Formation, evolution, and survival of massive star clusters
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The SUNBIRD survey: characterizing the super star cluster populations of intensely star-forming galaxies

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Abstract. Super star clusters (SSCs) represent the youngest and most massive form of known gravitationally bound star clusters in the Universe. They are born abundantly in environments that trigger strong and violent star formation. We investigate the properties of these massive SSCs in a sample of 42 nearby starbursts and luminous infrared galaxies. The targets form the sample of the SUperNovae and starBursts in the InfraReD (SUNBIRD) survey that were imaged using near-infrared (NIR) K-band adaptive optics mounted on the Gemini/NIRI and the VLT/NaCo instruments. Results from *i)* the fitted power-laws to the SSC K-band luminosity functions, *ii)* the NIR brightest star cluster magnitude − star formation rate (SFR) relation and *iii)* the star cluster age and mass distributions have shown the importance of studying SSC host galaxies with high SFR levels to determine the role of the galactic environments in the star cluster formation, evolution and disruption mechanisms.

Keywords. galaxies: interactions, galaxies: individual: IC 694, NGC 3690, galaxies: star clusters, infrared: galaxies

1. Introduction

Our current understanding of star formation activity in extragalactic sources has greatly increased since the commissioning of the IRAS satellite. With a strong infrared emission ranging in between $10^{11} - 10^{12}\,L_\odot$, luminous infrared galaxies (LIRGs) have been the subject of various studies. It has been found that the majority of these galaxies are interacting systems that harbor intense starburst activities in their nuclear regions (Sanders & Mirabel 1996). Such environments are ideal for the birth of the most massive star clusters in the local Universe. Also referred to as super star clusters (SSCs), these extreme form of star clusters are believed to contain vital information regarding the physical conditions under which strong and massive star formation occurs (e.g. Portegies Zwart *et al.* 2010). It has also been observed that active star-forming galaxies with ultra-dense giant molecular clouds (GMCs) favor the formation of the most massive SSCs ($\gtrsim 10^5\,M_\odot$) unlike the quiescent galaxies where the cluster masses average around $\sim 10^4 M_\odot$. However, the early stages of evolution as well as the role of the environment in shaping the cluster initial mass functions (CIMFs) are not yet fully understood (e.g. Adamo & Bastian 2015). The present work is designed to provide more insight into the universality of the CIMF and to pursue further investigations on whether external factors play an important role during cluster formation and disruption mechanisms.

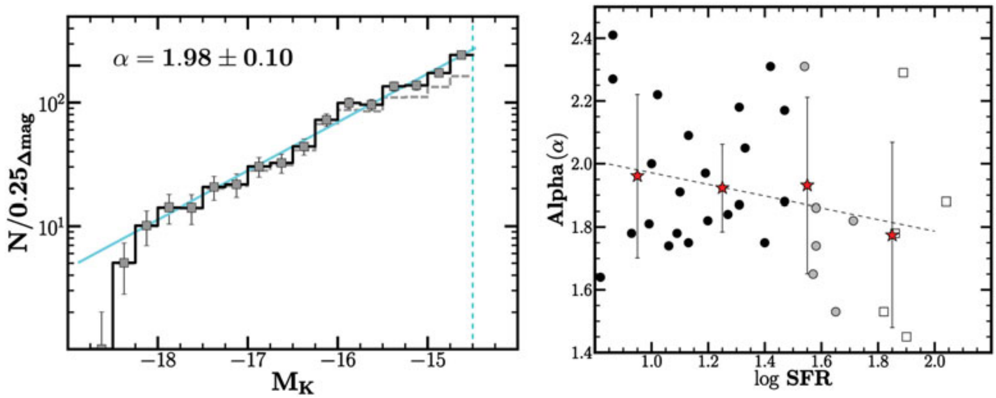

Figure 1. *Left:* K-band SSC LF of the sample, except the data from IRAS 19115−2124. The single power-law fit of the data points is represented by the solid line while the vertical line marks a completeness level of −14.5 mag. *Right:* The power-law slope α plotted against log-SFR. The targets with SFR $> 60\,M_\odot\,yr^{-1}$ are labelled as open squares, whereas the SFR $\leqslant 60\,M_\odot\,yr^{-1}$ targets are marked as cirlces: those with SFR $\leqslant 30\,M_\odot\,yr^{-1}$ are black and those in between 30 and 60 $M_\odot\,yr^{-1}$ are grey. A constant binning of the slopes results in values labelled as stars, and the dashed line represents a linear fit to these new points.

