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MASSIVE STARS IN CLUSTERS AND THE FIELD

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RESUMEN

¿Cuál es la relación entre las estrellas masivas en el campo y en cúmulos? ¿Representan un extremo en la ley de potencias de agrupamiento estelar? O ¿representan una modalidad diferente y sustancial de la formación estelar? ¿Cuál es el origen de la ley de agrupamiento? Examinamos la población de estrellas masivas de la Nube Menor de Magallanes y encontramos una relación contínua de ley de potencias entre estrellas en el campo y cúmulos. Ello implica que la fracción de estrellas masivas en el campo ocupa entre el 35% al 7% en la mayoría de las situaciones astrofísicas, con pobre dependencia en el tamaño de la galaxia y/o la tasa de formación estelar. También examinamos la historia de formación estelar de los complejos Galácticos W3/W4, un sistema de tres generaciones jerárquicas de formación estelar auto-disparada. Ello provee la más fuerte evidencia, a la fecha, de que las superburbujas disparan en realidad la formación estelar. Aquí de manera especulativa conectamos éste proceso jerárquico con la ley de potencias de agrupamiento de estrellas.

ABSTRACT

What is the relation between field massive stars and clusters? Do they represent an extreme in the universal, power-law relation for stellar clustering? Or do they represent a substantially different mode of star formation? What is the origin of the clustering law itself? We examine the massive star population of the Small Magellanic Cloud and find a continuous, power-law relation between field stars and clusters. This implies that the fraction of field massive stars ranges from about 35% to 7% for most astrophysical situations, with a weak dependence on the galaxy size and/or star formation rate. We also examine the star formation history of the Galactic complex W3/W4, which is a system of three generations of hierarchical, triggered star formation. This lends some of the strongest evidence to date that superbubbles indeed trigger star formation. We speculatively link this hierarchical process to the power-law clustering of stars.

Key Words: **GALAXIES: STAR CLUSTERS — ISM: BUBBLES — STARS: EARLY-TYPE — STARS: FORMATION — STARS: STATISTICS**

1. THE MASSIVE STAR CLUSTERING LAW

The population of massive stars ($m \gtrsim 10\,\mathrm{M}_\odot$) is linked to fundamental astrophysical phenomena, such as star formation, galaxy formation and evolution, and properties of the parent interstellar medium (ISM). Considering massive stars as a *population* refers to considering their distributions in *mass*, given by the stellar initial function (IMF), and in *space*, as described by a clustering law.

Evidence has emerged over the last decade, that the clustering law, like the IMF, has the form of a power law:

$$N(N_*)\;dN_* \propto N_*^{-2}\;dN_* \quad , \tag{1}$$

where N_* is the number of stars per association or cluster. Also analogous to the IMF, this relation appears to be universal in form, with the power-law exponent of –2 found for a variety of systems, including globular clusters, massive young clusters, starbursts, and the H II region luminosity function (e.g., Elmegreen & Efremov 1997; Harris & Pudritz 1994; Hunter et al. 2003; Zhang & Fall 1999; Meurer et al. 1995; Oey & Clarke 1998).

2. THE ROLE OF FIELD STARS: THE SMC

Field massive stars are known to exist, in the sense that isolated massive stars are seen, that show no other nearby, associated massive companions. Observational (Massey 2002) and statistical (Kroupa & Weidner 2003) arguments have been presented that suggest that the field star IMF varies from that in clusters. Theoretical considerations also suggest that the formation of individual field massive stars might be dominated by different physical effects (e.g., Li et al. 2003).

What does a universal clustering law mean for the existence of field massive stars? Are these stars truly isolated? What is the relation of field stars

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and the field IMF to stars in clusters? To investigate these issues, we obtained an empirical census of uniformly-selected massive star candidates in the Small Magellanic Cloud (SMC). The proximity of this galaxy yields superior spatial resolution for resolving individual stars, while simultaneously allowing us to examine the angular area of most of that galaxy.

