HIERARCHICAL STELLAR STRUCTURES IN THE LOCAL GROUP DWARF GALAXY NGC 6822

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ABSTRACT

We present a comprehensive study of the star cluster population and the hierarchical structure in the clustering of blue stars with ages \( \lesssim 500 \) Myr in the Local Dwarf Group dwarf irregular galaxy NGC 6822. Our observational material comprises the most complete optical stellar catalog of the galaxy from imaging with the Suprime-Cam at the 8.2 m Subaru Telescope. We identify 47 distinct star clusters with the application of the nearest-neighbor density method to this catalog for a detection threshold of \( 3\sigma \) above the average stellar density. The size distribution of the detected clusters can be very well approximated by a Gaussian with a peak at \( \sim 68 \) pc. The total stellar masses of the clusters are estimated by extrapolating the cumulative observed stellar mass function of all clusters to be in the range \( 10^3-10^4 M_\odot \). Their number distribution is fitted very well by a power law with index \( \alpha \sim 1.5 \pm 0.7 \), which is consistent with the cluster mass functions of other Local Dwarf galaxies and the cluster initial mass function

In addition to the detected star clusters of the galaxy, the application of the nearest-neighbor density method for various density thresholds, other than \( 3\sigma \), enabled the identification of stellar concentrations in various length scales. The stellar density maps constructed with this technique provide a direct proof of hierarchically structured stellar concentrations in NGC 6822, in the sense that smaller dense stellar concentrations are located inside larger and looser ones. We illustrate this hierarchy by the so-called dendrogram, or structure tree of the detected stellar structures, which demonstrates that most of the detected structures split up into several substructures over at least three levels. We quantify the hierarchy of these structures with the use of the minimum spanning tree method. We find that structures detected at 1, 2, and 3\( \sigma \) density thresholds are hierarchically constructed with a fractal dimension of \( D \approx 1.8 \). Some of the larger stellar concentrations, particularly in the northern part of the central star-forming portion of the galaxy, coincide with IR-bright complexes previously identified with Spitzer and associated with high column density neutral gas, indicating structures that currently form stars. The morphological hierarchy in stellar clustering, which we observe in NGC 6822, resembles that of the turbulent interstellar matter, suggesting that turbulence on pc and kpc scales has been probably the major agent that regulated clustered star formation in NGC 6822.

Key words: galaxies: dwarf – galaxies: individual (NGC 6822) – galaxies: irregular – galaxies: star clusters: general – open clusters and associations: general

Online-only material: color figures

1. INTRODUCTION

Star formation in galaxies is observed on a wide range of scales, from stellar complexes and aggregates over OB associations to compact embedded clusters, which again often show substructure. These systems are not distinct, independent entities, but rather appear to form a continuous hierarchy of structures over all these scales (e.g., Efremov & Elmegreen 1998; Elmegreen et al. 2000). The interstellar matter (ISM) also shows a hierarchical structure from the largest giant molecular clouds down to individual clumps and cores. The complex hierarchical structure of the ISM is believed to be shaped by supersonic turbulence (e.g., Ballesteros-Paredes et al. 2007). The scaling relations observed in molecular clouds (Larson 1981) can be explained by the effect of turbulence, where energy is injected at very large scales and cascades down to the smallest scales, creating eddies and leading to a clumpy, filamentary structure on all scales. These structures appear self-similar and are therefore often described as fractal. Turbulence is believed to play a major role in star formation by creating density enhancements that become gravitationally unstable and collapse to form stars. The spatial distribution of young stars and star clusters probably reflects this process.

There are only a few cases where the formation of stellar structures in star-forming galaxies with resolvable stars can be studied in the complete extent of the galaxy. NGC 6822 is one of these rare galaxies, because it is far enough from us for its whole extent to be fairly covered in small fields of view, but also close enough for its bright stellar content to be sufficiently resolved. NGC 6822 (IC 4895) is a Local Group dwarf irregular of type Ir IV-V (van den Bergh 2000). It is the closest dwarf irregular apart from the Magellanic Clouds (MCs), located at a distance of 490 ± 40 kpc from us (Mateo 1998), and belongs to an extended cloud of irregulars named the “Local Group Cloud.” Due to its close distance, NGC 6822 appears quite extended on the sky; its optical angular diameter is over a quarter of a degree, while its H\( \alpha \) disk measures close to a degree (de Blok & Walter 2000). NGC 6822 is relatively near the Galactic plane (\( b = -18\)°) and therefore suffers from significant foreground extinction from the Milky Way (MW). Massey et al. (2007) using multi-band imaging of NGC 6822 within the Survey of Local Group Galaxies Currently Forming Stars (SLGGCFS), derived a total interstellar reddening of \( E(B-V) = 0.25 \pm 0.02 \), with \( E(B-V) = 0.22 \) being Galactic. Other recent optical studies of the stellar content of the galaxy (de Blok & Walter 2003; Battinelli et al. 2003)
show that NGC 6822 has an extended stellar distribution, with the young blue stars following the distribution of the H\textsc{i} disk (Komiyama et al. 2003), while the old and intermediate-age stellar population is found significantly more extended than the H\textsc{i} disk (de Blok & Walter 2006).

The stellar and gas components of NGC 6822 could not explain the shape of the high-resolution rotation curve obtained with the ATCA, except the very inner regions (Weldrake et al. 2003), and therefore it is considered to be very dark matter dominated. NGC 6822 is a metal-poor, relatively gas-rich galaxy with ISM metal abundance of about 0.2 Z\textsubscript{\odot}, i.e., the total fraction of metal is Z \simeq 0.004 (Skillman et al. 1989), and total H\textsc{i} mass of \( \sim 1.3 \times 10^8 \ M\textsubscript{\odot} \) (de Blok & Walter 2000). Its star formation rate (SFR), based on H\textalpha{} and far-IR fluxes, is found to be around \( \sim 0.06 \ M\textsubscript{\odot} \text{yr}^{-1} \) (Mateo 1998; Israel et al. 1996) or \( \sim 0.01 \ M\textsubscript{\odot} \text{yr}^{-1} \) (Hunter & Elmegreen 2004). Evidence for increased star formation between 75 and 100 Myr ago is found by Hodge (1980), while Gallart et al. (1996a) found that the star formation in NGC 6822 increased by a factor of 2–6 between 100 and 200 Myr ago. Moreover, Hubble Space Telescope (HST) imaging showed that the recent SFR is spatially variable in the central parts of NGC 6822 (Wyder 2001). All these findings are consistent with the mostly constant but stochastic recent star formation histories often derived for other dwarf irregular galaxies (see, e.g., Weisz et al. 2008).

NGC 6822, like most dwarf irregulars, provides an ideal laboratory for the study of galaxy evolution, and in particular at early stages, since its low metallicity and rich gas content suggest that NGC 6822 is still in an early stage of its conversion from gas to stars. Moreover, its relatively simple structure, without dominant spiral arms or bulge, makes the study of the various physical processes related to star formation relatively straightforward. The scope of the present study is the comprehensive understanding of the structural behavior of star formation during the period of the last \( \sim 500 \text{ Myr} \) over the whole extent of NGC 6822. Specifically, we investigate the cluster population of the galaxy in terms of the size, mass, and structural characteristics of the detected stellar systems. We also study the clustering behavior of stars and its relation to hierarchically structured stellar concentrations within the whole extent of NGC 6822.