2. The survey

SSC properties of 42 nearby IR-bright galaxies, including LIRGs with extreme starburst activities are investigated in this work. The targets form a representative statistical sample of strongly star-forming galaxies. They are also part of an ongoing survey dubbed SUNBIRD (SUperNovae and starBursts in the InfraReD) to search for dust-obscured core-collapse SNe using NIR AO imaging mounted on the Gemini/NIRI and the VLT/NaCo instruments (e.g. Ryder *et al.* 2014, Väisänen *et al.* 2014). They are IRAS galaxies from the flux-limited RBGS catalogue, selected to have IR luminosities uniformly distributed from $\log{(L_\odot/L_{IR})} = 10.6$ to 11.9 and distances $D_L \sim 25 - 150\,Mpc$, with $D_L \approx 200\,\mathrm{Mpc}$ for a handful of the most distant galaxies. The targets are all starburst-dominated based on their cool IRAS colors ($f_{25}/f_{60} < 0.2$), though AGN were not excluded a priori. The sample were also selected in such a way that there are complimentary data set available in the Hubble Legacy Archive, most importantly optical imaging. Source extraction, aperture photometry and NIR selection of the SSC candidates are described in Randriamanakoto *et al.* (2013a) and Randriamanakoto *et al.* (2013b).

3. Luminosity functions of the star clusters

We constructed the K-band SSC luminosity functions (LFs) of the sample. Both constant and variable binning result in similar values of the power-law slopes $\alpha = 1.5 - 2.4$. The median and average of the indices are 1.86 ± 0.24 and 1.92, respectively. Out of the 34 constructed CLFs, 65 % have flatter distributions with $\alpha < 2$. Fitting a single power-law function to the LF of the combined dataset down to a $M_K = -14.5$ mag (which includes the SSCs from all the targets except for the most distant target IRAS 19115−2124 which has a significantly different magnitude), gives a slope $\alpha_1^{con} = 1.98$ with a formal uncertainty of 0.10 (left panel of Fig. 1). This is consistent with the average slope. One of the most important results of this work revealed that starburst galaxies have shallower slopes than normal spirals where $\alpha \approx 2.4$ (Whitmore *et al.* 2014). It is suggested that strongly star-forming galaxies such as LIRGs host SSCs that are disrupted in a way depending on their mass or environment. This would then result in a smaller value of the power-law

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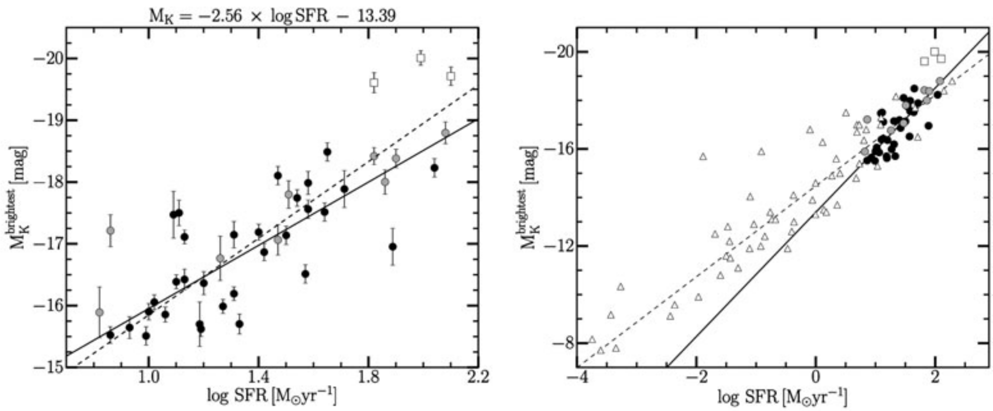

