22]. For example, $\beta = 2.3$ implies the galaxy IMF should have a slope of $-2.9$ [30], which is much steeper than the commonly observed Salpeter slope of approximately $-2.4$. Evidently, galaxy-wide IMFs are a sensitive measure of the slope of the mass function of clusters and of general regions of star formation.

The approximate agreement between summed IMFs and cluster IMFs implies, in practical terms, that stars of any mass can form in clusters of any mass. A cluster seems to choose its stars randomly from a universal IMF. Such random sampling would be illogical if a cluster were to choose a star more massive than itself, but this event has negligible occurrence in practice [22]. A related property is that a power-law IMF implies that the maximum likely
star mass out of N clusters of mass M equals the maximum likely star mass in one cluster of mass NM \(^{22}\).

Hierarchical structure with \(\beta = 2\) is also required by the observation that cluster IMFs are independent of cluster mass. More massive clusters have more sub-units for the local sum of sub-unit IMFs, and this would produce steeper IMFs for more massive clusters than low mass clusters if \(\beta > 2\).

3 Summary

The hierarchy of star formation extends from “star complexes” on \(\sim 500 \text{ pc}\) scales to the interiors of embedded clusters on sub-pc scales. This smooth continuation is evident from power spectra, mass functions, autocorrelation functions, and other studies. There is apparently no threshold or change at a “cluster” boundary other than the change from unmixed hierarchical structure outside the boundary to mixed stellar orbits inside the boundary. Clusters are best defined dynamically where the cluster age equals the dynamical time at a density much higher than the tidal limit. Cluster self-boundedness is a separate issue. In fact, the efficiency of star formation is automatically large at high density in a power law ISM \(^{19, 21}\), so self-boundedness is somewhat inevitable for very young clusters once the local star formation process ends.

Hierarchical structure produces a cluster mass spectrum with equal mass in equal logarithmic intervals. This means \(\beta \sim 2\), particularly with a Kolmogorov-like power spectrum for structure. In fact, \(\beta \sim 2\) is observed directly for many cluster systems. \(\beta \sim 2\) is also required by the observation that galaxy-wide IMFs are equal to individual cluster IMFs. One important implication of this is that stars of any mass can be associated with clusters with any number of stars.

The top of the hierarchy (flocculent spiral arms and star complexes) should have a characteristic cloud or cluster mass comparable to the ambient Jeans mass, although there are few observations to confirm this point. A peaked mass function for star complexes has been observed for only one galaxy so far; the bound clusters inside these star complexes have a power-law mass function \(^{30}\). If halo globular clusters had a peaked mass function at birth, then it seems possible they were at the top of a hierarchy of cloud structures also, but in ultra-high pressure regions to make them compact.

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