STAR-FORMING COMPLEXES IN GALAXIES

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Abstract

Star complexes are the largest globular regions of star formation in galaxies. If there is a spiral density wave, nuclear ring, tidal arm, or other well-defined stellar structure, then gravitational instabilities in the gaseous component produce giant cloud complexes with a spacing of about three times the width. These gas complexes form star complexes, giving the familiar beads on a string of star formation along spiral arms, or nuclear hotspots in the case of a ring. Turbulence compression, supernovae, and self-gravitational contraction inside the giant clouds produce a nearly scale-free structure, including giant molecular clouds that form OB associations and molecular cloud cores that form clusters. Without stellar density waves or similar structures, random gravitational instabilities form flocculent spirals and these fragment into star complexes, OB associations and star clusters in the same way. In this case, all of the structure originates with gravitational instabilities and turbulence compression, but the usual concept of a star complex applies only to the largest globular object in the hierarchy, which has a size defined by the flocculent arm width or galaxy thickness. The largest coherent star-forming regions are the flocculent arms themselves. At the core of the hierarchy are the very dense clumps in which individual and binary stars form. The overall star formation rate in a galaxy appears to be regulated by gravitational collapse on large scales, giving the Kennicutt/Schmidt law scaling with density, but the efficiency factor in front of this scaling law depends on the fraction of the gas that is in a dense form. Turbulence compression probably contributes to this fraction, producing a universal efficiency on galactic scales and the observed star formation rate in disk systems. The CO version of the Schmidt law, recently derived by Heyer et al. (2004), follows from the turbulent hierarchy as well, as do the local efficiencies of star formation in OB associations and clusters. The efficiency of star formation increases with cloud density, and this is why most stars form in clusters that are initially self-bound.

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Introduction to Star Complexes

Star complexes are the largest coherent groupings of young stars in galaxies. Shapley (1931) first noted that they appear like “small irregular star clouds” up to 400 pc in size in the Large Magellanic Clouds. McKibben Nail & Shapley (1953) later defined 12 “constellations” in the LMC. Baade (1963) considered the most active examples of star complexes and called them “superassociations,” such as 30 Dor in the LMC and NGC 206 in M31.

The definition of star complexes was broadened by Efremov (1979). He considered complexes to be collections of Cepheid variables with similar periods and velocities, that is, within a narrow range of ages (e.g., \( \sim 50 \) My) and moving as a group. This makes them distinct from “OB associations,” which are collections of OB stars within a narrower range of ages (\( \sim 10 \) My). Efremov noted that the OB associations in M31 defined by van den Bergh (1981) have an average size of 480 pc, which is much larger than local OB associations (80 pc). He concluded that the M31 associations are complexes, and that star complexes generally contain OB associations as sub-parts. Battinelli et al. (1996) quantitatively found stellar groupings in M31 and demonstrated this 2-component, or hierarchical, nature of associations and complexes.

Hierarchical structure in the LMC stars was first quantified by Feitzinger & Galinski (1987). Most recently, Maragoudaki et al. (1998) measured stellar groupings in the LMC using discrete magnitude limits in the U-band. They noted that the smaller groupings in the hierarchy are rounder. Gouliermis et al. (2000) did the same for B stars in LMC fields. Hierarchical structure as a general property of interstellar gas was discussed much earlier than this (see review in Scalo 1985). The observation that stellar groupings generally have the same type of hierarchical structure as the gas is not surprising since the stars form from the gas (e.g., see Bonnell, Bate & Vine 2003).