To select the candidate stars, we used the broadband $UBVR$ survey of the SMC by Massey (2002) in conjunction with the *Ultraviolet Imaging Telescope (UIT)* observations in the B5 filter ($\lambda_{\rm eff}$ = 1615 Å, $\Delta\lambda$ = 225 Å) of the SMC bar (Parker et al. 1998). We compiled two samples of candidates, designated the "OB sample," selected from the optical data only, but covering most of the galaxy; and the "O-star sample," selected from the combined optical-UV dataset. Only broadband criteria were used, thus 15 – 20% of the sample may be spurious detections. However, these criteria are applied uniformly between the field and clusters, thus, statistical results are valid provided that there is no significant difference in selection efficiency between field and clusters. The identified samples and selection criteria are described in detail by Oey, King, & Parker (2004a). The OB and O-star samples correspond roughly to stars with masses $m \geq 10$ M$_\odot$ and $m \geq 20$ M$_\odot$, respectively.

Having selected the two samples of massive stars, we then applied a friends-of-friends algorithm introduced by Battinelli (1991) to identify groups and associations in the SMC. The characteristic clustering length was taken to be the value that maximizes the number of groups having ≥ 3 massive star members (see Oey et al. 2004a for details). The resulting clustering relations for the two samples are shown in Figure 1. Two power-law fits to the distributions, weighted by the inverse variances, are shown: the solid lines show fits to the entire sample, while the dotted lines show fits excluding the first bin, which correspond to $N_* = 1$, i.e., field massive stars. The fits excluding the field stars agree with the –2 universal power law exponent for the clustering law, discussed above. When the field stars are included, the fits steepen somewhat, showing a slight excess for the optically-selected sample. The origin of this excess reflects a non-uniformity in the location of clusters across the SMC: most of the clusters and associations are located in the SMC bar, whereas field stars are more uniformly distributed. In addition, runaway O and B stars contribute a minor fraction (roughly 20% and 3%, respectively; Blaauw 1961) to the field population.

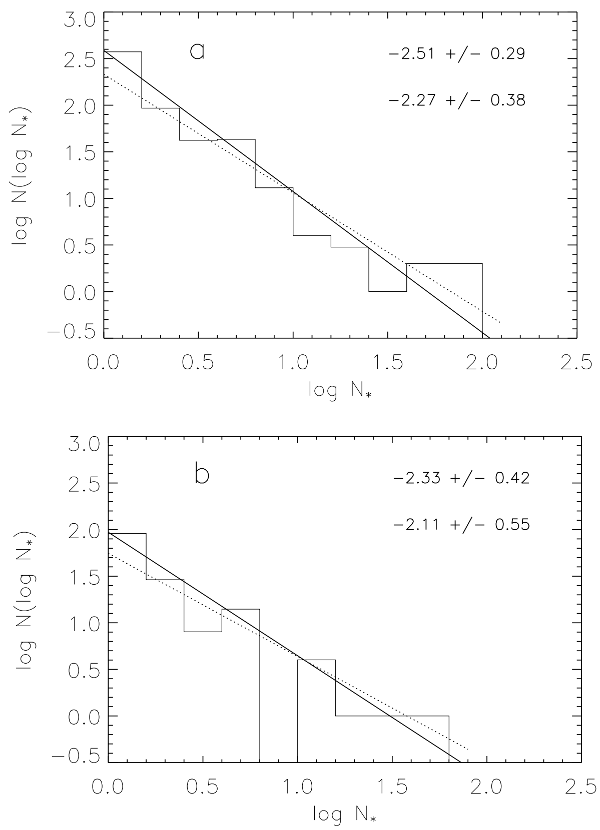

Fig. 1. Clustering relations for the candidate (a) OB sample and (b) O-star sample. The solid and dotted lines show power-law fits for the entire distribution and omitting the field stars, respectively.

A universal IMF implies that these field OB stars should have low-mass companions; indeed, that they represent the "tip of the iceberg" within small clusters of stars. To test this, we measured the stellar surface density as a function of radius from these individual field massive stars. We found that the stellar density indeed drops by roughly a factor of two between distances of 10 and 30 arcsec from the central stars.