Figure 2. *Left:* A correlation is seen between the NIR brightest star cluster magnitude and the SFR of the galaxy. A weighted linear fit to all the data, including the three most distant targets at $D_L > 150$ Mpc shown as open squares, is represented by the dashed line. The solid line fits the $D_L \leqslant 150$ Mpc targets labeled as circles; those at $D_L \leqslant 100$ Mpc are black and those at $100 < D_L \leqslant 150$ Mpc are grey. *Right:* Another version of the $M^{brightest}$ − SFR relation with an expanded scale including data from Adamo *et al.* 2011 (the triangles) added to the present work (symbols as in the left panel). The solid line results from our best fit and the dashed line is the fit to the optical V-band data after a constant $V - K = 2$ conversion.

index α of the CLF. In fact, a weak correlation has been found between α and the SFR (right panel of Fig. 1). Note, however, that star clusters with different ages were binned together while drawing the LFs. Analyses based on Monte-Carlo simulations and star cluster population in a redshifted Antennae showed that shallower slopes cannot be the result of blending for a target less distant than ≈ 100 Mpc, unless the cluster surface densities are close to confusion limit (Randriamanakoto *et al.* 2013b). Such a limit is quickly reached in case of more distant targets and/or with data taken with poorer resolution. An interesting avenue would be to investigate whether or not the values of α vary with the different merging stages of our targets.

4. The brightest star cluster magnitude - NIR relation

We also used the NIR AO observations of the SUNBIRD survey to check whether one could reproduce a well-known empirical relation that has been established in the optical regime (Bastian 2008). We found a positive correlation between the brightest cluster magnitude and the galaxy SFR (left panel of Fig 2). It is expressed as $M_K^{brightest} = -2.56 \times \log \mathrm{SFR} - 13.39$, considering a distance cutoff $D_L = 150$ Mpc. The slope is within the same uncertainty range to those from optical points with lower SFR levels, assuming a single $V - K$ conversion (right panel of Fig 2). Note that the galaxy IR luminosity was the tracer being used to estimate the corresponding SFR for each target. The conversion eventually assumes that the IR energy is starburst-dominated. We have provided statistical interpretations of the relation: a size-of-sample effect. This simply means that it is more likely for more luminous clusters to form in an environment with extreme star formation activity. However, we also suggested physical interpretations to explain the small scatter seen in the relation. The effects of the galactic environments on cluster formation efficiency Γ or/and possibly other internal cluster effects such as the mass-luminosity relation are likely to play an important role as well (Randriamanakoto *et al.* 2013a). Apart from an estimate of the star cluster physical properties, determining