The definition of star complexes was broadened further by Elmegreen & Efremov (1996) to mean the largest “globular” scale in a hierarchy of star formation ranging from multiple stars to flocculent spiral arms. They showed that bigger scales evolve slower, with \( t \propto L^{0.5} \), that all scales evolve on about a dynamical crossing time, and that the largest globular scale for star formation should be about the disk thickness (times \( \sim \pi \)), at which point the shear time becomes comparable to the crossing time. Bigger regions form the same way and are part of the hierarchy, but they look like flocculent spiral arms instead of roundish star complexes. Efremov & Elmegreen (1998) also found that the size-duration correlation for star formation is about the same as the size-crossing time correlation for molecular clouds, which suggests that turbulence regulates star formation on scales comparable to or smaller than the ambient ISM Jeans length.
The observation that star formation is somewhat scale-free, even up to \( \sim 0.1 \) times galactic scales, received considerable support after the gas was found to be scale-free over similar lengths. Fractal structure in the gas on very small scales had been observed for a long time (e.g., Falgarone, Phillips & Walker 1991 and references therein), but the first observations of fractal structure in whole galaxies was by Westpfahl et al. (1999) and Stanimirovic et al. (1999). Westpfahl et al. found the fractal dimension for gas in M81 group galaxies using area-perimeter relations and box counting techniques on HI maps, while Stanimirovic et al. found that the power spectrum of HI emission from the entire Small Magellanic Clouds is a scale-free power law. A similar power-law was later found for the LMC (Elmegreen, Kim & Staveley-Smith 2001). In the LMC, much of the gas also resembles shells rather than blobs, and these shells are hierarchical too (ibid.). The exact relation between this shell structure, turbulence, and star formation is not clear yet (Wada, Spaans, & Kim 2000). Yamaguchi et al. (2001a,b) showed that some of the shells and other high-pressure sources trigger star formation directly in the LMC. Gouliermis et al. (2003) found that stellar systems line the edges of the supershells found by Kim et al. (1999). Thus some of the stellar hierarchy could be the result of high-pressure triggering in hierarchical shells.

The connection between the hierarchical structures of the gas and stars is emphasized further by the power spectra of optical emission from galaxies. Elmegreen, et al. (2003a,b) found that power spectra of optical emission along azimuthal cuts through several galaxies have the same near-power law form as the power spectra of HI emission from the LMC. In one case, M81, a spiral density wave contributes to the power spectrum at the lowest wavenumber, but otherwise the power spectrum is the same as in a flocculent galaxy.

We might summarize these observations as follows: “Star complexes” are the largest globular regions of star formation in galaxies. They include associations of Cepheid variables, red supergiants, WR stars, HII regions, and OB-associations (e.g., Ivanov 2004). They could be the origin of moving stellar groups (Asiain et al. 1999). They are part of a continuum of star-formation scales between clusters and swing-amplified spirals. This continuum has at least two characteristics of turbulence: power-law power spectra and a velocity-size relation. We would like to know how star complexes form and how stars form in them. Is there any evidence also for star complexes with a characteristic scale, rather than an observationally selected scale among many scales?

1. **Formation of Star Complexes**

Most galaxies with star formation have at least a few regions with sizes comparable to the main stellar structures – spiral arms, tidal arms, resonance
rings, etc. Comparable sizes means comparable to the minor dimensions, e.g.,
the widths of the arms or rings. These regions are star complexes. They are
probably the largest scale in a local hierarchy of scales beginning with some
instability length and extending down to OB associations and clusters. If this
is the case, then the complexes will have a characteristic length and mass.
Galaxies without stellar spiral waves or rings would not have a characteristic
scale limited by these structures, so they could produce an even wider range
of scales in the hierarchy of star formation. For example, the optical structures
could range from flocculent arms, which are driven primarily by sheared grav-
itational instabilities, down to star complexes, OB associations, and clusters,
which are fragments produced by self-gravity and turbulence (e.g., Huber &
Pfenniger 2001).

Recent CO observation of M33 (Engargiola et al. 2004), combined with
stellar complex data (Ivanov 2004) and older HI observations (Deul & van
der Hulst 1987) show star complexes associated with molecular and atomic
gas. They also show that most molecular clouds are inside giant HI clouds,
as observed locally (Grabelsky et al. 1987; Elmegreen & Elmegreen 1987)
and in other galaxies (Lada et al. 1988). In addition, in M33, the CO cloud
spin axes are correlated up to scales of ~ 1 kpc, suggesting coherence on this
scale. This is also the scale of the giant HI clouds. Thus star formation pro-
ceeds first by forming giant HI clouds, and then by forming molecular clouds
inside of them and OB associations inside the molecular clouds. Each collec-
tion of OB associations, aged by ~ 30 – 100 My, is a star complex (Efremov
1995). The Gould’s Belt region (e.g., Lallement et al. 2003) may be an ex-
ample. The regular distribution of giant HI clouds along spiral arms has been
known for many years, starting with the first HI observations of the Milky Way
(McGee & Milton 1964) and proceeding through the 1970’s and 1980’s when
HI was routinely mapped in nearby galaxies (e.g., Boulanger & Viallefon
1992). Regularity implies a characteristic scale, which is most likely the Jean
length (Elmegreen & Elmegreen 1983; Kuno et al. 1995).

