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THE RANGE IN SCALES OF STAR FORMATION

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RESUMEN

Las regiones de formación estelar que contienen estrellas masivas muestran una gran variedad en el número de estrellas que se han formado y en la concentración de estas estrellas en el espacio. Ejemplos de los valores de estos parámetros muestran que la formación de un gran número de estrellas masivas no está necesariamente acompañada de una gran concentración. Los super cúmulos muy compactos de estrellas, que se han encontrado, parecen formarse en complejos gaseosos cuya formación es facilitada por eventos especiales globales en la galaxia, a veces producidos externamente. La función inicial de masas estelares, tomada como un diagnóstico de los procesos de formación estelar, parece ser similar en eventos de formación estelar de tamaño modesto, en diferentes medio ambientes galácticos y aún para estrellas de masa intermedia en el intenso medio ambiente del cúmulo compacto R136. Por otra parte, las estrellas masivas formadas en regiones de formación estelar muy pequeñas, parecen tener una muy diferente función de masas, lo que implica que los eventos de formación estelar de distintos tamaños pueden tener diferentes productos de estrellas masivas.

ABSTRACT

Star-forming regions containing massive stars span a large range in the numbers of stars that have formed and the concentration of those stars in space. Illustrations of the range in these parameters show that the formation of large numbers of massive stars is not necessarily accompanied by a large concentration in space. The highly compact super star clusters that are being found today appear to form in gas complexes whose formation is facilitated by special global, sometimes externally triggered, events in galaxies. The stellar initial mass function, taken as a diagnostic of the star formation process, appears to be similar among modest-sized star-forming events in different galactic environments and even for intermediate mass stars in the intense environment of the compact cluster R136. On the other hand, massive stars formed in very small star-forming regions appear to have a very different mass function, implying that different sizes of star-forming events can have different massive star products.

Key words: **STARS: FORMATION — STARS: LUMINOSITY FUNCTION, MASS FUNCTION — GALAXIES: STAR CLUSTERS**

1. INTRODUCTION

Normal star-forming regions come in a wide range of sizes from tiny dark clouds forming a single intermediate or lower mass star (Bok 1977) to supergiant H II regions which have recently formed groups of globular-like clusters. Similarly, H II regions, the signposts for massive star formation, range from small regions containing one or a few massive stars, like the Orion Nebula, to those that are many times larger than 30 Doradus in the Large Magellanic Cloud (LMC) and contain hundreds of massive stars. H II region luminosity functions of the Milky Way, spiral, and irregular galaxies show that the number of H II regions follows a power-law with luminosity, such that the smaller star-forming regions are much more numerous (Smith & Kennicutt 1989; Kennicutt, Edgar, & Hodge 1989). On the other hand, small galaxies like NGC 2366 sometimes choose to put a large fraction of their total massive star formation into a single giant H II region (Hunter & Gallagher 1985).

There are actually two parameters in the "scale" of a star-forming region that I would like to consider. There is the total number of stars in a given mass or luminosity range that have formed in a particular event and there is the density of the stars, the amount by which those stars are concentrated in space. The hundreds of massive stars in giant H II regions, for example, may be concentrated in compact clusters or they may be more spread out, as in OB associations or open clusters.

Our understanding of star formation can profit by such a diversity of star-forming regions which serve as unique clues to the star formation process. An interesting question is whether the star formation process in any way differs with the size of the region: Are 10 small regions equivalent to one region that is 10 times bigger? Furthermore, what are the galactic conditions necessary to form stellar groups of different sizes and/or concentrations? The question of sizes is really a question of what conditions are necessary to form gas clouds of different sizes since it seems likely that larger clouds are necessary to form larger star-forming units. But, the question of concentrations of stars may be related to more than just the size of the cloud. In this paper I would like to illustrate the range in scales of star-forming units and summarize some of what is known about the star-formation process, particularly from the stellar products.