A comprehensive study of the star complexes, i.e., large-scale star-forming regions with sizes of the order of few hundreds pc, was recently presented by Karampelas et al. (2009). These authors provide a complete catalog of star complexes in NGC 6822, their positions and sizes, based on the data collected within the SLGGCFS (Massey et al. 2006, 2007). This study is limited to the brightest stars of the galaxy with \( B < 22.5 \) due to the detection limit of the SLGGCFS and only to its central part, which is covered by the survey. In our investigation here, we extend the study of the spatial distribution of young stars and hierarchical star formation in NGC 6822 to the smallest detectable structures and to the complete extent of the galaxy, including the potentially tidal systems, with the use of original photometric material that comprises a stellar sample six times larger than that used by Karampelas et al. (2009). Our catalog extends to fainter magnitudes by \( B \sim 2.5 \text{ mag} \) on the main sequence, and covers the whole area of the H\textsc{i} disk of the galaxy (Figure 1 top). As a consequence, in the present study, we investigate star formation in a wider range of lengthscales, covering structures with sizes from few tens pc (clusters and small associations) to few hundreds pc (stellar aggregates and complexes). Apart from the study of hierarchy, our detection method allows us to also address important issues

Figure 1. Three views of NGC 6822. Top: integrated ATCA H\textsc{i} column density or zeroth-moment map of NGC 6822. The contour indicates the edge of the H\textsc{i} disk of the galaxy at \( 5 \times 10^{20} \text{ cm}^{-2} \). The grayscale levels run up to \( 4.3 \times 10^{21} \text{ cm}^{-2} \) (black), which is the maximum column density occurring in this map. The beam of \( 42^\prime\prime \times 12^\prime\prime \) is indicated in the bottom right. This column density map is adapted from dBW06; for additional representations see Weldrake et al. (2003). Middle: spatial distribution of the blue stars with \( B - R < 0.5 \) on the sky. This distribution highlights the concentration of the blue stars with ages \( \leq 500 \text{ Myr} \) in the inner parts of the galaxy, and the general extent of these stars in a disk-like structure, similar to the H\textsc{i} disk of the galaxy. Bottom: number density map of the blue stars shown in the middle panel, measured in 64’ \times 64’ boxes. The isodensity contour levels run from the mean background density in steps of 1σ, with σ being the standard deviation of the background density. Isopleths of density \( >5\sigma \) are plotted with thicker lines.
of star formation, such as the structural behavior of the clusters in NGC 6822 and the cluster mass function (CMF) of the galaxy.

The observational material, which includes the most complete stellar sample observed in NGC 6822 (de Blok & Walter 2006, from here on dBW06) is described in Section 2. In Section 3, we define the stellar content of the galaxy for the purpose of our study and select the type of stars our analysis focuses on. We identify the clusters of the galaxy with the application of the nearest neighbor (from here on NN) method in Section 4, and we discuss their sizes and masses in Section 5. In Section 6, we construct the CMF of NGC 6822 and compare our results with those of other galaxies. The structural parameters of the detected clusters are measured and cross-correlated in Section 7. The hierarchical behavior in the spatial distribution of the blue stellar content of NGC 6822 is investigated in Section 8, with the detection of stellar structures in various lengthscales larger than typical clusters, and the construction of their dendrogram, to determine the degree of hierarchical clustering. We discuss our results concerning hierarchy in Section 9. Finally, we summarize the findings of this study in Section 10.

2. OBSERVATIONAL MATERIAL

2.1. Photometric Stellar Catalog

In this investigation, we use the photometric data derived from images of NGC 6822 taken with Suprime-Cam on the 8.2 m Subaru Telescope at Mauna Kea, Hawaii. Suprime-Cam consists of 5 × 2 CCDs of 2048 × 4096 pixels each, providing a total field of view of 34′ × 27′ with a 0.2′ pixel size (Miyazaki et al. 2002). We make use of the results based on two sets of archival Suprime-Cam images observed in $B$, $R$, and $I$. The first set consists of two deep pointings, covering the whole of the H	extsc{i} disk of NGC 6822 (see Figure 1 top). It was observed on 2001 October 15 and 19 and is described in detail by Komiyama et al. (2003). The second set of images was taken in 2000 June, during the early days of Suprime-Cam, and it consists of a single shallow pointing toward the optical center of NGC 6822. dBW06 stress the importance of the combination of the deep photometry with the shallow for a complete understanding of the stellar population of NGC 6822, due to the high light gathering power of Subaru, which saturates stars down to quite faint magnitudes. The present study is based on the comprehensive photometric analysis of both data sets performed earlier in dBW06 for the investigation of the stellar content of NGC 6822. As a consequence, much of the information provided in this section comes from the results of these authors. We repeat it here for reasons of completeness.

2.2. Color–Magnitude Diagram

In the present study, we utilize the final merged photometric catalog of stellar sources derived in dBW06 by combining the catalogs of stars detected in both deep and shallow exposures. This catalog contains 250,237 stellar sources identified in all three $B$, $R$, $I$ wavelengths. In our analysis, we limit ourselves to only those “high-quality” objects with a photometric uncertainty $\sigma \lesssim 0.1$ mag in all three bands, constraining the stellar catalog to 208,894 members. The $B$, $B-R$ color–magnitude diagram (CMD) of these stars is shown in Figure 2. This CMD has a larger dynamic range than those derived from previous investigations (Komiyama et al. 2003; Battinelli et al. 2003; de Blok & Walter 2003), and that of SLGGCFS (Massey et al. 2006, 2007), probing to fainter magnitudes. By adding in the shallow data

![Figure 2: B – R, R CMD of all 208,894 stars detected with good photometry in the observed Subaru fields of NGC 6822. Indicative isochrones for 20 (blue), 200 (orange), and 500 Myr (red) from the Padova evolutionary grid of models (Girardi et al. 2002) are overlaid for a nominal metallicity $Z = 0.004$ (Skillman et al. 1989), reddening $E(B – V) = 0.25$ (Massey et al. 2007), and distance modulus $m – M = 23.53$ (Gallart et al. 1996a). The green vertical line sets the limits of the “blue plume” stars, and the light blue box signifies the CMD area of the MS stars with $(B – R) \lesssim 0.5$, selected in this study for the identification of young stellar structures with ages down to roughly 500 Myr (see the text in Section 3).](https://example.com/fig2)

(A color version of this figure is available in the online journal.)

our stellar sample also covers the O- and B-type star regime of NGC 6822, and consequently it is the ideal stellar sample for the investigation of the most recent clustered star formation in this galaxy.

3. YOUNG STELLAR POPULATIONS IN NGC 6822

The CMD of Figure 2 contains a mixture of different stellar populations. A complete discussion on all observed stellar types in NGC 6822 is given by dBW06. In short, this CMD shows three important distinct components as follows. (1) The vertical “blue plume” centered on $B – R \sim 0.3$, which consists mostly of young stars in NGC 6822. (2) The red population of stars covering the area of the CMD with $1 \lesssim B – R \lesssim 1.75$ and $m_B \gtrsim 23$ (named the “red-tangle” by Gallart et al. 1996b), which contains mainly the old and intermediate-age stellar content of NGC 6822 with ages between 1 and 10 Gyr. (3) A vertical band around $B – R \sim 1.5$, which consists of contaminant Galactic foreground stars (see also Massey et al. 2007). Also clearly identified as being due to foreground stars is the region with $2 \lesssim B – R \lesssim 3$ and $m_B \gtrsim 24.5$ (dBW06).

For our study, we focus on the blue populations, and therefore we select our stellar sample from the “blue plume.” This area in the CMD with $B – R < 0.75$ consists mostly of young main-sequence (MS) and more evolved helium-burning blue loop (BL) stars down to an age of roughly 0.5 Gyr. In the absence of variable foreground extinction as found toward NGC 6822, MS stars would occupy the blue side of the plume and BL stars the red. Therefore, since we are interested in the youngest observed populations, we constrain our selection of stars to those with
Independent repetitions of the method, for different density thresholds (Section 8), revealed less dense stellar concentrations systematically belonging to larger ones, providing evidence of hierarchy in the distribution of the blue MS stars in NGC 6822. We refer to all these concentrations generally as structures.

4.1. The Nearest Neighbor Density Method

Star clusters are usually identified as regions of a certain overdensity with respect to the background stellar density. The NN method, introduced by Casertano & Hut (1985) based on earlier work by von Hoerner (1963), estimates the local source density \( \rho_j \) by measuring the distance from each object to its \( j \)th NN:

\[
\rho_j = \frac{j - 1}{S(r_j)}^m, \tag{1}
\]

where \( r_j \) is the distance of a star to its \( j \)th NN, \( S(r_j) \) is the surface area with the radius \( r_j \), and \( m \) is the average mass of the sources (\( m = 1 \) when considering number densities). The chosen value of \( j \) depends on the sample size, and is correlated with the sensitivity to the density fluctuations being mapped. A small \( j \) value increases the locality of the density measurements while increasing the sensitivity to random density fluctuations. On the other hand, a large \( j \) value will reduce that sensitivity at the cost of some locality.