These observations demonstrate that star complexes form in CO/HI cloud
complexes. The stellar parts are hierarchically clumped, but still coherent up
to ~ 1 kpc in the main disks of galaxies, while the gaseous parts can extend
for two or three times this distance. The primary objects formed by galactic
processes are ~ 10^7 M⊙ HI clouds, while giant molecular clouds (GMCs) are
their fragments. This 10^7 M⊙ mass is the Jeans mass in the ambient ISM,
suggesting that the HI clouds and ultimately the star complexes form by grav-
itational instabilities. The formation of GMCs follows by a combination of
self-gravitational contraction and turbulence compression inside the 10^7 M⊙
clouds, but GMCs are not special, distinct objects. The CO/HI ratio depends
primarily on self-shielding, not cloud formation processes. Low pressures, low
metallicities, or high radiation fields imply low CO/HI ratios in each cloud.
CO/HI varies with galactic radius or galaxy type because of variations in pressure, radiation field and metallicity, without any change in physical cloud structure or star formation properties (Elmegreen & Elmegreen 1987; Elmegreen 1993; Honma, Sofue, & Arimoto 1995; Engargiola et al. 2004).

There are 2 basic dynamical phases and 2 basic chemical phases for neutral clouds: atomic or molecular gas in a self-gravitating cloud, and atomic or molecular gas in a non-self-gravitating cloud. Usually the atomic phase dominates at low density, the molecular phase at high density, the non-self-gravitating phase at low column density, and the self-gravitating phase at high column density (Elmegreen 1995). The virial theorem also plays a role: considering the presence of some external pressure, both diffuse and self-gravitating clouds occur at low mass but only self-gravitating clouds occur at high mass. In the general ISM, gravitating cloud complexes are evident mostly from knots in spiral arms, spurs, and the presence of star formation (e.g., Kim & Ostriker 2002). In accord with the virial theorem result above, the FCRAO Outer Galaxy Survey (Heyer, Carpenter & Snell 2001) shows that self-gravity is important only in the most massive CO clouds, \( M > 10^4 \, M_\odot \). This is the same mass at which the virial theorem suggests a transition from both diffuse and self-gravitating clouds (at lower mass) to purely self-gravitating clouds (at higher mass), given a near-constant diffuse cloud density of \( \sim 50 \, \text{cm}^{-3} \) (Elmegreen 1995). This mass limit should depend on pressure and the molecule detection threshold. Small self-gravitating cores are undoubtedly present inside these FCRAO clouds (because stars are forming), but they have a higher density threshold for detection and a smaller angular size, making their detection not as likely in large-scale CO surveys.

2. **Characteristic Size versus Scale-Free?**

If a galaxy has a global spiral density wave in the stars, or if it has a stellar ring, then gaseous gravitational instabilities in these structures have a size and mass defined by the stellar geometry: i.e., the instability length is \( \sim 3 \times \) the spiral arm (or ring) width. Examples are the well-known “beads on a string of star formation” along spiral arms, and the “nuclear ring hotspots.” If a galaxy has no spiral density wave, then the stars and gas become unstable together, forming multiple spiral arms or flocculent arms that are made of old stars, gas and star formation. The instability involved is the swing amplifier (Toomre 1981), usually enhanced by magnetic fields (Kim, Ostriker & Stone 2002, 2003). The instability should also drive turbulence, producing scale-free clouds and star formation as observed.

Stellar spirals define two characteristic scales: \( 2\pi G\Sigma/\kappa^2 \), which is the Toomre (1964) length for the separation between spiral arms, and \( 2c^2/G\Sigma \), which is the Jeans length for pressure balance against self-gravity. Here, \( \kappa \) is the epicyclic
frequency, \( \Sigma \) is the mass column density, and \( c \) is the gas velocity dispersion. The Jeans mass is \( c^4/G^2 \Sigma \). Inside spiral arms, the Jeans instability is one-dimensional, i.e., the collapse is parallel to the arms, and the characteristic length is usually about 3 times the arm width (Elmegreen & Elmegreen 1983; Bastien et al. 1991). The condition for rapid instability in this case is not the Toomre \( Q \) condition, but the 1-dimensional analog: \( \pi G \mu/c^2 > 1 \) for mass/length \( \mu \) (Elmegreen 1994).