2. NORMAL ASSOCIATIONS AND CLUSTERS

When one thinks about star-forming regions, one usually pictures OB associations or open clusters. These units are the most common of what is readily visible in other galaxies. They contain some tens to hundreds of massive stars in relatively loose groups, and, therefore represent a modest concentration of young stars. Table 1 lists some concentrations of luminous stars for a variety of objects, including the study by Massey, Johnson, & Degioia-Eastwood (1995b) of a dozen OB associations in the Milky Way and the LMC. (Massey et al. counted stars with masses $> 10\ M_\odot$ whereas the other entries in Table 1 count stars with $M_V < -4$). Massey et al. found a density of 0.02 stars pc^{-2} for stars $>10\ M_\odot$ with a factor of two variation from this for all but one association. Interestingly, this density is much higher than that in the giant OB association NGC 206 in M31 which has a density of massive stars of only 0.0007 stars pc^{-2} for the half of the association surveyed by Hunter et al. (1995c). Even the giant H II region NGC 604 in M33 has a massive star density of only 0.02 stars pc^{-2} (Hunter et al. 1995b). Thus, a larger number of massive stars does not necessarily imply a higher concentration of those stars.

TABLE 1

SOME STELLAR DENSITIES

Object	N_*	Density (stars pc^{-2})	Reference
R136	122	1.8	Hunter et al. 1995a
30 Doradus	450	0.05	Parker & Garmany 1993 Hunter et al. 1995a
Milky Way–OB	6–82	0.02	Massey et al. 1995b
LMC–OB	40–84	0.02	Massey et al. 1995b
I Zw18–shell	225	0.02	Hunter & Thronson 1995
I Zw18–south	79	0.004	Hunter & Thronson 1995
NGC 604	186	0.02	Hunter et al. 1995b
NGC 206	187	0.0007	Hunter et al. 1995c

Although we do not understand the physics behind the stellar initial mass function (IMF), people use that as an observational diagnostic of the star formation process. The assumption is that if the IMF is the same in different regions, then the star formation process was the same too. Numerous OB associations in our Galaxy and the Magellanic Clouds have been tediously examined star-by-star in order to determine the IMF of the stars that have formed. Table 2 lists the results of some of these studies. With one exception, the IMFs for massive and intermediate mass stars appear to be near that of a Salpeter's IMF (Salpeter 1955; slope~ -1.35). Since the galaxies cover a factor of about 8 in oxygen abundance and the associations are found at varying distances from the center of these galaxies, these results suggest that the stellar products of this type of star-forming unit is independent of most large-scale galactic properties, at least within the range found in these three galaxies. The exception to this is a study by Mateo (1988) which found a much steeper slope for six old LMC clusters. The reasons for this exception are not known.

3. INTENSE REGIONS OF MASSIVE STAR FORMATION

3.1. Superstar Clusters

Ground-based and now *Hubble Space Telescope* (*HST*) images are revealing the presence of young star clusters that are remarkable for their compactness and luminosity. These "super star clusters," which have surface brightnesses at least 100 times that of normal OB associations (O'Connell, Gallagher, & Hunter 1994), are interesting because they represent an extreme mode of the star formation process and because they may resemble what globular clusters looked like when globular clusters were young.

In an *HST* imaging study O'Connell et al. (1994) examined three super star clusters in two dwarf irregular galaxies at a scale of 0.044″ per pixel. Two of the clusters are located in the starburst galaxy NGC 1569 and were studied from ground-based data in detail by Arp & Sandage (1985). However, Arp & Sandage could not decide conclusively whether these stellar-like objects were actually clusters in the galaxy or foreground stars in our Galaxy. The *HST* images resolved the objects and showed definitively that they are star clusters in NGC 1569. Furthermore, the clusters have half-light radii, $R_{0.5}$, of 2.2 and 3.0 pc and visual luminosities, related to an age of 3 Myr using the cluster evolution models of Bruzual (1994), of −15.3 and −14.5. The third cluster studied by O'Connell et al. is located in NGC 1705, and had been studied from ground-based data by Melnick, Moles, & Terlevich (1985) and Meurer et al. (1992). That cluster is just resolved by *HST* and has $R_{0.5}\sim3.4$ pc and an integrated 3-Myr magnitude of −15.2.

