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Dissecting the star cluster population in M51: the LEGUS view

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Abstract. Stellar clusters are the products of star formation at the most dense peaks of its hierarchy. Their properties can help understanding how the star formation process proceeds in regions where the gas is dense and strongly bound. Recent studies have shown that the properties of clusters can change as a function of the environment where they form and evolve, implying that the star formation process can be affected by the environment inside galaxies. In this work we study the mass function of the cluster population in the M51 galaxy at sub-galactic scales. A comparison with the mass function of giant molecular clouds is also carried out to understand how the environment can locally affect the cluster properties.

Key words. Galaxies: star clusters: general – Galaxies: star formation

1. Introduction

Young star clusters (YSCs) are one of the outcomes of the star formation process in galaxies. In particular, they are formed in regions where the density of the parental gas is high enough that its collapse results in a system of gravitationally bound stars. Since YSCs can survive for hundred of Myr, they remain in their host galaxy as probes of its star formation activity. Cluster populations in the nearby universe have been extensively studied, revealing some common general features in the mass and age distributions but also differences in function of the hosting galaxy properties (see review by Adamo & Bastian 2015). An environmental dependence of the cluster properties has been recently observed at sub-galactic scales in M83 (Adamo et al. 2015). Such an analysis requires however large cluster populations and is still limited to very few galaxies. Another issue only recently addressed is the link between the properties of clusters and of giant molecular clouds (GMCs), which seem to follow a similar environmental dependence (Hughes et al. 2013; Colombo et al. 2014). In this study we use the data from the Legacy Extra-Galactic UV Survey (LEGUS) to analyse the cluster mass function of the M51 galaxy, looking for possible variations as a function of position in the galaxy and comparing it to the mass distribution of GMCs in the same galaxy.

2. Data and cluster catalogue production

Standard procedures for imaging data reduction and for the production of cluster catalogues have been developed within the LEGUS collaboration and are described in Calzetti et al. (2015) and Adamo et al. (2017), respectively. The M51 data sample consists of 5 new pointings with the WFC3 *UV* (F275W) and *U* (F336W) filters, along with archival *B*

(F435W), V (F555W) and I (F814W) observations. In Messa et al. (2017) we describe the steps used to produce the final cluster catalogue of M51. In the same paper, the photometric completeness of the sample is discussed. The final catalogue consists of 2837 potential clusters. For each cluster candidate, age, mass and extinction are derived fitting their (broadband) SEDs with *Yggdrasil* SSP models (Zackrisson et al. 2011), as described in Adamo et al. (2017). In order to study the mass function of the sample, we considered a mass-limited subsample selecting only cluster candidates more massive than 5000 $M_{\odot}$. At those masses we are photometrically complete for ages younger than 200 Myr and we therefore apply a cut on the ages at that value. The mass-limited complete sample selected in this way counts 1313 sources.

3. Analysis of the mass function

3.1. At galactic scale

The mass function is analysed in a cumulative form via a maximum-likelihood fit with `mspecfit.pro` (Rosolowsky et al. 2007). The code considers a power-law function, but implements also the possibility of a truncation at the high-mass end of the function, i.e.

$$N(M' > M) \propto \left[\left(\frac{M}{M_0}\right)^{\beta+1} - 1\right], \tag{1}$$

with M_0 as the maximum mass in the distribution and β as the slope of the power-law. The best fit of the mass function gives $\beta = -2.01 \pm 0.02$ and $M_0 = (1.00 \pm 0.12) \times 10^5$ $M_{\odot}$. Monte Carlo populations, counting the same number of sources as the observed one, were simulated both from a single power-law and from a power-law exponentially truncated (at 10^5 $M_{\odot}$) mass function. The simulated populations were compared to the observed one via an Anderson-Darling (AD) test, confirming that the latter better describes the observed mass distribution (p-value of 0.334).

The result confirms that clusters form following the hierarchical structure of star formation, except at high masses where the mass function deviates from a simple −2 power-law.

Table 1. Results of the mass function fit with Eq.1. The radial bins goes from the most inner (Bin 1) to the most external one (Bin 4).