Wada & Norman (2001) modeled 2D hydrodynamics of galaxy disks without spiral density waves and found that gravitational instabilities drive turbulence, giving a log-normal density pdf that is typical for isothermal compressible turbulence (Vazquez-Semadeni 1994). Three-dimensional SPH models of galaxy disks without spiral density waves get the Schmidt/Kennicutt laws of star formation (Li et al. 2004).

3. Theory of the Star Formation Rate

A sensible local SF law is (Elmegreen 2002b)

\[
\text{SFR}/V = \epsilon \rho(G\rho)^{1/2},
\]

which is the efficiency times the mass per unit volume, times the conversion rate from gas into stars. Kennicutt (1998) observes

\[
\text{SFR/Area} = 2.5 \times 10^{-4} \left( \Sigma/M_\odot \text{ pc}^{-2} \right)^{1.4} M_\odot \text{ kpc}^{-2} \text{ yr}^{-1} \sim 0.033 \Sigma \Omega
\]

for average mass column density \( \Sigma \) in the whole disk and rotation rate in the outer part \( \Omega \).

If we convert the global SFR/A into a local SFR/V using the local tidal density for gas, \( \rho = 3\Omega^2/2\pi G \), a flat rotation curve, and an exponential disk with scale length \( r_D/r_{edge} = 0.25 \), then the average SFR/A converts to a local

\[
\text{SFR}/V = 0.012 \rho(G\rho)^{1/2}.
\]

Why is the efficiency \( \epsilon = 0.012 \), and is this the right star formation law? Boissier et al. (2003) compared the star formation rates versus radii in 16 galaxies with three simple expressions, finding factor of 3 variations around each law with no apparent cause, and no preferred law. Either we do not know the “right” star formation law, or additional processes give big variations around one of the assumed laws. By the way, all of the Boissier et al. laws, and that discussed by Hunter, Elmegreen, & Baker (1998) for dwarf irregular galaxies, are consistent with a local star formation rate proportional to the stellar surface density. Whether this is a cause or an effect of star formation is not clear. That is, one might expect the star formation rate to scale with
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the existing stellar surface density if star formation is building up that surface density and the exponential scale length does not change much with time. On the other hand, the relationship might also exist if background stars trigger star formation, as might be the case if supernova and HII regions directly compress the gas to trigger star formation or if these pressures indirectly compress the gas by driving supersonic turbulence.

Let us proceed with equation (3) and ask what determines the star formation efficiency, $\epsilon$. Assume that stars form in dense cores where the efficiency is $\epsilon_c \sim 0.5$ and $\rho_c \sim 10^5 \text{ cm}^{-3}$, giving

$$\frac{\text{SFR}}{V_{\text{core}}} = \epsilon_c \rho_c (G\rho_c)^{1/2}. \quad (4)$$

Then make a conversion:

$$\frac{\text{SFR}}{V_{\text{gal}}} = \frac{\text{SFR}}{V_{\text{core}}} \times \left( \frac{V_{\text{core}}}{V_{\text{gal}}} \right) = \frac{\text{SFR}}{V_{\text{core}}} \times \left( \frac{M_{\text{core}}}{M_{\text{gal}}} \right) \times \frac{\rho}{\rho_c}, \quad (5)$$

where $\rho_c = M_{\text{core}}/V_{\text{core}}$, $\rho = M_{\text{gal}}/V_{\text{gal}}$, $M_{\text{core}}$ and $V_{\text{core}}$ are the summed mass and volume of all cores, while $M_{\text{gal}}$ and $V_{\text{gal}}$ are the total gas mass and gas volume of the galaxy. Now substitute from equation 4 and set $\text{SFR}/V_{\text{gal}}$ equal to the observed rate $0.012 \rho (G\rho)^{1/2}$. Then we get the gas mass fraction in star-forming cores:

$$f_M \equiv \left( \frac{M_{\text{core}}}{M_{\text{gal}}} \right) \equiv 0.012/\epsilon_c \times (\rho/\rho_c)^{1/2} \sim 10^{-4}. \quad (6)$$

Thus the observed average efficiency of $\epsilon = 0.012$ (per dynamical time) requires $10^{-4}$ of the total ISM mass to be in star-forming cores if all regions evolve on a dynamical timescale (Elmegreen 2002b). This is the same mass fraction as in the Wada & Normal (2001) log-normal for $\rho/\rho_{\text{ave}} > 10^5$, as assumed above with $\rho_c \sim 10^5 \text{ cm}^{-3}$ and $\rho \sim 1 \text{ cm}^{-3}$. This result depends on the density pdf for the ISM, which is not observed yet, and it assumes a log-normal form for this pdf. In fact, the high density portion may become a power-law after collapse starts (Klessen 2000). Nevertheless, the agreement between the simple theory and the Kennicutt (1998) star formation rate, which applies to essentially all late-type galaxy disks and their nuclear regions, suggests that something universal like turbulence helps partition the gas in a hierarchical fashion and that only the dense regions at the bottom of the hierarchy form stars.