The positions of the cluster centers are defined as the density-weighted enhancement centers (Casertano & Hut 1985):

\[
x_{a,j} = \frac{\sum_i x_i \rho_j^i}{\sum_i \rho_j^i}, \tag{2}
\]

where \( x_i \) is the position vector of the \( i \)th cluster member and \( \rho_j^i \) is the \( j \)th NN density around this object. Similarly, the density radius \( r_{\text{dens}} \) is defined as the density-weighted average of the distance of each star from the density center:

\[
r_{a,j} = \frac{\sum_i |x_i - x_{a,j}| \rho_j^i}{\sum_i \rho_j^i}. \tag{3}
\]

This radius typically corresponds to the core radius of the cluster (Casertano & Hut 1985).

We applied the NN method to our data considering several values for the NNs (\( j \)). Casertano & Hut (1985) have shown that low \( j \) values, in particular \( j = 1 \) or 2, are extremely sensitive to statistical fluctuations, therefore they suggest using a value of \( j \gtrsim 6 \). On the other hand, the choice of a too large \( j \) value results in a loss of sensitivity to real density variations on smaller scales. Monte Carlo simulations have shown that a value of \( j = 20 \) is adequate to the detection of clusters with about 10–1500 members (B. Ferreira 2009, private communication). However, since we aim at the detection of clusters even poorer than 10 members, we applied several test runs of the method that showed that \( j = 10 \) is a reasonable choice of number of NN.

The 10th NN density map of the blue MS stars in NGC 6822 is shown in Figure 3. This map demonstrates that the selected blue MS stars are distributed in almost the whole extent of the disk of the galaxy and the northwestern cloud, as has been demonstrated by the isodensity contour map of Figure 1. The NN density map, however, along with the general (average) stellar distribution of these stars throughout the galaxy, can also track in detail individual stellar concentrations. Specifically, while the low-density distribution of the blue MS stars, shown in blue and green scales, clearly outlines the disk of NGC 6822 and the

\[
B - R \lesssim 0.5, \text{ which correspond to ages roughly } \lesssim 500 \text{ Myr, according to the Padova evolutionary models (Girardi et al. 2002).}
\]

Figure 1 (middle) shows the spatial distribution of the selected sample of blue stars with \( B - R \lesssim 0.5 \). Since the final photometric catalog of dbW06 is the combined shallow photometric catalog in the inner part with the deep catalog in the outer part of the galaxy, these authors checked the outer field for saturated stars that should have been incorporated in an equivalent shallow catalog of the outer field. They found that there are very few saturated stars present, and therefore the stellar distribution shown in the middle panel of Figure 1 represents very well the whole observed blue stellar sample, despite the lack of a shallow photometry for the outer field. The corresponding surface density distribution of the blue MS stars constructed by simple star counts in a smoothed grid of elements \( 64'' \times 64'' \) in size is shown in the bottom panel of Figure 1.

From the maps of Figure 1, one may conclude that the young blue stars (1) are distributed across the whole H II disk, apart from maybe its southeastern part, (2) they are mostly concentrated in the central part of the galaxy in an “S-like” feature, and (3) their distribution is rather clumpy. It should be noted that the density contour map of Figure 1 (bottom) is a smoothed visualization of the large-scale stellar structures that exist in NGC 6822. The application, later, of the NN method (Section 4) allows a far more detailed identification of the smallest possible stellar concentrations of the galaxy.

Interestingly, the star counts of Figure 1 revealed as an independent stellar structure the so-called northwestern cloud, located at a position (R.A., Decl.) \( \approx (295.9, -14.6) \), which is speculated to be a separate system that is currently interacting with the main body of NGC 6822 and is thought to be responsible for the tidal arms in the southeast of the galaxy (de Blok & Walter 2000, 2003). It could also have triggered the star formation that currently interacting with the main body of NGC 6822 and is thought to be responsible for the tidal arms in the southeast of the galaxy (de Blok & Walter 2000, 2003). It could also have triggered the star formation that
northwestern cloud, the high-density levels (shown in yellow and red) show a more clumpy and centrally concentrated stellar distribution, revealing individual stellar systems as density peaks.

4.2. Detected Young Clusters

A reasonable density level, above which the detected density enhancements are accepted as star clusters, is $3\sigma$ above the average density, where $\sigma$ is the standard deviation of the background density. As a consequence, the original list of detected objects comprises all stellar density enhancements with density peaks at and above the $3\sigma$ threshold. However, since our method does not set any dimensional limit for the detected objects, this list includes the smallest density peaks that could be possibly identified. Indeed, the smallest objects in the list are found to be minute density peaks, which include only one or two stars, and therefore they are most probably spurious detections at the level of the noise. Naturally, these detections cannot be related to real physical stellar concentrations, but rather to the background density fluctuations. As a consequence, we exclude them from the final catalog of detected young clusters in NGC 6822, which thus comprises all stellar concentration with density peaks $\geq 3\sigma$ above the average density.

The detected clusters contain MS stars in the whole observed magnitude range of $B \lesssim 25$. However, the range of brightness of the majority of the stars included in every cluster can be used to assign an indicative maximum age to each of them. We divided, thus, the observed catalog of MS stars into four magnitude ranges and again computed the corresponding 10th NN density and applied a $3\sigma$ threshold for the detection of clusters. Each of the selected magnitude ranges corresponds to a specific range of stellar ages, with the older age, specified by the turn-off of the best-fitting isochrone, being associated with the faint magnitude limit. The four magnitude ranges were selected to include almost equal number of stars so that each run of the method would have the same statistical significance. We assign this age limit to each of the stellar sub-catalogs with the use of the evolutionary models of Girardi et al. (2002) for the distance, metallicity, and reddening of NGC 6822 by applying isochrone fitting of the CMD. In this manner, we are able to have a direct estimate of the age range of the clusters identified in the corresponding stellar sub-catalogs, with those detected in the whole catalog having the oldest observable age of $\sim 500$ Myr.

Although we cannot have an estimate of the actual age of each cluster, this approach is important for two reasons. First, age determination of the detected clusters by isochrone fitting of their individual CMDs is not really possible, due to their poor stellar number statistics. Moreover, the derivation of ages from integrated surface brightness of each cluster would require the application of population synthesis techniques, which would introduce important model-dependent uncertainties, again due to low stellar numbers, especially for the faint clusters. The maximum ages of the clusters are given in Column 4 of Table 3 for comparison to their dynamical timescales derived in Section 7. In the following section, we discuss in detail the characteristics of the detected clusters.

Figure 3. Stellar density map of NGC 6822 (in logarithmic scale), constructed with the NN density method applied to stars with ages $\lesssim 500$ Myr for the 10th NN. All stellar concentrations detected with density higher than $3\sigma$ above the average background are identified as members of the cluster population of NGC 6822. (A color version of this figure is available in the online journal.)
and 7) is the radius of a circle with the same area as the area enclosed by the cluster defining 3σ contour ($r_{\text{equiv}} = \sqrt{\pi A_{3\sigma}}$). The total expected number of stars $N$ (Column 10) and mass $M_{\text{cl}}$ (Column 11) are estimated from the extrapolation of the mass spectrum of each cluster assuming that it resembles the average Galactic initial mass function (IMF; see Section 5.2).