In another *HST* study, Hunter, O'Connell, & Gallagher (1994) examined the central star forming region in the amorphous galaxy NGC 1140 and found a collection of 6–7 blue, luminous, compact clusters located in the inner 1/2 kpc of the galaxy. These clusters are not resolved at the scale of the *HST* PC, but they have integrated luminosities of −12.4 to −15.5, relative to an age of 3 Myr. Similary, O'Connell et al. (1995) have found over 130 super star clusters in the center of the starburst galaxy M82.

The only familiar objects comparable to these are globular clusters, at least as we might expect them to have been at the same young age. According to van den Bergh, Morbey, & Pazder (1991), globular clusters have $R_{0.5}$ of 1–8 pc, and this is a slight function of position in the Galaxy. Thus, the super star clusters described above are as compact as the more compact globular clusters, assuming that the half-light radius of globulars has not changed significantly with time. Furthermore, *if* globular clusters had the same IMF as that of these super star clusters and the luminositiy evolved with time according to the models of Bruzual (1994), the magnitudes of Harris (1991) would indicate that globular clusters had integrated magnitudes of -13.7 ± 1.3 when they were 3 Myr old. Thus, the super star clusters are as bright as globular clusters were. The compactness and brightness of the super star clusters taken together suggest that they are young globular-like clusters.

Of course, this assumes that the super star clusters and globular clusters had the same, Salpeter IMF. Since these particular clusters are not resolved into individual stars that can be counted, we cannot directly test this assumption. However, there is another, although less extreme, cluster in which the IMF can be directly measured. That cluster is R136.

3.2. R136

R136, the luminous, compact star cluster at the heart of the 30 Doradus nebula in the LMC, is not nearly as extreme as the super star clusters discussed in the previous section. Although as compact ($R_{0.5}\sim1.7$ pc) as any of the superstar or globular clusters, R136 has a luminosity ($M_V=-11.1$) and mass ($2.2\times10^4\ M_\odot$ for stars with mass $\geq 2.8\ M_\odot$) that place it at the small end of the range expected of globular clusters at the same young age. Nevertheless, R136 is still quite remarkable compared to normal OB associations or even compared to the "populous" clusters of the LMC. NGC 1866, which is often referred to as a blue, globular-like cluster, has a half-light radius that is 8 times larger and a surface brightness that would have been 17 times smaller than that of R136 at the same age (Hunter et al. 1995a). What is impressive about R136 is the large number of massive stars that are congregated in a small space. There are 121 O stars located within a radius of 4.7 pc and 46 within 0.5 pc (Hunter et al. 1995a; see also Hill et al. 1993; Parker & Garmany 1993). These densities are 100–300 times higher than those of normal OB associations (Table 1), and so R136 represents an example of a concentrated star-forming event even if it is not as extreme as the other super star clusters.

HR diagrams derived from *HST* images by Hunter et al. (1995a) reveal the presence of massive stars although no red supergiants, a main sequence down to at least an $M_{V,o}$ of 1.5, and stars on pre-main sequence tracks with $M_{V,o} \geq 0.5$. One sees immediately that the lower stellar mass limit in R136 has to be at least less than 2.8 $M_{\odot}$. This is contrary to some suggestions in the literature that the lower mass limit (M_l) in regions of intense massive star formation would be unusually high. For example, Silk (1977) and Larson (1985) have suggested that massive stars form in hotter, more turbulent environments than do lower mass stars. Therefore, Güsten & Mezger (1983) concluded that $M_l > 2$–$3\ M_{\odot}$ in spiral arms, and Silk (1986) suggested that M_l could be as high as 10 $M_{\odot}$ in giant H II regions. In studies of a few starburst galaxies, as well, people have come to the conclusion that lower mass stars must not have formed in the recent starburst in those systems (c.f., Rieke, Loken, & Rieke 1993; Augarde & Lequeux 1985; Olofsson 1989; Wright et al. 1988). Unfortunately, because these galaxies are at large distances, individual stars cannot be resolved and the arguments for high M_l's have necessarily been indirect and highly uncertain (Scalo 1990). The normalcy of R136, therefore, is perhaps unexpected.