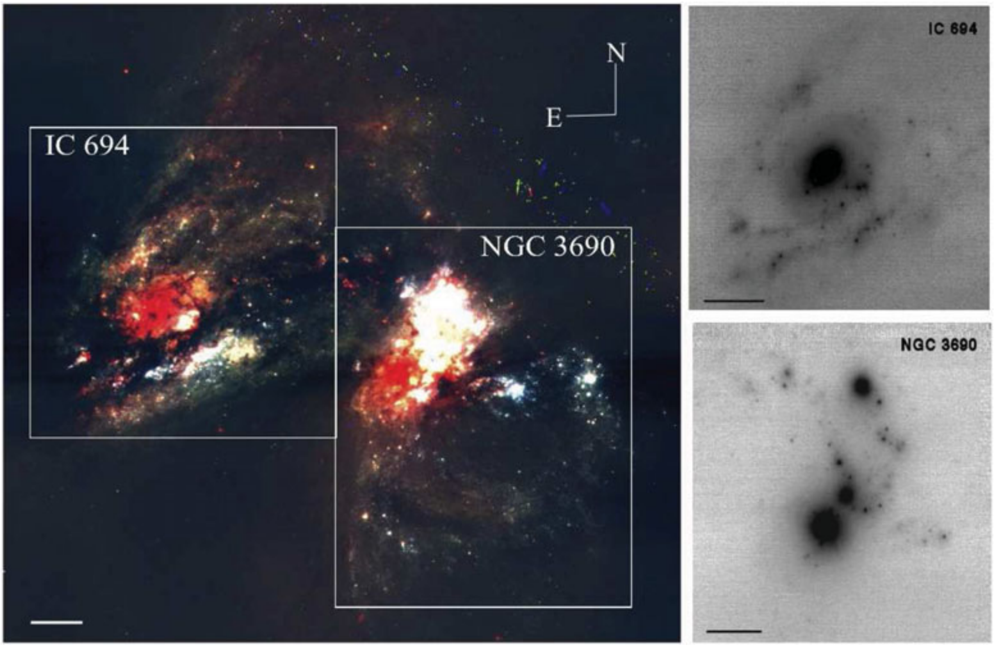

Figure 3. *Left:* WFC3/UVIS three-color image of Arp 299 in a 1.4 by 1.2 arcmin field: F336W (U-band, blue), F438W (B-band, green), and F814W (I-band, red). The boxes represent the FoV of the NIR data. North-East orientation and a length scale of 1 kpc (the horizontal line) are also indicated. *Right:* K-band images of the individual components taken with Gemini/NIRI AO systems in a 22×22 arcsec field: IC 694 (top) and NGC 3690 (bottom). The horizontal lines represent a 1 kpc scale.

the exact roles of the environments and the galaxy reddening would be the next steps required to fully understand the NIR relation.

5. Mass and age modelling of the optically-selected SSCs

NIR AO observations were also combined with HST optical images, whenever available, and new star cluster catalogues were derived based on optical detection. The selection criteria resulted in hundreds of SSCs for each target. We compared `Yggdrasil` SSP models (Zackrisson *et al.* 2011) with the observed SEDs to fit the cluster age, mass, and extinction of starburst-dominated galaxies. A large fraction of the star cluster populations have ages younger than 30 Myr. In the case of Arp 299 (Fig. 3), age-extinction degeneracy could reliably be broken due to inclusion of a UV-filter (F336W). The cluster masses of the interacting systems are generally between $10^4 - 10^8\ M_\odot$ (top panels of Fig 4). Such values are quite massive compared to the mass ranges associated with star clusters hosted in more quiescent environments. Nevertheless, more analyses should be performed to quantify the overestimate of the cluster mass in case of a BIK-fit. The spatial distributions of ages of some cases supported the cruel cradle effect scenario (Kruijssen *et al.* 2011, Väisänen *et al.* 2014) while others indicated the possibility of a mixed population (see middle panels of Fig 4 in the case of Arp 299). At least one of the LIRGs (NGC 3690) has its star cluster population disrupted in a mass-dependent manner. The turnover in the LFs, a truncation of the CMFs at high-mass end (lower right panel of Fig. 5), and the distribution of the cluster frequency (lower panels of Fig 4) serve as a basis for such an argument. Moreover, the cluster formation histories of the LIRG subsample revealed

