Star Clusters: From the Milky Way to the Early Universe
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Young massive clusters in Arp 299

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Abstract. Because of their young ages and compact densities, young massive star clusters (YMCs) are widely considered as potential proto-globular clusters. They are ubiquitous in environments with ongoing star formation activity such as interacting luminous infrared galaxies. To determine the galactic environmental effects on the star cluster formation and evolution, we study the YMC population of Arp 299 (NGC 3690E/NGC 3690W) using data taken with the HST WFC3/UVIS camera. By fitting the multiband photometry with the `Yggdrasil` models, we derive the star cluster masses, ages and extinction. While the cluster mass-galactocentric radius relation of NGC 3690E indicates that there could be an influence of the gas density distribution on the cluster formation, the age distribution of the western component suggests that YMCs in that galaxy endure stronger disruption mechanisms. With a cluster formation efficiency of 19 percent, star formation happening in bound clusters in Arp 299 is 3−5 times higher than that of a typical normal spiral.

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1. Arp 299, an ideal laboratory for YMC studies

Young massive star clusters (YMCs) are gravitationally bound systems with masses ($>10^4$ $M_\odot$) similar to those of classical old globular clusters. Although being present in almost all types of galaxies, they are particularly ubiquitous in strongly star-forming galaxies and mergers where starburst events are very compact. Luminous infrared galaxies (LIRGs, with an 8–1000 μm $L_{IR} > 10^{11}$ $L_\odot$), which are often interacting, host extreme star formation (SF) activity in the form of a large population of YMCs.

At a luminosity distance of 45 Mpc, and an infrared luminosity of $\sim 7.6 \times 10^{11}$ $L_\odot$, Arp 299 (NGC 3690E/NGC 3690W) is a nearby interacting LIRG with a molecular gas fraction of 31 percent (Larson *et al.* 2016). The evolution of the star formation activity in the merger has been extensively studied by Alonso-Herrero *et al.* (2000, 2002, 2009). They have found that the dusty nuclear regions host a recent episode of massive SF and that the system hosts a large population of luminous HII regions and YMCs which are indicative of extreme SF processes. By cross-matching the WFC3/UVIS UBI-band catalogues of Arp 299, Randriamanakoto *et al.* (2019) recovered more than 2000 optically-selected star cluster candidates. With such a large number of YMCs, this nearby merger is thus ideally suited to help determine the role of the galaxy environments on the formation and evolution of the YMCs that reside in. Do external effects govern and shape the physical properties and lifetime of these young proto-globular clusters (see e.g. Portegies Zwart *et al.* 2010; Bastian *et al.* 2012; Chandar *et al.* 2015; Adamo *et al.* 2015)?

2. Analyses and key results

Arp 299 is one of the SUNBIRD (Supernovae UNmasked By Infra-Red Detection, Randriamanakoto 2015; Kool *et al.* 2018) targets being surveyed using near-infrared adaptive optics imaging to search for core-collapse SNe in strongly star-forming galaxies such as LIRGs. While the resulting NIR catalogue is comprised of 81 YMCs for each galaxy component (Randriamanakoto *et al.* 2013a,b), the ability of the WFC3/UVIS camera to produce sharper images with PSF values between 0.07 and 0.09 arcsec enabled the extraction of 2182 YMC candidates with $\sigma_m \leqslant 0.35$ mag in the whole system.

To derive the age and mass of each cluster, its spectral energy distribution based on the photometric UBI-bands was compared with `Yggdrasil` simple stellar population models (Zackrisson *et al.* 2011). An extinction map based on the $U - I$ colour map was used for each cluster to have its own range of extinction constrained when performing the age and mass fitting. With a mass range between $\approx 10^{3-8}$ M$_\odot$, around 62 percent of the YMCs have ages less than 15 Myr. While NGC 3690W mainly hosts clusters younger than 10 Myr, the most massive ones ($\geqslant 10^7$ M$_\odot$) preferentially lie in the nuclear regions of NGC 3690E. Note that three YMC candidates with masses $\geqslant 10^8$ M$_\odot$ were excluded in the analysis to avoid bias from blending effects.