5.1. Size Distribution of the Clusters

From Table 1, it can be seen that our catalog of young clusters covers a variety of systems, starting with those of the minimum of three stellar members with dimensions $\leq 20$ pc (cluster 47), up to those with maximum size of almost 240 pc, including 77...
stars (cluster 1). The size distribution of the clusters constructed by binning them according to their dimensions is shown in Figure 4. Dimensions are given in physical units (pc) assuming a distance modulus of $m - M = 23.53$. A functional fit to this histogram shows that the size distribution of the detected clusters can be very well approximated by a normal distribution. According to the best-fit Gaussian, drawn with a red line in Figure 4, the dimensions of the detected systems are clustered around an average of $\sim 68$ pc with a standard deviation of $\sim 18$ pc. This is a rather interesting result, considering that, as pointed out earlier by various authors (e.g., Efremov et al. 1987; Ivanov 1996; Gouliermis et al. 2003), young stellar associations in different galaxies seem to have typical dimensions close to this value (between 65 and 93 pc) with an average of 80 pc. However, whether this lengthscale is characteristic for star formation is still under debate (see, e.g., Bastian et al. 2007; Gouliermis 2010).

5.2. Masses of the Clusters

The sample of detected clusters naturally includes a variety of systems not only concerning their physical dimensions, but also their stellar content and in consequence their total mass. While our data are not deep enough to cover the whole extent of masses for the stellar members of the detected clusters, and not complete enough to provide us with the actual numbers of stars (per luminosity or mass range) for each of them, it is worth performing a first-order calculation of the total stellar mass included in each detected cluster, based on several assumptions. We identify the number of stars included in each cluster and their luminosities from our photometric catalog. Then in order to have a first estimation of the total mass of each cluster, we (1) build the observed luminosity function (LF) of each cluster, (2) apply a mass–luminosity relation (M–LR) based on the stellar evolutionary models for the conversion of this LF to the mass function (MF) of the cluster, and (3) extrapolate this observed MF to the lower masses for the calculation of the total mass of each cluster.

5.2.1. Mass–Luminosity Relation

For the establishment of the conversion of stellar luminosities to masses, we use the evolutionary models by Girardi et al. (2002). Our clusters identification is applied for all detected stars of NGC 6822 formed within the last $\sim 500$ Myr, and therefore the identified clusters are expected to have different ages from each other within this time range. As a consequence, in order to construct a realistic M–LR for each cluster, one should establish a correct age with the use of the CMD of the detected stars in the cluster. However, the construction of individual M–LR for each cluster is not possible, because in all cases the stellar numbers found within the detected clusters are not sufficient to build complete and informative CMDs.

On the other hand, one may construct a global M–LR to be used for the conversion of LFs to MFs for all clusters, but this M–LR should be established from evolutionary models that cover a large range in ages. Indeed, as is seen in the CMD of Figure 2, the observed MS is populated by stars in an increasingly larger variety of ages toward fainter magnitudes down to $B \simeq 25$ mag. Therefore, we construct a global M–LR for all identified clusters using the evolutionary models of Girardi et al. (2002) for the correct quantification of the uncertainties in the determination of the cluster masses due to age differences among the identified clusters. (A color version of this figure is available in the online journal.)

Figure 4. Histogram of the size distribution of detected young star clusters in NGC 6822, with a bin size of 10 pc. Parameters of the best-fit Gaussian (red line) are also given.

(A color version of this figure is available in the online journal.)

Figure 5. M–LR constructed with the use of isochrones from the grid of evolutionary models by Girardi et al. (2002) for the metallicity and at the distance of NGC 6822. Isochrones of a large variety in ages are used for the correct quantification of the uncertainties in the determination of the cluster masses due to age differences among the identified clusters.

(A color version of this figure is available in the online journal.)
of the luminosity of each star detected within the limits of one of the NGC 6822 clusters into mass.

5.2.2. The Stellar Mass Spectrum of the Clusters

The stellar mass function (SMF) is the number distribution of stars according to their masses, constructed for a given volume of space in a cluster. This function is known as the stellar present day mass function, which is usually called simply the MF of the cluster. In this study, we refer to this function as the SMF to distinguish it from the CMF discussed later. The SMF of a cluster is described by the function $\xi(\log m)$, which gives the number of stars per unit logarithmic (base ten) mass interval $d \log m$ per unit area (e.g., per kpc$^2$). Alternatively, one may refer to the stellar mass spectrum (SMS) of the cluster, $f(m)$, which is the number of stars per unit mass interval $dm$ per unit area. The common use of both these functions is based on the definition of the stellar IMF, various forms of which are discussed by, e.g., Kroupa (2002) and Chabrier (2003). All these distributions are usually parameterized by their indices. Specifically, for the SMS $f(m)$, and the SMF $\xi(\log m)$, these indices are defined as

$$\gamma = \frac{d \log f(m)}{d \log m} \quad (4)$$

and

$$\Gamma = \frac{d \log \xi(\log m)}{d \log m}. \quad (5)$$

These two indices are basically the logarithmic derivatives or slopes of $f(m)$ and $\xi(\log m)$, respectively, and for power-law distributions they are independent of mass (Scalo 1986). A reference value for the SMF slope is $\Gamma = -1.35$, which is the index of the classical IMF for stars in the solar neighborhood with masses $0.4 \lesssim M/M_\odot \lesssim 10$, found by Salpeter (1955). The corresponding SMS index is $\gamma = \Gamma - 1 \simeq -2.35$. For comparison, the lognormal field-star IMF by Miller & Scalo (1979) has $\Gamma \simeq -(1 + \log m)$. A basic relation between SMF and SMS is $\xi(\log m) = (\ln 10) \cdot m \cdot f(m) \simeq 2.3 \cdot mf(m)$ (see Scalo 1986).

The construction of the SMS of each cluster is essential for the calculation of its expected total mass through extrapolation of its SMS. However, in most of the cases of identified clusters in NGC 6822, the detected stellar numbers are not sufficient for the construction of a meaningful SMS for each cluster. This problem can be surpassed with the use of a common SMS constructed by all stars detected within the identified clusters. This approach, naturally, assumes that the SMS is indeed universal, in line with most findings in the local universe (see, e.g., Massey 2006; Bastian et al. 2010). We construct the global SMS of the clusters in NGC 6822 by counting all stars detected within the limits of all the 47 identified clusters according to their masses, and distributing the stellar masses in mass-bins $1 M_\odot$ wide. This SMS is given in Table 2, and is also shown in Figure 6. This figure also shows the best-fit line derived from the application of a linear regression to the most complete mass bins corresponding to masses between $5$ and $13 M_\odot$.

The determination of the slope of power laws from uniformly binned data using linear regression is found to comprise biases, which are caused by the correlation between the number of stars per bin and the assigned weights (Maíz Apellániz & Úbeda 2005). However, we measured the average mass of the stars counted in each bin for the construction of the global SMS, and found that it is almost equal to the mean mass of the bin. The corresponding standard deviations per bin are found to be smaller than $1 M_\odot$, the width of each bin, and therefore there is no “leak” of stars expected from one mass bin to its neighboring, and thus no random fluctuations in the constructed SMS. The measured average mass per bin, rather than the mean mass of each bin, is plotted in Figure 6, and the corresponding $\sigma(m)$ are shown as error bars on the $x$-axis, demonstrating the accuracy of the pointing of each mass bin. The linear regression for the most complete mass range of $5 \lesssim m/M_\odot \lesssim 13$ provides an SMS slope $\gamma$, which is exceptionally close to the average Galactic field value, equal to $-2.5 \pm 0.5$ (black solid line in Figure 6).

5.2.3. Total Masses of the Clusters

An estimate of the total mass of each cluster in NGC 6822 can be achieved through integration of its SMS. However, as we...
discussed earlier, the construction of a meaningful SMS for each cluster is not possible due to low stellar numbers, and therefore we make use of the global SMS assuming that this distribution is universal and representative of all clusters. While, according to our assumption, the slope of the SMS should not be different from one cluster to the other, the absolute stellar numbers per mass bin of the SMS in each cluster are different and thus the corresponding total cluster mass. Indeed, the individual SMS of the clusters does deviate from the global SMS, mostly in stellar numbers and, in some cases of clusters with very few stars, in the slope. This is demonstrated in Figure 7, where the SMS of seven selected indicative clusters from our sample are plotted. In this figure, it can be seen that the general trend of the SMS slope indeed seems consistent with the global SMS (solid line), but the stellar numbers (per surface unit) are quite different. These differences will determine the differences in the total mass of the clusters. We estimate the cluster masses in three steps.