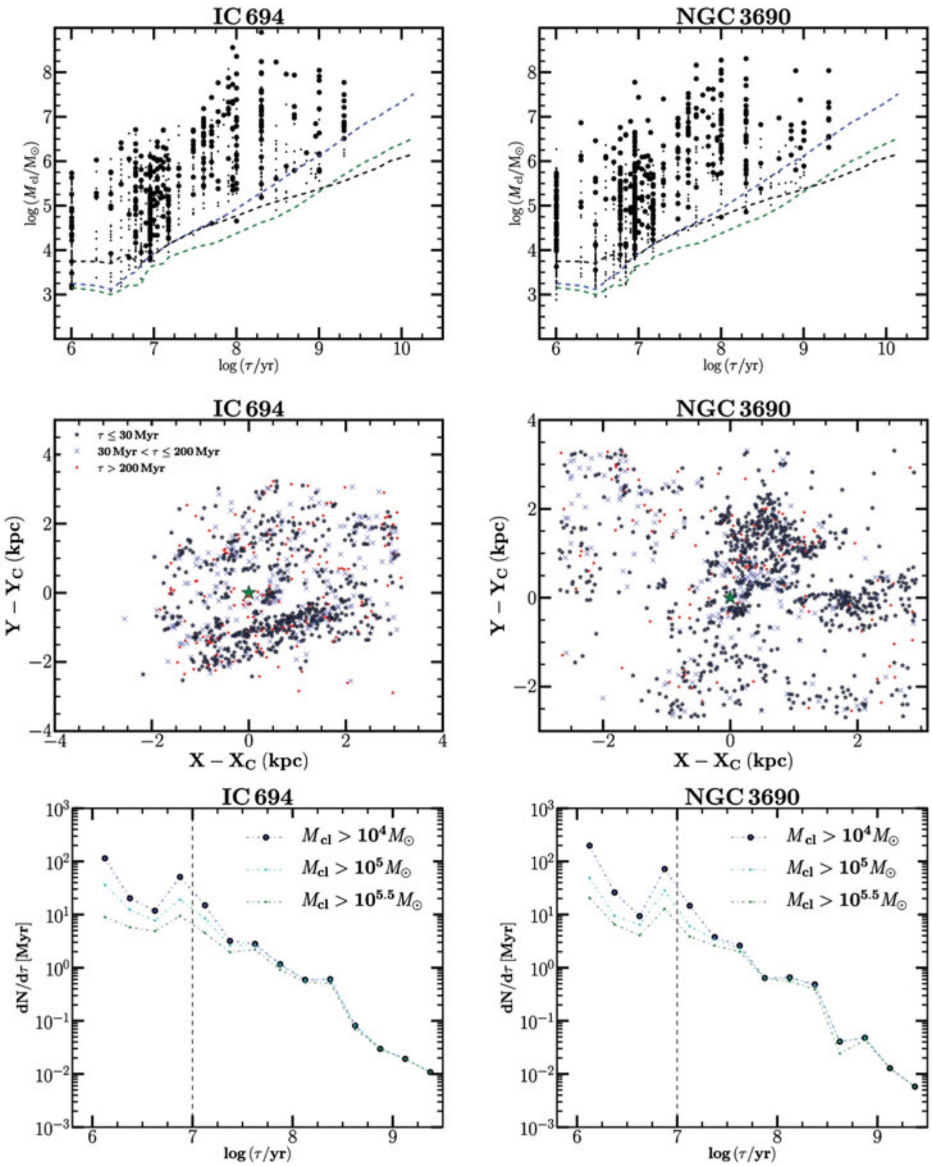

Figure 4. *Top:* The cluster age-mass planes from the χ^2-fit. Black points are the objects with $\sigma \leqslant 0.35$ in all four $UBIK$-images, whereas the dots are those below the error cutoff but in UBI-filters only. The dashed lines denote the photometric detection limits ($\sim 80\,\%$) considering U- (blue), B- (green), and I-band (black) evolutionary tracks. *Middle:* The age spatial distributions of the SSC candidates in the field of Arp 299. The green star represents the position of the galaxy center. The different labels correspond to different age bins. *Lower:* Star cluster frequency $\mathrm{dN}/\mathrm{d}\tau$ as a function of age for Arp 299. Three different lower mass limits were considered to derive various formation rates of the observed clusters.

that more formation of the star clusters are foreseen since the galaxy environments are rich of GMCs necessary for the birth of massive clusters. The next steps of this work would be to correct the cluster mass functions from observational incompleteness and to derive accurate values of Γ on global and local scales.