Even more remarkable is the normalcy of the IMF in R136. For stars with masses in the range 2.8–15 $M_{\odot}$ and distances 0.5–4.7 pc from the center of the cluster the slope of the IMF is -1.2 ± 0.06, similar to values found for more normal OB associations (see Table 2). Thus, we see that even in the concentrated environment represented by R136, the star formation process, at least for intermediate mass stars, has been similar to that in less dense star-forming environments.

TABLE 2

SOME IMF MEASUREMENTS

Galaxy	Object	IMF Slope	Mass Range ($M_{\odot}$)	Reference
SMC	NGC 346	-1.4 ± 0.1	≥ 25	Massey et al. 1995a
SMC	Field	-3.7 ± 0.5	≥ 25	Massey et al. 1995a
LMC	30 Doradus	-1.5 ± 0.2	≥ 12	Parker & Garmany 1993
LMC	R136	-1.2 ± 0.1	2.8–15	Hunter et al. 1995a
LMC	4 OB Assoc.	-1.1 ± 0.1 to -1.7 ± 0.2	≥ 25	Massey et al. 1995a
LMC	NGC 2004	-1.3	2–20	Bencivenni et al. 1991
LMC	5 young clusters	-1.1	2–14	Sagar & Richtler 1991
LMC	6 old clusters	-2.5 ± 0.2	0.9–11	Mateo 1988
LMC	Field	-4.1 ± 0.2	≥ 25	Massey et al. 1995a
Milky Way	3 OB Assoc.	-1.0 ± 0.1 to -1.3 ± 0.2	≥ 25	Massey et al. 1995a
Milky Way	10 OB Assoc.	-1.1 ± 0.1	≥ 7	Massey et al. 1995b
Milky Way	8 Open Clusters	-1.4 ± 0.1	1.4–7.9	Phelps & Janes 1993
Milky Way	Small H II	-1.3 ± 0.4	≥ 15	Hunter & Massey 1990
Milky Way	Field	-1.7 ± 0.2	2–10	Scalo 1986
Milky Way	Field	-3.2 ± 1.4	≥ 25	Massey et al. 1995a
M33	NGC 604	-1.6 ± 0.7	6.5–18	Hunter et al. 1995b

3.3. Large Does Not Mean Concentrated

However, the presence of a large number of massive stars does not necessarily require that those stars be concentrated in space (Kennicutt & Chu 1988). NGC 604, the giant H II region in M33, for example, has a comparable number of massive stars as are found in R136, but they are much more loosely distributed in NGC 604. In fact the density is like that in typical OB associations with a few small subclumps having densities only a factor of 10 higher. It is only averaged over the much larger 30 Doradus region studied by Parker & Garmany (1993) that the density of massive stars in 30 Doradus is comparable to that of OB associations.

Another example of "large but not concentrated" is found in the blue compact dwarf irregular I Zw18. Like other blue compact dwarf galaxies, I Zw18 is a tiny galaxy that is dominated by intense H II regions. Thus, they have been thought to represent a different and extreme environment for star formation compared to the Milky Way and many other nearby galaxies. Hunter & Thronson (1995) have used *HST* to resolve this galaxy into individual stars for the first time. They found 396 massive stars including blue and red supergiants. Half of these stars are located in two groups, corresponding to the two knots of gaseous emission identified in ground-based images. The spatial concentration of these massive stars is, in fact, closer to that of large OB associations in nearby galaxies rather than to that exemplified by the compact cluster R136 in the LMC. The density of stars with $M_V \leq -4$ in the northern group is comparable to what Massey et al. (1995b) found for OB associations in the Milky Way and LMC. So, in the case of this one blue compact dwarf, the star-forming units look remarkably normal in terms of the density of massive stars.