1. We first extend the observed global SMS to the low-mass regime below our detection limit according to the generally accepted Galactic field mass spectrum. This mass spectrum is usually parameterized with a series of power laws, with exponents changing in different mass ranges (see, e.g., Scalo 1998). The most recent parameterization is that by Kroupa (2002), according to which the slope \( \gamma \) changes from \( \gamma = -0.3 \) in the substellar mass range to \( \gamma = -1.3 \) for masses between 0.08 \( M_\odot \) and 0.5 \( M_\odot \), \( \gamma = -2.3 \) for 0.5 \( M_\odot \) \( \leq m/M_\odot < 1 \), and \( \gamma = -2.7 \) \( \pm 0.3 \) for stars with higher masses. This SMS is generally characterized as the Galactic average in the sense that it is reasonably valid for different regions of the Galaxy. Considering that the SMS of all clusters identified in NGC 6822 should have a multi-power law form, with exponents that change at the same mass limits as the Galactic SMS, we assume that the global SMS of the clusters has the average slope of those measured in Section 5.2.2, equal to \( \gamma = -2.5 \pm 0.5 \), for stars with masses down to our completeness limit of about 5.5 \( M_\odot \), and we extrapolate it with the same slope down to the mass limit of 1 \( M_\odot \). For the extrapolation of the global SMS to subsolar masses, we consider the exponents of the Galactic SMS, as they are discussed above for stars with masses down to \( \sim 0.1 M_\odot \). The extrapolated global SMS, following the parameterization by Kroupa (2002), is thus a three-part power-law function of the form

\[
f(m) \propto \left( \frac{m}{m_i} \right)^{\gamma_i} \quad \text{with } i = 1, 2, 3.
\]

The slopes \( \gamma \) depending on the mass range are

\[
\begin{align*}
\gamma_1 & = -1.3 \pm 0.5, \quad 0.1 \leq m/M_\odot < 0.5 \\
\gamma_2 & = -2.3 \pm 0.3, \quad 0.5 \leq m/M_\odot < 1.0 \\
\gamma_3 & = -2.5 \pm 0.5, \quad 1.0 \leq m/M_\odot.
\end{align*}
\]

2. We then normalize the extrapolated global SMS to fit the stellar numbers observed in every cluster. Specifically, we normalize the extrapolated global SMS to the mass bin of around 5–6 \( M_\odot \), because all detected clusters, including those with only three stars, show to have at least one star at this specific mass range. Therefore, by normalizing the global SMS to this mass limit, we apply a comparable approach to all, rich and poor, clusters.

3. We finally integrate the normalized SMS of each cluster from the largest mass observed in the cluster to the smaller stellar mass assumed to exist in all clusters of 0.1 \( M_\odot \), and derive an estimation of the total cluster mass, from its surface stellar density

\[
M_{cl} = \rho_\star \pi r_{equiv}^2,
\]

where

\[
\rho_\star = \int_{0.1}^{m_{max}} f(m) dm.
\]

The total stellar numbers of the clusters derived from this method and the corresponding total stellar masses are given in Table 1 (Columns 10 and 11, respectively).

6. MASS DISTRIBUTION OF THE CLUSTERS

The total stellar masses of the clusters of NGC 6822, as derived above, cover a range over an order of magnitude with the smaller cluster mass being around \( 10^3 M_\odot \). The number distribution of the clusters according to their masses, i.e., the mass spectrum of the clusters, which is widely termed the CMF, is shown in logarithmic scale in Figure 8. The CMF derived from young (\( \lesssim 10 \) Myr) star clusters is defined as the \textit{cluster initial mass function} (CIMF). Considering that the CMF follows the functional form of a power law, as is generally assumed, we applied a linear regression to the data of Figure 8. The best fit returns the function

\[
\log N_{cl} = (-1.47 \pm 0.72) \log M_{cl} + (1.60 \pm 0.31).
\]

We found, thus, that the CMF of the massive clusters of NGC 6822 can be described by a power law with index \( \sim -1.5 \pm 0.7 \).
Clouds (LMC and SMC), respectively. The CMF index in the LMC is given as a function of minimum mass and maximum age, based on mass-limited samples (see de Grijs & Anders 2006, their Table 3 and Figure 8). For log \( (m_{cl}/M_\odot)_{\text{min}} = 3 \) and log \( (r/\text{yr})_{\text{max}} = 8.7 \), which corresponds to our sample, de Grijs & Anders (2006) find a CMF index \(-1.98 \pm 0.08\), an average value which is somewhat different than ours, but nevertheless covered by our uncertainties, and quite similar to the CIMF. In addition, in the SMC, de Grijs & Goodwin (2008) find a CMF with index \( \alpha \lesssim 1.2 \) for almost the same cluster mass range with ours. This slope falls within \( 1\sigma \) of our CMF slope, and is therefore also consistent with it.

7. STRUCTURAL PARAMETERS OF THE CLUSTERS

We estimate the stellar density, \( \varrho_{cl} \), in the half-mass radius, \( r_{cl} \), of each cluster and the disruption time, \( t_d \), of the cluster due to interaction with passing-by interstellar clouds, as described in, e.g., Gouliermis et al. (2002, their Section 6). The former is calculated assuming spherical symmetry for all clusters as

\[
\varrho_{cl} = \frac{M_{cl}}{4\pi r_{cl}^3} \left( \frac{M_{\odot}}{\text{pc}^{-3}} \right). \tag{12}
\]

while the latter is given as (Spitzer 1958)

\[
t_d = 1.9 \times 10^8 \varrho_{cl} \text{ (years)}. \tag{13}
\]

The dynamical status of a young star cluster is defined by two additional timescales, the crossing and the two-body relaxation time, which are given as (e.g., Kroupa 2008)

\[
t_c \equiv \frac{2r_h}{\sigma} \quad \text{and} \quad t_{\text{relax}} = 0.1 \frac{N}{\ln N} t_c, \tag{14}
\]

respectively. The three-dimensional velocity dispersion of the stars in the cluster, \( \sigma \), is given as

\[
\sigma = \sqrt{\frac{GM_{cl}}{\epsilon r_h}}, \tag{15}
\]

where \( \epsilon \) is the star formation efficiency (SFE) and \( r_h \) is the half-mass radius of the cluster. We estimate these timescales for the clusters of our sample, with the application of Equations (14), assuming the same SFE with several nearby Galactic gas-embellished clusters, which has been found to range typically from 10\% to 30\% (Lastra & Lada 2003). In our calculations, we assume an average value of \( \epsilon \approx 0.2 \), which leads to values of \( \sigma \) between 12 and 89 km s\(^{-1}\) for our clusters.

For the measurement of the \( r_{\text{rh}} \) of each cluster, we estimate the so-called Spitzer radius, \( r_{Sp} \). Considering that \( r_h \approx 0.9 r_{Sp} \) only for dynamically relaxed spherical clusters (e.g., Spitzer 1969), we can only approximate the actual \( r_h \) of our clusters. The Spitzer radius is a dynamically stable radius, defined by the mean-square distance of the stars from the center of the cluster (e.g., Spitzer 1987) as

\[
r_{Sp} \equiv \sqrt{\frac{\sum_{i=1}^{N} r_i^2}{N}}, \tag{16}
\]

where \( r_i \) is the projected radial distance of the \( i \)th star of the cluster in a total sample of \( N \) stars. We estimate this radius for each cluster in our sample only from the stars identified within...
its limits, for which there are positions available, and not from the expected total number of stars according to the extrapolated mass spectrum of each cluster. As a consequence, the accuracy of the derived \( r_{sp} \) of each cluster is subject to the number of its identified stars.

The estimation of \( r_{sp} \) allows the evaluation of \( \sigma \) and \( \rho_{cl} \) of the clusters and consequently of their \( t_0 \), \( t_{rz} \), and \( t_{\text{relax}} \) according to Equations (13) and (14). For the latter, we use the expected total number of stellar members, \( N \), as derived from the extrapolation of the mass spectrum of each cluster. All additional estimated structural parameters for the young clusters of NGC 6822 are provided also in Table 3.