We highlight below the key results from investigating the YMC properties of Arp 299:

Cluster mass functions. For star clusters with ages between $10-200$ Myr, a power-law representation of the mass distribution ($dN \sim M^{-\beta} dM$) until a critical mass of $\log(M_{cl}/M_\odot) = 5.37$ results in a slope $\beta = 1.91 \pm 0.34$ for the whole system. An underlying truncation at the high-mass end is also being observed and by fitting a Schechter distribution to the cluster mass function, we derive a characteristic mass of $M_\star = 1.6 \times 10^6 M_\odot$. Such a value is more massive than those of quiescent dwarfs and normal spiral galaxies ($M_\star = 2.5 \times 10^5 M_\odot$, Larsen 2009).

Cluster age distribution. The number of clusters per time interval of the same sub-sample, which is complete down to $10^{4.8} M_\odot$, was fitted with a power-law distribution of the form $dN/d\tau \sim \tau^{-\delta}$ to evaluate the intensity of the cluster disruption. Based on the derived values of the slope, the YMCs of the eastern component ($\delta = -0.59$) undergo less disruption than those in the western component ($\delta = -0.84$).

Cluster-mass galactocentric radius relation. The morphological feature of NGC 3690E resembling that of a spiral galaxy enabled to study the cluster mass-galactocentric radius relation of this component. The increase in the cluster mass as we move closer to the galactic centre tightly correlates with the high gas density distribution within 2 kpc of the nuclear regions. This suggests that the formation of the YMCs could also be driven by external effects but not only limited to stochastic sampling.

Cluster formation efficiency. Assuming a SFR of $86\, M_\odot\, yr^{-1}$ (Herrero-Illana *et al.* 2017) and a time interval $\Delta t = 10-50$ Myr to derive the cluster formation rate, we record a cluster formation efficiency (CFE or Γ) of 19 percent in the case of Arp 299. Such a value is approximately $3-5$ times higher than those of gas-poor spiral galaxies (Silva-Villa & Larsen 2011; Ryon *et al.* 2014). Given the extreme environments of LIRGs, it is more likely for their stars to form in gravitationally bound systems. The nearby merger, with a SFR density of $\Sigma_{\rm SFR} = 0.11\, M_\odot\, yr^{-1}\, kpc^{-2}$, follows as well the CFE - SFR density relation where it falls within 3σ uncertainty of the theoretical model by Kruijssen (2012). A recent version of the relation is shown in Figure 1 with the blue point representing Arp 299 and the other datapoints taken from Messa *et al.* (2018) and references therein. The solid line indicates the fiducial model.

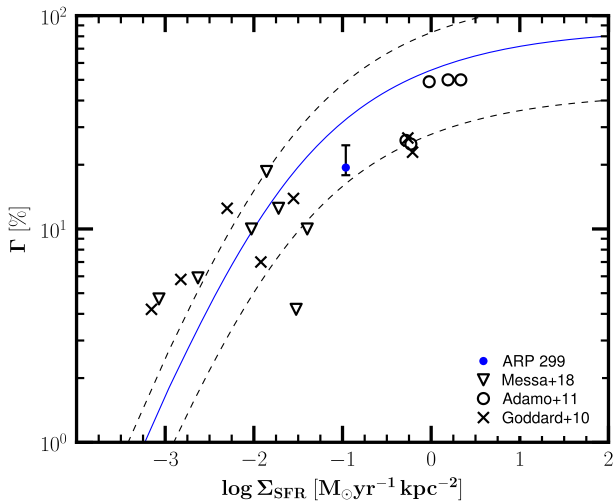

Figure 1. The cluster formation efficiency Γ plotted against the SFR surface density in a logarithmic scale. The blue datapoint corresponds to Arp 299 compared to other datasets taken from the literature including Goddard *et al.* (2010), Adamo *et al.* (2011) and Messa *et al.* (2018). The solid line represents the fiducial model by Kruijssen (2012) with its 3σ uncertainty (dashed lines).

3. Conclusion

This paper summarizes the major findings from analysing the photometric properties of young massive clusters hosted by the interacting LIRG Arp 299 (a comprehensive report on this work is available in Randriamanakoto *et al.* 2019). The derived results clearly indicate that the extreme star-forming environments of the merger likely affect the formation, evolution and disruption mechanisms of its young star cluster population. A size-of-sample effect alone cannot explain e.g. the spatial distribution of the star clusters or the shape of its cluster mass functions.

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