3.4. What Does it Take to Form Concentrated Clusters?

The large numbers of massive stars concentrated into luminous, compact super star clusters presumably require unusually large concentrations of gas to form. Young clusters found today are located in small dwarf irregular galaxies like the LMC as well as larger systems, so the size of the galaxy does not seem to be a factor. It is interesting, however, that no examples of these types of clusters are seen forming today in truly isolated and normal galaxies.

In NGC 1140, the galaxy containing a group of super star clusters, the supergiant H II region in which they sit is part of a ridge of H I at the center of the galaxy (Hunter, van Woerden, & Gallagher 1994). The column density in the vicinity of the H II region, averaged over the inner 700 pc radius, is 2×10^{21} cm^{-2}. A rough estimate of the star formation efficiency in the inner 1.5 kpc shows that it could have been as high as 25%. Hunter et al. argue that NGC 1140 is a merger in progress, and as a result of this interaction the H I is unusually concentrated to the center of the galaxy. It is unfortunate that CO has not been detected in NGC 1140 (Hunter & Sage 1993), so we know nothing about the molecular clouds out of which these objects have formed.

However, the 30 Doradus complex in the LMC is an example of this phenomenon that we do know more about. Cohen et al. (1988) found that 30 Doradus sits at the northern end of a 2-kpc long molecular complex. The mass of the complex itself is 60×10^6 $M_\odot$ or 40% of all of the molecular gas in the galaxy. The cloud associated with 30 Doradus contains about 9×10^6 $M_\odot$ which is 20–100 times the mass of a typical giant molecular clouds in the Milky Way (Scoville & Sanders 1987). The 30 Doradus region also contains 14×10^6 $M_\odot$ of atomic hydrogen, which is 2.6% of the total H I in the LMC (McGee & Milton 1966). The peak density at a resolution of 220 pc is currently 3×10^{21} cm^{-2} (Luks & Rohlfs 1992).

Thus, we see that the formation of R136 has taken place in a large atomic and molecular cloud which in turn is located in an extensive atomic and molecular complex. This may be, however, only a necessary, not a sufficient, condition to produce an R136-like event (Kennicutt & Chu 1988). For example, Cohen et al. (1988) have suggested that Constellation III in the LMC formed from a molecular and atomic gas complex that was comparable to what is now seen associated with 30 Doradus, and yet no group comparable in stellar density to R136 is seen there today.

Although special, NGC 1140 and the LMC are not unique; other cases of young globular-like clusters have been found with *HST*: the dwarf galaxy He2-10 which may also be a merger product (Conti & Vacca 1994), the "cooling-flow" galaxy NGC 1275 (Holtzman et al. 1992), and the merger galaxy NGC 7252 (Whitmore et al. 1993). NGC 1569, although not obviously interacting, is undergoing an unusual global burst of star formation. Many of these systems, therefore, are mergers or are undergoing unusual global bursts of star formation, and it is these external processes that may help produce the unusually large gas complexes that these clusters are associated with (Noguchi 1988). Even R136 has formed in a galaxy that is interacting with another. These cases, then, suggest that special circumstances are required to produce the conditions necessary for such concentrated star-forming events.

But, what about galaxies that are not obviously perturbed by an external event? No example of an unusually concentrated star-forming event is found in normal, isolated galaxies today, but there are plenty of examples of *large* star-forming events in such systems. In irregular galaxies some especially large H II regions are sometimes found near the ends of stellar bars. Elmegreen & Elmegreen (1980) found that in about half of all barred Magellanic irregular galaxies the largest H II region was located near the end of a bar. Two examples are 30 Doradus in the LMC and NGC 2363 in NGC 2366. Elmegreen & Elmegreen suggest that the bar potential coupled with solid-body rotation in that region causes compression of the gas there, giving rise to large clouds and H II regions. However, large star-forming events are not always found near the ends of bars as Constellation III demonstrates. Furthermore, in spiral galaxies there does not appear to be any preferred location for giant H II regions, and they follow the general distribution of all H II regions (Kennicutt & Hodge 1984). Therefore, it is not clear that there exists, or needs to exist, a non-stochastic mechanism for producing large clouds not associated with bar potentials in normal galaxies.