### 7.1. Parameters Correlations of the Clusters in NGC 6822

A correlation between the number of stars in a cluster and the radius of the cluster has been found in Galactic embedded clusters (Adams et al. 2006; Allen et al. 2007). While \( n_s \) and \( r \) vary by about 2 orders of magnitude, the average surface density of cluster members \( n_s/\pi r^2 \) is nearly constant. We find the same correlation, following a power law, between \( n_s \) and \( r_{\text{equiv}} \) for the clusters identified in NGC 6822, which span an even wider range in radius, \( n_s \), and age (Figure 9). The correlation has a slope in the log–log plot of \( k \approx 0.6 \), comparable to that found by Adams et al. (2006) for their sample of young Galactic.
8. HIERARCHICAL CLUSTERING IN NGC 6822

The majority of stars form in clusters and aggregates of various sizes and masses (Lada & Lada 2003; Allen et al. 2007). Young star clusters are often found inside larger complexes, which can be parts of even larger structures. In turn, stellar clusters often consist of distinct subclusters, appearing to form a hierarchy of systems over a wide range of scales (e.g., Efremov & Elmegreen 1998; Elmegreen et al. 2000). The ISM is also hierarchically structured (sometimes described as fractal) in scales starting from the largest giant molecular cloud down to individual clumps and cores. Within this scheme, the cluster population of NGC 6822, as presented above, should represent one specific lengthscale of a whole spectrum of stellar concentrations in this galaxy, and the detected clusters themselves are most probably members of larger structures. In this section, we uncover the complete structural spectrum of stellar clustering and quantify the hierarchical distribution of the blue stars in NGC 6822 with \( \tau \lesssim 500 \) Myr, as they are selected in Section 3.

8.1. Detection of Stellar Structures in NGC 6822

In order to search for stellar concentrations of various length-scales, we apply again the NN density method, as described in Section 4.1, for the 10th NN. The selection of the 10th NN is made for reasons of consistency with the detection of star clusters in the previous sections. Our tests showed that the application of the NN method for a larger number of neighbors (e.g., 30 or 50) would “smooth” the derived structures and unify many of them into single larger ones, losing the ability to detect any fine structure in the spatial distribution of stars. For the identification of stellar structures of different densities, we select different density thresholds in the application of the NN method. Specifically, apart from the 3\( \sigma \) detection applied in Section 5 for the identification of the cluster population of the galaxy, we apply the method for the lower density thresholds of 1\( \sigma \) and 2\( \sigma \) above the average background density level to identify structures that correspond to lower stellar density enhancements. For the detection of concentrations that correspond to high stellar density, we apply the NN method with higher (4\( \sigma \) and 5\( \sigma \)) density threshold above the background level.

The stellar structures identified with the 10th NN density method are shown in the density contour map of Figure 10. Isopleths of different colors indicate the structures derived with the application of the method for different detection density thresholds. The cluster population of the 3\( \sigma \) detection is shown with green contours. This map is constrained to the main part of the galaxy, where all significant stellar concentrations, including its clusters, appear and which is known to host star formation (Cannon et al. 2006). From the map of Figure 10, it can be seen that the low-density threshold detections reveal large stellar structures, while the application of the method for higher density thresholds gives rise to smaller and more compact stellar concentrations, which are actually located in the larger structures of the galaxy. This combination of high-density enhancements that correspond to small stellar systems and aggregates with low-density concentrations that represent large structures and stellar complexes is a clear signpost of the hierarchical structure (Elmegreen 2010).

8.2. Dendrograms

An intuitive way to illustrate hierarchical structures is through the so-called dendrograms, introduced as “structure trees” for the analysis of the molecular cloud structure by Houlahan & Scalo (1992), refined by Rosolowsky et al. (2008). A dendrogram is constructed by cutting the image at different thresholds and identifying connected areas, while keeping track of the connection to “parent structures” (on a lower level) and “child structures” (on the next higher level, lying within the boundaries of its parent). A geometrically perfect hierarchy would be represented by a dendrogram where each parent branches out into the same number of children at each level.

We construct the dendrogram of the stellar structures detected in NGC 6822 with the NN density method for the various density thresholds considered, i.e., 1–5\( \sigma \) above the background density. In this dendrogram, shown in Figure 11, the structures found at each density level are represented not only by the “leaves” that end at the particular level, but by all branches present at that level. For example, at the 3\( \sigma \) level, there are 47 branches of the dendrogram (regardless whether they end here, continue to a higher level, or split into two or more branches), corresponding to the 47 detected stellar clusters. This dendrogram demonstrates that, while there are few centrally concentrated structures with a single peak, most structures split up into several substructures over at least three levels. The combination of this dendrogram with the contour map of Figure 10 illustrates graphically the hierarchical spatial distribution of stars younger than 500 Myr in NGC 6822.

In the lower detection density threshold of 1\( \sigma \) (black isopleths in Figure 10), there are few structures revealed, three of them being major stellar concentrations that qualify as large stellar complexes. These structures comprise a number of...
Figure 10. Density contour map constructed with the application of the 10th NN density method on our photometric data of NGC 6822. Isoptles within different density levels in $\sigma$, drawn with different colors, signify the corresponding identified stellar structures in the galaxy. All statistically important stellar structures are detected only in the main part of the NGC 6822 disk. Therefore, the drawn contour map covers only this part of the galaxy instead of the whole observed field of view for reasons of clarity.

(A color version of this figure is available in the online journal.)

Figure 11. Dendrogram of the stellar structures identified at different levels in the 10th NN density map (Figure 10), illustrating the hierarchical behavior of the clustering of the blue MS stars.

smaller multiple concentrations seen in the $2\sigma$ red isopleths of Figure 10, which most probably correspond to the so-called stellar aggregates of the galaxy. The detected clusters (green $3\sigma$ isopleths) are actually members of these aggregates, fulfilling the typical image of hierarchical structuring of stars in a galaxy scale. Higher density ($4$ and $5\sigma$) detections correspond to the condensed stellar density peaks, which are seen to be the most compact centers of the larger structures.

8.3. Quantification of Hierarchy

Another popular method in studies of hierarchical clustering is the minimum spanning tree (MST) method, which may be applied with different cutoff lengths for the detection of different lengthscales (e.g., Bastian et al. 2007, 2009). The MST method is excellent in quantifying the hierarchy in the discovered structures through the so-called $Q$ parameter (see e.g., Cartwright & Whitworth 2004; Schmeja & Klessen 2006). It allows us to distinguish between clusters with a central density concentration and hierarchical stellar concentrations with possible fractal substructure. Large $Q$ values ($Q > 0.8$) describe centrally condensed clusters having a volume density $n(r) \propto r^{-\alpha}$, while small $Q$ values ($Q < 0.8$) indicate concentrations with fractal substructure. $Q$ is correlated with the radial density exponent $\alpha$ for $Q > 0.8$ and anti-correlated with the fractal dimension $D$ for $Q < 0.8$. We determine $Q$ for all structures detected at all levels with more than 45 members, since for poorer concentrations the method becomes unreliable due to increasing errors. Recent simulations of artificial clusters have shown that for clusters with $N \lesssim 45$ members, the expected error in the determination...
of the $Q$ parameter is of the order of less than 0.05 (Schmeja 2010). $Q$ varies systematically for structures showing a more elongated shape (Cartwright & Whitworth 2009; Bastian et al. 2009); therefore, we apply the correction suggested by Bastian et al. (2009) when necessary.