Region	$-\beta$	M_0 [$10^5 M_{\odot}$]
Total	2.01 ±0.02	1.00 ±0.12
Bin 1	1.85 ±0.02	1.11 ±0.16
Bin 2	1.97 ±0.07	0.96 ±0.22
Bin 3	2.06 ±0.09	0.76 ±0.21
Bin 4	2.05 ±0.03	1.16 ±0.25
Spiral arm	1.83 ±0.03	1.01 ±0.12
Inter-arm	2.14 ±0.05	0.96 ±0.31

A similar shape has been observed also in the cluster populations of other galaxies. Nearby spirals, like M83, NGC 628, and NGC 1566, present a truncation which is similarly on the order of $\sim 10^5$ $M_{\odot}$ (Adamo et al. 2015, 2017; Hollyhead et al. 2016). On the other hand, M31, a spiral galaxy with low star formation rate density (Σ_{SFR}), presents a truncation in the mass function at the lower value of $M_0 \sim 10^4$ $M_{\odot}$ (Johnson et al. 2017), and the mass function of the Antennae galaxies, an interacting system with very high Σ_{SFR}, is consistent with no truncation up to $M \sim 10^6$ $M_{\odot}$ (Whitmore et al. 2010). The analysis of the cluster mass function in the nearby universe suggests therefore that the maximum cluster mass achievable depends on the properties of the host galaxy.

3.2. At sub-galactic scale

In order to test if the mass function changes as function of the environment inside the galaxy, we have determined the mass functions dividing the cluster population in sub-regions. A first division is made considering 4 circular concentric annuli at different galactocentric distances, each annulus containing the same number of clusters. The resulting best fits for the mass functions are truncated power-laws which in almost all bins are consistent, within 2σ, with a $\beta = -2$ slope and a $M_0 = 10^5$ $M_{\odot}$ truncation (see Tab. 1).

We considered the possibility that the truncation mass is set by the maximum gas mass that can collapse without fragmenting. Reina-Campos & Kruijssen (2017) developed a model where the maximum GMC mass in a disk galaxy is the Toomre mass, or a fraction of it in case the timescale of stellar feedback is shorter than the collapsing timescale. This shear-feedback hybrid model depends only on the gas surface density, gas velocity dispersion and the epicyclic frequency of the galaxy. Applying the model to M51, and converting the maximum GMC mass into a maximum cluster mass (via the star and cluster formation efficiencies), we find that the maximum mass is set by the shear in the inner 4 kpc of the galaxy and by feedback in the outer part. Their combination gives an expected maximum mass which is close to 10^5 $M_\odot$ everywhere in the galaxy.

A second division of the galactic environment is based on the the spiral arm and inter-arm division, separated by the surface brightness. We repeated the cluster mass function analysis in these two regions, finding that the slope of the function in the arm region is shallower than in the inter-arm (Tab 1). This difference remains even when using different divisions of the arm/inter-arm regions or when using different mass limits (simulating a more conservative completeness).

The difference in the mass function slopes resembles the difference observed in the mass function of the GMCs in different environments inside M51 by Colombo et al. (2014). In particular, the authors found slopes $\beta \sim -1.8$ in the arm compared to $\beta \sim -2.5$ in the inter-arm for the GMCs. In a similar way, the analysis of GMCs from the simulation of a two-armed spiral galaxy by Dobbs & Pringle (2013) reveals that GMCs in the arms are expected to show a shallower mass function profile (see discussion in Section 8.1 of Colombo et al. 2014).

We argue therefore that the shape of the cluster mass function is strictly related to the GMCs mass distribution, and in particular is affected by the fact that, on average, more massive GMCs are assembled in the spiral arms, compared to the inter-arm environment.

4. Conclusions

Using the HST multi-band observations collected within the LEGUS project, we created a catalogue of the star cluster population of the M51 galaxy. Via broadband SED fitting we retrieved ages and masses of the clusters in the catalogue. The mass function of a complete mass-limited subsample can be described by -2 power-law shape, expected from the hierarchy of star formation, but also reveals an exponential truncation at 10^5 $M_\odot$, above which very few sources are formed. The analysis of the mass function in subregions inside the galaxy and the comparison with the mass distribution of GMCs suggest that both the slope of the power-law part and the truncation mass can be influenced by the environment. In particular, the properties of the cluster masses seem to be directly related to the properties of the parental GMCs.

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