Having confirmed the presence of low-mass companions, we therefore expect a selection effect in the observed clustering relation: we are only selecting clusters that formed at least one star with a mass above our cutoff criterion. Another factor that could affect the form of the observed clustering relation is aging. Oey et al. (2004a) modeled both of these effects and found that they tend to cancel each other. The selection effect tends to flatten the clustering law in the smallest N_* bins, while the aging effect tends to steepen it. Neither effect is particularly strong, and the SMC sample is unlikely to be sensitive to them.

Thus, the clustering relation for massive stars in the SMC appears to be fully consistent with the universal clustering law (equation 1) within these uncertainties. We note that this continuous, power-law clustering relation implies a constant IMF between the field and clusters. As mentioned above, the field IMF for massive stars has been suggested to be steeper than that in clusters from both empirical and statistical arguments (Massey 2002; Kroupa & Weidner 2003). If this is the case, then it implies fewer field massive stars. Our results for the SMC would therefore imply that the intrinsic clustering relation must be steeper for $N_* = 1$ to compensate for such a lack of field OB stars, in order to reproduce the observed smooth power law. Further studies are needed to determine whether this is indeed the case, or whether the simpler scenario of joint, universal power laws for the IMF and clustering applies.

For joint universal IMF and clustering laws, the fraction of massive field stars can be estimated as,

$$F_{\rm field} \simeq \Big(\ln N_{*,\rm up} + 0.5772\Big)^{-1} \quad . \qquad (2)$$

We see that the field fraction is weakly dependent on $N_{*,\rm up}$, the number of massive stars in the largest cluster of the ensemble. For most astrophysical situations, $F_{\rm field}$ ranges between 35% and 7%, depending on galaxy size and/or star formation rate. This has significant consequences for feedback effects. It is quantitatively consistent with the fraction of the warm ionized medium energized by field stars in M33 (Hoopes & Walterbos 2000), and implies that roughly half of the volume produced by mechanical feedback in disk galaxies results from the field (Oey & Clarke 1997).

3. HIERARCHICAL TRIGGERED STAR FORMATION

What is the origin of the clustering law? The power-law mass function of molecular clouds and power-law distribution of spatial structure in the ISM is often linked to fractal descriptions of the ISM. Yet, we also know that superbubble activity driven by supernovae, and the resulting superbubble structure, also exists in the ISM. What is the relation between the fractal and superbubble descriptions (see Oey 2002 for a review)?

It is often assumed that superbubbles trigger new star formation at their shell edges. Numerous examples exist of superbubbles showing secondary star formation on their edges (e.g., Walborn & Parker 1992; Williams et al. 1995; Oey & Smedley 1998).

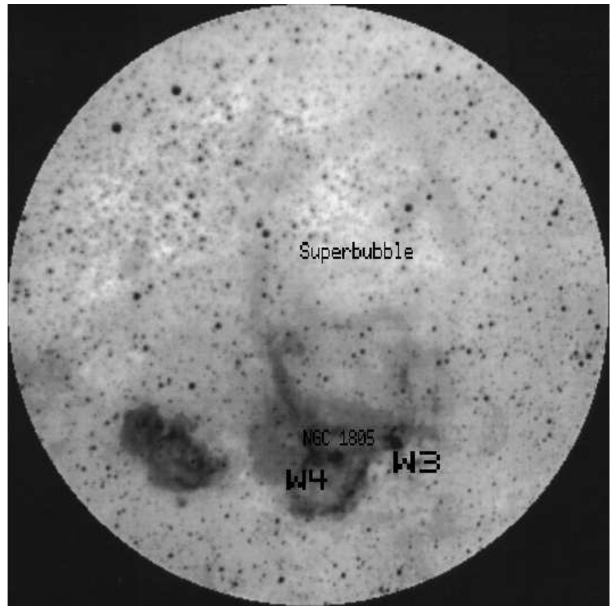

Fig. 2. Hα image of the Perseus superbubble, from Dennison et al. (1997). The field of view is 10° in diameter.