A turbulent ISM has a small fraction of its mass at a high enough density to form stars. Most of the mass is either too low a density to form stars, or is not self-gravitating enough to resist turbulent disruption. For a turbulent medium, every structure forms on a local crossing time, but the progression to high density is not monotonic. The low-density clumps are destroyed easily and they are smashed and sheared into smaller pieces by transient pressure bursts. The
progress toward high density is more like a random walk, with some inter-
actions making denser regions and some making lower densities. Eventually
the lucky ones that had a long succession of compressive interactions become
dense enough and massive enough to be strongly self-gravitating at the typi-
ical pressure in the cloud. Then they presumably produce stars quickly. The
delays from magnetic diffusion, disk formation, and turbulent energy dissipa-
tion are not nearly as time consuming as the fragmentation process on larger
scales. Thus the largest scales control the overall rate. All that a microscopic
delay might do is change the form of the density pdf, producing a bump at
high density, for example, or a power-law instead of a log-normal, if the col-
lapse slows down. If only turbulence is involved, though, the random walk
in density produces a log-normal density pdf (Vazquez-Semadeni 1994). Our
integration over the pdf for densities \( \rho_c/\rho > 10^5 \) involves an assumption that
the collapse delays occur at higher densities, where the detailed shape of the
pdf will not affect the integral under it if there is a steady flow toward higher
density during the star formation process.

If we now denote the galactic average quantities by a subscript “0”, then the
efficiency at any density is given by:

\[
e_0 \rho_0 (G \rho_0)^{1/2} = \epsilon(\rho) \rho (G \rho)^{1/2} f_V(\rho) = \epsilon_c \rho_c (G \rho_c)^{1/2} f_V(\rho_c).
\]

(7)

But \( \rho f_V(\rho) = \rho_0 f_M(\rho) \), etc., so

\[
\epsilon(\rho) = \epsilon_c (\rho_c/\rho)^{1/2} \left[ f_M(\rho_c) / f_M(\rho) \right].
\]

(8)

Here, \( f_V(\rho) \) is the fraction of the volume having a density larger than \( \rho \) and
\( f_M(\rho) \) is the fraction of the mass having a density larger than \( \rho \).

Figure 1 shows as a decreasing line the mass fraction, \( f_M(\rho) \), versus density
\( \rho \) using the log-normal found by Wada & Norman (2001) for a 2D disk with
star formation, turbulence, and self-gravity. The scale for \( f_M \) is on the left-
hand axis. The figure also shows as an increasing line the efficiency \( \epsilon(\rho) \),
using the right-hand axis. The efficiency increases with increasing average
density because the hierarchical nature of clouds gives them a higher filling
factor for dense gas at higher average density. The mass fraction decreases with
density because only a small fraction of the matter is dense. Several commonly
observed values for the efficiency are indicated: the average galactic value of
0.012, derived above, the range of \( \sim 1–5\% \) for whole OB associations, and the
range of \( \sim 10–30\% \) for the cores of OB associations, where most stars actually
form, producing clusters. Note that this efficiency is not the local efficiency
where single stars form; that is assumed to be the constant value of \( \epsilon_c = 0.5 \)
at \( \rho/\rho_{ave} = 10^5 \). Rather, it is the efficiency inside a cloud whose boundary
density is \( \rho \). OB associations form with an overall low efficiency because there
is a lot of inactive gas at low density. Only the cores, and in them, only the
small dense cores of these cores, form stars with high efficiency. This increase of efficiency with cloud density is commonly observed and easily explained for hierarchical stellar regions when all star formation occurs locally at the highest density. Note that star formation in simulations (e.g., Mac Low & Klessen 2004) proceeds over some prolonged time as does dense core formation, but the total time for this is still about the crossing time on the largest scale, making equation 1 appropriate.