All but one of the $Q$ values for the structures detected at 1, 2, and 3σ density thresholds are in the hierarchical regime ($Q < 0.8$), reaching $Q$ values as low as $Q = 0.55$, corresponding to a fractal dimension of $D \approx 1.8$. The detections at higher density thresholds did not provide stellar structures rich enough to allow such an analysis. The $Q$ values for the five 1σ structures with more than 45 stellar members range from 0.56 to 0.73, and those for the 10 2σ structures from 0.55 to 0.83. There are only two clusters detected in the 3σ density threshold that include more than 45 stars, clusters 1 and 2 in Table 1. They are also found to be hierarchically structured with values of $Q = 0.62$ and 0.77, respectively. The average $Q$ value for the structures revealed in all three density levels gives evidence of fractal concentrations with $Q = 0.70$. This value demonstrates the hierarchical nature of the clustering in NGC 6822. All but one of the analyzed structures are classified as hierarchical, i.e., they have significant (possible fractal) substructure rather than a smooth density gradient. It should be noted that the numbers of stars in the objects revealed at density levels with thresholds $\geq 3\sigma$ are too low to permit a meaningful $Q$ analysis, but taking as example the two star clusters for which this analysis was possible, most—if not all—of the 3σ clusters should be expected in the hierarchical regime as well.

Nevertheless, the unusual distribution of blue stars in the central part of NGC 6822 and their apparent hierarchy may be the result of differential extinction. For example, the two vacant areas to the east and west of the central S-shaped distribution of blue stars (Figure 10) may be caused by high levels of extinction. Indeed, a comparison of the spatial distribution of the cool component of neutral hydrogen with that of the blue stars shows an anticorrelation on large scales (dBW06, their Figure 7). However, while this extinction seems to affect the large-scale stellar distribution (at 1σ density level), giving it the S-shape, it does not seem to affect the hierarchical distribution of smaller stellar structures detected in higher density levels (2 and 3σ). Concerning the smallest detected structures (at 4 and 5σ), the resolution of the available observations of the ISM in NGC 6822 does not allow the detection of any patchy extinction in smaller scales. As such, we cannot assess how small-scale differential extinction may affect the apparent hierarchy of stellar structures, and therefore we certainly cannot exclude it as a possible bias.

In this case, the derived $Q$ values would indicate that the stars were in fact not in total hierarchically spread. It is also worth noting that if the largest stellar structures, shown in Figure 10, are approximately two dimensional (i.e., much longer and wider than deep), the $Q$ values returned by the MST method should be interpreted differently, since the crossover between “fractal” and “centrally concentrated” in the two-dimensional case becomes 0.72 (see, Bastian et al. 2009), and thus the structures may be found to be less hierarchical.

### 8.4. Correlation of Number of Stars and Radii

The correlation between the number of stars and radius seen for the clusters of NGC 6822 detected at the 3σ level (Section 7.1) is also observed for the structures we identify with the application of the NN method with different detection levels. This correlation is shown in Figure 12 for detections with density thresholds of 1, 2, 4, and 5σ. The number of stars correlates with the radii of the structures with about the same slope of $k \approx 0.53$. Only the 5σ structures show a different behavior, but this plot suffers from the small number of objects. Adams et al. (2006) found a slope of $k = 0.54$ for young Galactic clusters, very close to the slope we find for the detected stellar structures and clusters in NGC 6822. As pointed out by Allen et al. (2007), these results are similar to those of Larson’s relations for molecular clouds, $\rho \sim R^{-3}$ (Larson 1981), implying a constant column density of the gas in molecular clouds.

### 8.5. Current Star Formation in NGC 6822

Cannon et al. (2006) performed Spitzer Space Telescope imaging of NGC 6822 and combined it with Hα, H1, and radio continuum observations to study the nature of the emission in these wavebands on spatial scales of $\sim 130$ pc. They found strong variations in the relative ratios of Hα and IR flux throughout the central disk of the galaxy, and that the localized ratios of dust to H1 gas are about a factor of 5 higher than the global value of NGC 6822. These authors identified 16 IR emission complexes in the central part of the galaxy, six of which correspond to detections in the radio continuum image. The major H II regions, i.e., the strongest Hα sources of the galaxy, are also luminous in the IR and identified among the IR emission complexes, but in general Hα and IR emission are not always co-spatial. The H1 distribution in the same area contains mostly high surface brightness (column densities $\geq 10^{21}$ cm$^{-2}$), and it is clumpy with dense comps of neutral gas surrounding various emission peaks in other wavebands.

It is worth comparing the star-forming complexes identified by Cannon et al. (2006) with the structures revealed from our study. The IR emission complexes are indicated by circles in Figure 13, overlaid on our NN density map of the central part of NGC 6822 disk. This map appears more smooth than those shown before, because we constructed it by applying the NN density method for the more gross number of the 50th NN in order to achieve an angular resolution comparable to that provided by the nebular and dust emission observations. The comparison of our stellar structures with the IR-bright regions of Cannon et al. on the map of Figure 13 shows a correlation of the stellar density peaks with the maximum IR emission only in the northern part of the galaxy; in particular, their regions 9 and 10 coincide with peaks in the stellar density. In the southern part, they are significantly displaced from each other. Here, current star formation takes place at the western rim of the region of high stellar density. This is reminiscent of the spatial distribution of stellar birth in spiral arms or tidal tails, and points toward an external interaction (see also Karampelas et al. 2009). On the other hand, this spatial disagreement between peaks in IR emission and in stellar density in the southern central region of NGC 6822 may simply suggest that young stars are not yet revealed in their natal clusters, and we only detect the most evolved stellar concentrations in this part of the galaxy.

### 9. DISCUSSION AND CONCLUSIVE REMARKS

The formation of stars and star clusters in the ISM is controlled by the complex dynamical interplay between self-gravity and supersonic turbulence (Mac Low & Klessen 2004). On large scales, the turbulent motions in the ISM are highly supersonic with Mach numbers up to several tens in giant molecular clouds. On scales of individual star-forming cloud cores, the turbulent velocity field becomes subsonic, with a well-defined power-law connecting these scales (Larson 1981).
which could be the result of the scale-free nature of the turbulent cascade (Elmegreen & Scalo 2004; Scalo & Elmegreen 2004). The resulting morphological structure has often been interpreted in terms of hierarchical fractals (e.g., Elmegreen & Falgarone 1996; Stutzki et al. 1998; see also Federrath et al. 2009, 2010).

Turbulence plays a dual role. On global scales it provides support, while at the same time it can promote collapse locally. It creates strong density fluctuations with gravity taking over in the densest and most massive regions, where collapse sets in to build up individual stars (Klessen 2001a). Together with the thermodynamic properties of the gas and magnetic fields, this regulates the fragmentation behavior in star-forming clouds. The properties of young star clusters are thus directly related to the statistical characteristics of the underlying turbulence in the star-forming gas (Ballesteros-Paredes et al. 2007). This holds for the stellar IMF (Klessen & Burkert 2000, 2001; Hennebelle & Chabrier 2008, 2009), the protostellar accretion rates (Klessen 2001b; Schmeja & Klessen 2004), the SFE and timescale (Klessen et al. 2000; Heitsch et al. 2001; Vázquez-Semadeni et al. 2003; Krumholz & McKee 2005), or the question of when and where dense clusters with high-mass stars form and when and where to expect a more distributed population of lower mass stars (e.g., Vázquez-Semadeni et al. 2009).

Quite a number of different measures have been proposed to support and statistically characterize the link between the morphological and kinematical structure of the ISM and the population of star clusters that form in it. Efremov & Elmegreen (1998) find a correlation between the separation of stars and star clusters and their age, and interpret that result in terms of the linewidth–size relation in the ISM first discussed by Larson (1981). As velocity and size convert into a timescale, they conclude that the formation of molecular clouds and stellar birth in their interior proceeds on timescales of a few turbulent crossing times (Elmegreen et al. 2000; Elmegreen 2007; see also Ballesteros-Paredes et al. 1999; Hartmann et al. 2001; Glover et al. 2010) which is a signpost of star formation controlled by interstellar turbulence (Elmegreen & Efremov 1997; Mac Low & Klessen 2004). Further evidence is provided by the fact that the mass spectrum of molecular clouds and clumps within the clouds follows a power law, \( dN/dM \propto M^{-\alpha} \), with an exponent in the range \( 1.5 \leq \alpha \leq 2.0 \) (Stutzki & Guesten 1990; Williams et al. 1994; Kramer et al. 1998) which is very similar to the mass spectra of young star clusters as discussed in Section 6. The value of \( \alpha = 1.5 \pm 0.7 \) that we derive for the young clusters in NGC 6822 is fully consistent with this picture.