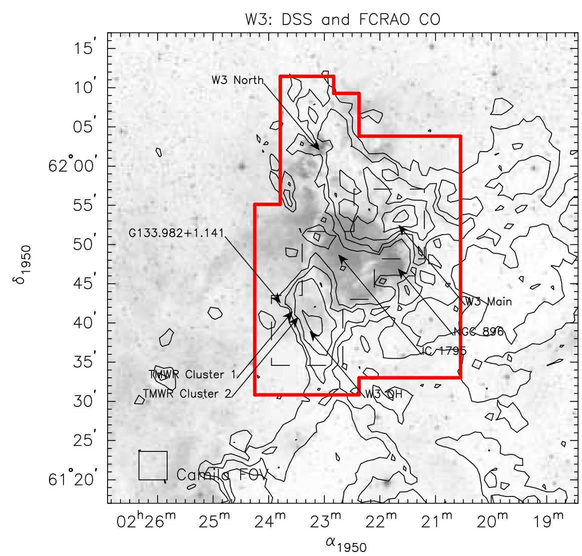

Fig. 3. Digital Sky Survey image of the IC 1795 region, with CO contours from the FCRAO Outer Galaxy Survey (Heyer et al. 1998) overlaid.

However, sequential star formation does not necessarily imply a causal effect.

Three generations of star formation in a system of hierarchical shells, on the other hand, is much more compelling evidence of actual triggered star formation. The W3/W4 system in the Perseus Arm of the Milky Way appears to be an example of such a three-generation complex. The largest shell is the well-known Perseus superbubble, associated with the W4 / IC 1805 star-forming region (Figure 2). On the edge of this superbubble is the W3 / IC 1795 complex. Figure 3 shows that the active W3 regions are embedded in a shell of molecular gas surrounding the optical association IC 1795. Dennison et al. (1997) estimate the age of the Perseus superbubble to be 6 – 10 Myr old, while the active star-forming regions W3-North, W3-Main, and W3-OH are roughly $10^4 - 10^5$ yr old (e.g.,Tieftrunk et al.1998).

If the W3/W4 complex indeed represents hierarchical triggered star formation by superbubbles, then IC 1795 should be intermediate in age between the Perseus superbubble and the embedded W3 star-forming regions. We obtained *UBV* photometry of IC 1795 at the 0.84-m telescope of the OAN at San Pedro Mártir (SPM), and spectroscopic observations of the bluest, most luminous members at the SPM 2.1-m telescope. A preliminary H-R diagram for IC 1795 is shown in Figure 4, indicating an estimated age of 3 – 5 Myr. The final H-R diagram and a more complete discussion of the star formation history is presented by Oey et al. (2004b).

Thus, the age sequence in the W3/W4 complex is fully consistent with the scenario of hierarchical superbubbles and provides compelling evidence that superbubbles indeed trigger star formation. We also note that the IC 1795 superbubble is several times smaller than the Perseus superbubble. When considering the relation between superbubble and fractal ISM structure, it is intriguing to note that these hierarchical superbubbles could also be viewed as a fractal relationship.

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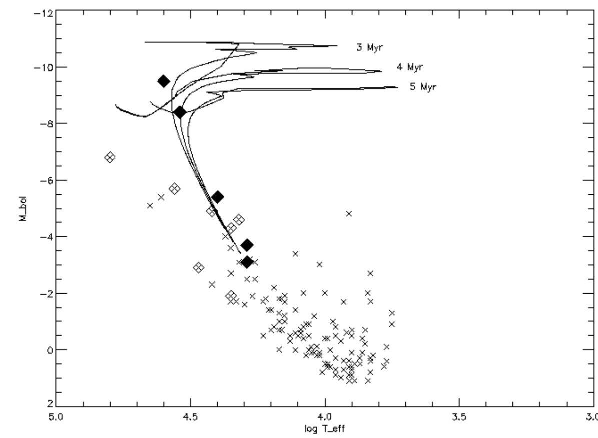

Fig. 4. Preliminary H-R diagram of IC 1795. Solid points show stars having spectroscopic classifications; open squares show stars placed on the basis of high quality photometric data; and crosses show the remainder of the stars observed. Isochrones for 3, 4, and 5 Myr from Schaller et al. (1992) are overlaid.

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