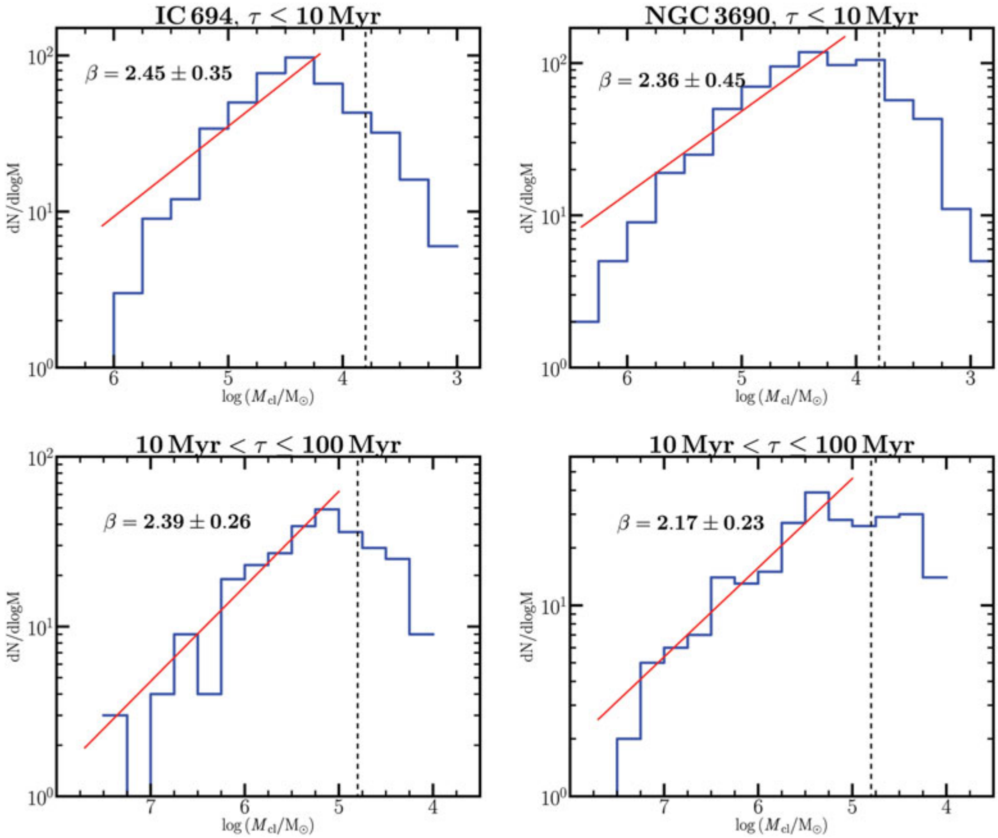

Figure 5. The cluster mass functions of IC 694 (*left*) and NGC 3690 (*right*) plotted with different age bins. The solid lines represent the resulting power-law fit to the high-mass end of the distribution. The dashed lines show approximate cluster mass completeness limits estimated using the age-mass plane. The top panels correspond to the distribution of young clusters with ages less than 10 Myr, and the lower panels for cluster ages between 10 and 100 Myr. The MFs of NGC 3690 seem to have an underlying turnover especially for 10 Myr $< \tau \leqslant$ 100 Myr.

6. Summary & conclusions and ongoing work

Overall, we have shown the capability of NIR AO systems in opening a new window into the understanding of SSC formation, evolution, and disruption mechanisms. It has also been found that interacting systems such as LIRGs offer a totally different environment which can bias the long-term survival chance of its star cluster population. The SUNBIRD survey offers useful data, with the potential of answering some of the most important questions in the field of star cluster research. However, there are still limitations in studying these most massive clusters. New instruments such as the multi-conjugate AO systems mounted on Gemini-South (GeMS/GSAOI) will push down the detection limit and therefore allow the analyses of faint and low-mass star clusters. On the other hand, extending the sample of the survey into a lower SFR baseline would also offer more insights into the star formation process in general. Finally, it will also be interesting to study the kinematics, underlying stellar populations, and the gas of the host galaxies to correlate SSC properties with physical characteristics of the host as a whole in the SUNBIRD sample using the available data from SALT/RSS spectroscopic observations.

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