As the ISM exhibits a very complex, hierarchical morphological structure, it stands to reason that stars follow a similar spatial pattern. We have studied that aspect in Section 8 in terms of the distributions of blue stars in individual stellar structures. Using the 10th NN map to identify clusters, we find that these stars in NGC 6822 can indeed be grouped into larger and larger aggregates in a hierarchical fashion when we vary the detection
threshold. Similar results are found in the MCs (Gieles et al. 2008; Bastian et al. 2009; see also Hunter et al. 2003), M33 (Bastian et al. 2007), and M51 (Bastian et al. 2005). We note that the Q-parameters derived for the individual star clusters in NGC 6822 indicate that the stars in the clusters themselves are hierarchically structured. It is a common feature of young star clusters that they reveal a high degree of subclustering when observed with sufficient resolution and sensitivity to identify individual stars down to the peak of the IMF (e.g., Cartwright & Whitworth 2004, 2008, 2009; Schmeja et al. 2008, 2009) with values that are consistent with numerical calculations of star–cluster formation (Schmeja & Klessen 2004). We conclude that we find direct evidence that the blue stars in NGC 6822 exhibit a hierarchical spatial pattern from the scales of individual objects all the way up to the scale of the galaxy as a whole.

It is interesting to note in this context that when it is indeed true that the spatial distribution of stars and star clusters traces the statistical properties of ISM turbulence, then the absence of a clear break in the hierarchy could indicate that turbulence is driven on kpc scales. Possible mechanisms are global gravitational instability (e.g., Li et al. 2005), the magneto-rotational instability (MRI) in the disk of NGC 6822 (Beck et al. 1996; Balbus & Hawley 1998; Piontek & Ostriker 2007), or the accretion of fresh gas through the halo in the form of cold streams or gas-rich satellites (Santillán et al. 2007; Sancisi et al. 2008; Klessen & Hennebelle 2010). Indeed, the “northwestern cloud” clearly visible in Figure 1 has been speculated to be a separate system, possibly interacting with NGC 6822 (de Blok & Walter 2000, 2003). This interaction could also be responsible for a possible increase of the SFR in the past 100 Myr (Hodge 1980; see however Gallart et al. 1996a, for a different opinion).

10. SUMMARY

In this paper, we present a thorough investigation of the cluster population with age \( \lesssim 500 \) Myr and the hierarchy in the spatial distribution of main-sequence stars of this age in the Local Group dwarf irregular galaxy NGC 6822. Our observational material comprises optical imaging from the 8.2 m Subaru Telescope, providing the most complete point-source catalog of the galaxy in terms of dynamic range and spatial coverage.

Star clusters are identified with the application of the NN density method for the 10th NN on the blue main-sequence stars in NGC 6822. Forty-seven distinct concentrations with \( \geq 3 \) stellar members that are found with our method to have 10th NN density values \( 3\sigma \) above the average background density are identified as the star clusters of the galaxy. The physical dimensions, stellar density, and limiting radii of the clusters are

Figure 13. 50th NN density map of the blue MS stars in the central region of NGC 6822 (in logarithmic scale) with blue circles overlaid indicating the IR-bright complexes identified by Cannon et al. (2006) with Spitzer. (A color version of this figure is available in the online journal.)
defined by this density limit. The size distribution of the detected clusters can be very well approximated by a Gaussian peaked at \( \sim 68 \text{ pc} \) (with \( \sigma \sim 18 \text{ pc} \)).

The total stellar masses of the clusters are estimated by extrapolation of the total observed SMF of all clusters to the lower stellar masses, assuming that it has the shape of the average Galactic MF (Kroupa 2002) down to \( 0.1 M_\odot \). The derived cluster masses range in the range \( 10^3 - 10^4 M_\odot \). Their distribution follows very well a power law with index \( \sim -1.5 \pm 0.7 \), somewhat shallower but consistent with the CIMF and the mass spectra found for clusters in other Local Group galaxies. Structural parameters, such as their Spitzer radius, the corresponding three-dimensional stellar density and velocity dispersion, as well as their crossing and the two-body relaxation times are computed for the clusters from their total masses and stellar numbers. We find a correlation between the radii and stellar numbers of various lengthscales, with clusters being the representative of one of them. High-density stellar structures are revealed from the application of the NN method with higher (4\( \sigma \) and 5\( \sigma \)) density threshold above the average density level, while the larger loose stellar structures, which include the denser ones, are recognized by the application of the method for lower (1\( \sigma \) and 2\( \sigma \)) density thresholds. All significant stellar concentrations, including the clusters, appear in the main (star-forming) part of the galaxy. The density maps constructed with this technique provide clear indications of hierarchically structured stellar concentrations in NGC 6822 in the sense that small dense stellar concentrations are located inside larger and looser ones. We illustrate this hierarchy by the so-called dendrogram, or the structure tree of the detected stellar structures in NGC 6822, which demonstrates that most of the detected structures split up into several substructures over at least three levels.

The majority of the detected star clusters in NGC 6822 has ages between 250 and 500 Myr, which is longer than the crossing time of the galaxy, the timescale on which hierarchical cluster distributions in the LMC and SMC are erased (e.g., Bastian et al. 2009). As a consequence, the finding that these clusters have preserved their structure is in itself very interesting. However, our catalog of “stellar clusters” comprises large stellar groups with sizes larger than the typical pc-scale Galactic clusters; the smallest cluster in our catalog is about 20 pc in size. As such, their large size is a possible explanation of why these clusters have preserved their structure longer than one crossing time of the galaxy.

We quantify the hierarchy of these structures with the use of the MST method and the \( Q \) parameter. We find that the \( Q \) values for the structures detected at 1, 2, and 3\( \sigma \) density thresholds reside in the hierarchical regime (\( Q < 0.8 \)), reaching \( Q \) values that correspond to a fractal dimension of \( D \approx 1.8 \). The correlation between the number of stars and radius seen for the clusters of NGC 6822 is also observed for the larger stellar structures, identified at the 1 and 2\( \sigma \) density levels, as well as for the smaller dense concentration identified at the 4\( \sigma \) density level. It is worth noting that some of the large high-density stellar concentrations, particularly in the northern part of the star-forming portion of the galaxy, coincide with IR-bright structures earlier identified with Spitzer, associated with high column density (\( \gtrsim 10^{21} \text{ cm}^{-2} \)) neutral gas, indicating structures that currently form stars.

The clusters of NGC 6822, which we identify at the 3\( \sigma \) density level of the NN method, are found to be themselves internally structured. Considering the ages of these clusters, this result is also interesting, because as found for small compact clusters, any substructure is expected to have been rapidly erased on very short timescales (Allison et al. 2010). However, the clusters we detect in NGC 6822 are large stellar groups, which may have survived strong disruptions for periods of time longer than their crossing times. Previous simulations of fractal star clusters by Goodwin & Whitworth (2004) have shown that even an initially homogeneous cluster can develop substructure, if it is born with coherent velocity dispersion. As a consequence, the substructure we observe in our clusters may not be the present exhibition of their original “primordial” substructure, but one induced later. The same authors find that the velocity dispersion is a key parameter, determining the survival of substructure, which can last for several crossing times. Therefore, it is possible that at least some of our clusters may have sustained their initial substructure. In favor to this, spatial substructure has been identified in open clusters of the Milky Way as old as \( \sim 100 \) Myr (Sánchez & Alfaro 2009).

The morphological structure of the stellar concentrations we identified in NGC 6822 resembles the structural behavior of the interstellar matter, which in principal is hierarchical and dominated by turbulent motions. As such, this coincidence between the clustering of stars and the hierarchical structure of the ISM, as is demonstrated in the present study, suggests that turbulence may play the major role in regulating clustered star formation in NGC 6822 on pc and kpc scales.

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