4. SMALL H II REGIONS AND FIELD STARS

At the other extreme of regions forming massive stars are tiny H II regions containing only one or a few massive stars. These Hα regions and molecular clouds are so faint and small that they are not usually individually detected or resolved in galaxies beyond the Magellanic Clouds. However, the mass spectrum of molecular clouds suggests that there are far more small clouds than giant molecular clouds in, for example, our Galaxy (N $\propto M^{-1.6}$, Scoville & Sanders 1987), and therefore, these small clouds are an important constituent of a galaxy's star-formation activity.

In a study of the most massive star contained in a sample of relatively small H II regions in the Milky Way, Hunter & Massey (1990) concluded that the ensemble of upper mass limits was statistically sampling a normal IMF. In particular the slope of the IMF for stars from 15–60 $M_{\odot}$ is -1.3 ± 0.4. This would suggest that the IMF for the massive stars in even small regions is normal. A similar result has been found for the most massive stars in small LMC H II regions (Wilcots 1994). Furthermore, Hunter, Thronson, & Wilton (1990) found no relationship between the upper mass limit and the radius from the center of the Galaxy or with cloud mass for clouds 1–60$\times10^3$ $M_{\odot}$.

However, Massey et al. (1995a) have found an interesting and contradictory result for field stars in the Magellanic Clouds. Since massive stars live such short lives, field O stars should be massive stars that were born in small stellar units. Massey et al. find stars as massive as those in OB associations, and when all of the field stars are put together and corrected for differences in ages, the slope of the resulting IMF is -4.1 ± 0.2 for the LMC and -3.7 ± 0.5 for the SMC. The difference in the IMFs between the field stars and those in OB associations is not subtle and is well beyond the expected uncertainties.

The reason for the difference between Massey et al. and Hunter & Massey's results is not clear yet. But, if Massey et al. are correct and massive stars born in small star-forming units have a different IMF from those born in OB associations, it opens up the possibility that the IMF of at least the massive stars may be a function of the natal environment. This would imply that the IMF slope is steeper in smaller star-forming units, and is perhaps a function of the size or density of the molecular clouds as suggested by Larson (1982) or of the density of newborn stars as some sort of feedback process. In this regard, it will be interesting to obtain a proper IMF for the massive stars in the much denser environment of R136. The implication would be that R136 would have an abnormally shallow massive star IMF slope, and if it does, this IMF would be quite different from that for the intermediate mass stars.

5. SUMMARY

So, at this point we do not really know the answer to the question of whether star formation in 10 units is the same as star formation in one unit that is 10 times bigger in terms of the stellar products. Evidence suggests that intermediate and massive stellar populations are the same in modest and concentrated stellar groups while other clues point to a significant difference between massive stars in very small regions and those in more intense star-forming events. There may, however, be a consequence to the galaxy that *is* different if the 10 units are not as temporally coherent as the single large unit. That has to do with the ability of large concentrations of approximately coeval massive stars to blow holes in the interstellar medium, and even out, of a galaxy. The 30 Doradus region is already full of bubbles and X-ray emission even before the stars at its center have begun to explode. If highly successful, the clusters in NGC 1140, for example, may clear a significant amount of gas out of the center of the galaxy. Thus, the degree of feedback to the surrounding interstellar medium and the impact on the global process of star formation could well be different in the two modes of star formation even if the local processes are the same.

As to the question of what conditions are necessary to form star-forming units of different sizes and concentrations, we have seen that globular-like clusters are associated with large gas complexes and appear to be preferentially found today in galaxies undergoing unusual, global, and sometimes externally triggered, star-forming events. For galaxies not perturbed by external processes, the formation of large, although not usually dense, star-forming units may be helped by kinematical processes around bar potentials which can pile up sufficiently large gas clouds. However, large star-forming events not clearly associated with bar potentials perhaps indicate stochastical processes. In this regard recent reports of the effects of "stochastical addition" in terrestrial phenomena may prove interesting.

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