Figure 1 highlights the boundary between bound and unbound stellar regions, which is where the average efficiency is greater than several tenths (Lada & Lada 2003). Bound regions have high densities and may therefore be identified with clusters rather than OB associations or any other part of the hierarchy on larger scales. The masses of the bound regions are not specified by this derivation but may be anything, always distributed as \( dN/dM \sim M^{-2} \) for hierarchical gas structures (Fleck 1996; Elmegreen & Efremov 1997). This is the essential explanation for the formation of most stars in clusters. After \( \sim 10 \) My, most clusters dissolve and their stars fill in the region where they once clustered together. This is an OB association. In another \( \sim 30 – 100 \) My, these OB associations dissolve and fill in the region where they clustered together; this makes a star complex. Star complexes are so big that their dispersal is relatively slow and therefore accompanied by significant shear in normal galaxy disks. Thus there is no globular-shaped super-collection of star complexes, only flocculent spiral arms on larger scales.
Heyer et al. (2004) studied the star formation rate versus radius for molecular gas in M33. Both the SFR and the column density increase toward the center, with a mutual relationship

\[ \text{SFR} = 3.2 \left( \frac{\Sigma_{H_2}}{M_\odot \text{ pc}^{-2}} \right)^{1.36} M_\odot \text{ pc}^{-2} \text{ Gyr}^{-1}. \]  

This may be written as in eq. (1), \( \text{SFR} \sim 0.6 \rho_{H_2} (G \rho_{H_2})^{1/2} \), assuming a disk thickness of 150 pc. The efficiency is higher for the distributed CO density \( (\epsilon_{H_2} \sim 0.6) \) than it is for the total gas density \( (\epsilon_0 \sim 0.012) \) because the average density of \( H_2 \) spread around a disk is lower than the total density by \( \rho_{H_2}/\rho_0 = (\epsilon_0/\epsilon_{H_2})^{2/3} = (0.012/0.6)^{2/3} = 0.08 \) (i.e., 0.6 is not the \( \epsilon \) inside a CO cloud). This is the \( M_{H_2}/M_{gal} \) mass ratio actually obtained from Figure 1 if the density of CO-emitting material is taken to be \( \sim 300 \text{ cm}^{-3} \) (use the left-hand axis). Thus the CO-Schmidt law follows from this hierarchical model too.

As mentioned briefly above, giant molecular clouds, OB associations, and star clusters all get their mass distribution functions from the structure of a compressibly turbulent medium. These mass functions are a property of fractals, sampled in various ways (Elmegreen 2002a; also see Elmegreen 2004). For a region sampled at low density, far from the peak, the mass function is approximately a power law with a shallow slope, \( \sim -1.5 \), as observed for GMCs. When the same region is sampled at a higher density, the mass function has a steeper slope, \( \sim -2 \), as observed for clusters. This explains how GMCs and clusters can both form from the same gas distribution and yet have slightly different mass functions. Note that this works because the ratio of cluster mass to cloud-core mass is about constant when there is a threshold efficiency required for bound cluster formation.

4. Conclusions

Star complexes usually form in clouds that result from a gravitational instability in the ISM. If there is an imposed structure on the gas distribution, such as a stellar spiral arm or ring, then the clouds can line up along this structure with a semi-regular spacing, producing beads on a string in spiral arms, tidal arm star-forming clumps, collisional ring star formation, nuclear ring hotspots, dwarf galaxy hot spots, etc. The cloud typically has \( 10^7 \ M_\odot \) of gas in the main galaxy disk, and it makes a \( 10^7 \ M_\odot \) star complex over a \( \sim 50 - 100 \) My period. In galaxies with no imposed stellar structures, gaseous instabilities and turbulence compression still make giant clouds and their fragments, but the star complexes are usually selected to be the largest globular scale, excluding the flocculent arms themselves. In both cases, star complexes appear as groupings of intermediate-age stars, such as Cepheid variables and red supergiants.

For a turbulent self-gravitating medium, star formation should operate on about the local dynamical time over a wide range of scales. Turbulence struc-
tures the gas, placing only a small fraction of the mass at a high enough density to form stars. The resulting hierarchical structure is somewhat continuous from the scale of the disk thickness to individual pre-stellar condensations. Stars form in the turbulent structures, making a hierarchy of stellar complexes, associations, clusters, multiple stars, and binaries. The efficiency of star formation increases with density in such a hierarchical medium. Only high density regions have high enough efficiencies to form bound clusters.

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