Resolving the Rise and Fall of Star Formation in Galaxies
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Hierarchical star formation in the Magellanic Clouds with the VMC survey

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Abstract. The VISTA Magellanic Clouds Survey (VMC) is a near-infrared survey of the Magellanic system. The VMC data has been exploited to detect and study statistically correlated young groups of stars — also known as "young stellar structures" — in the Large and Small Magellanic Clouds (LMC and SMC). We showcase the ∼3000 recently detected young stellar structures in the LMC and their similarity to the fractal interstellar medium. We discuss how their properties indicate their formation mechanisms and that there are no preferred scales of star formation in the LMC.

Keywords. stars: formation - galaxies: Magellanic Clouds - stars: early-type - methods: statistical

1. Introduction

Within star-forming galaxies we generally observe a young stellar hierarchy composed of (listed in decreasing density) stars, clusters ($\sim 10^0$ pc), associations ($\sim 10^1 - 10^2$ pc), and complexes ($\sim 10^3$ pc). This hierarchical distribution of young stars is found to disperse rapidly, on timescales of ≥100 Myr (Bastian *et al.* 2009; Sun *et al.* 2017b). There is evidence that most stars form in clusters, but there is also evidence that stars form in more isolated environments, leading to two distinct star formation channels being proposed: 'clustered' and 'distributed' star formation (Lada & Lada 2003). However, there is emerging evidence that star forming structures exist in a continuous range of sizes, masses, and densities (Bressert *et al.* 2010). Further analysis of the young stellar hierarchy is necessary to improve understanding of the star formation distribution and to search for characteristic sizes that may correspond to physical star formation mechanisms.

When discussing the star formation hierarchy, most studies focus on the densest regions, clusters, or the loosest regions, galaxies. These two disparate spatial scales must be unified; therefore, we focus on the intermediate scale, from 10–1000 pc. To study this intermediate scale, Sun *et al.* (2017a,b, 2018) employed a contour–based clustering analysis of young stars in two small regions covering the Large Magellanic Cloud (LMC) and

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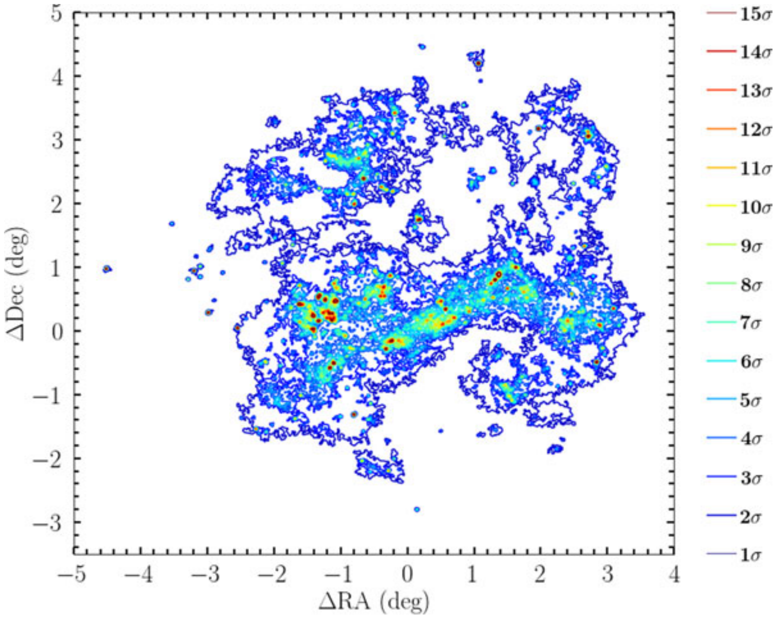

Figure 1. The identified young stellar structures coloured by 1σ to 15σ. After Miller *et al.* (2022).

the entire Small Magellanic Cloud (SMC). Their methodology was inspired by and incorporated work done by Gouliermis *et al.* (2010, 2015, 2017). We applied their methodology to the entire LMC in Miller *et al.* (2022). Our goals were to check for preferred scales of star formation, probe the dominant physical properties behind star formation, and to compare to the interstellar medium. In the following sections, we describe the data used, the detection methodology, results, and the implications of our work.

2. VMC data and young stellar structure identification

The Visible and Infrared Survey Telescope for Astronomy (VISTA) Magellanic Clouds Survey (VMC; Cioni *et al.* 2011), is a deep near-infrared YJK_s survey of the Magellanic system with spatial resolution of $\leq$1 arcsec. The VMC covers $\sim$120 square degrees on the LMC. We use point spread function photometry catalogues and deredden the magnitudes based on the extinction map provided by Skowron *et al.* (2021). We construct $(J - K_s)$ versus K_s colour–magnitude diagrams and use them to select $\sim 400,000$ young upper main-sequence stars (see Figure 2 of Miller *et al.* 2022). After binning the stars, we apply kernel density estimation (KDE) and make a surface density map with a resolution of 10 pc (see left panel of Figure 3 from Miller *et al.* 2022). From this map, we identify structures at 1 to 15σ above the median background density. After applying selection criteria that each structure on the $1 - 2\sigma$ levels have at least one structure at a higher significance level and that each structure have at least 5 stars, we identify about 3000 young stellar structures (see Figure 1).

3. Results and comparison to gas structures

The main result from our work that we want to emphasize is the size (radius) distribution of the young stellar structures (see left panel of Figure 3). For such a size distribution, it is important to assess if the distribution is lognormal or a power-law. In

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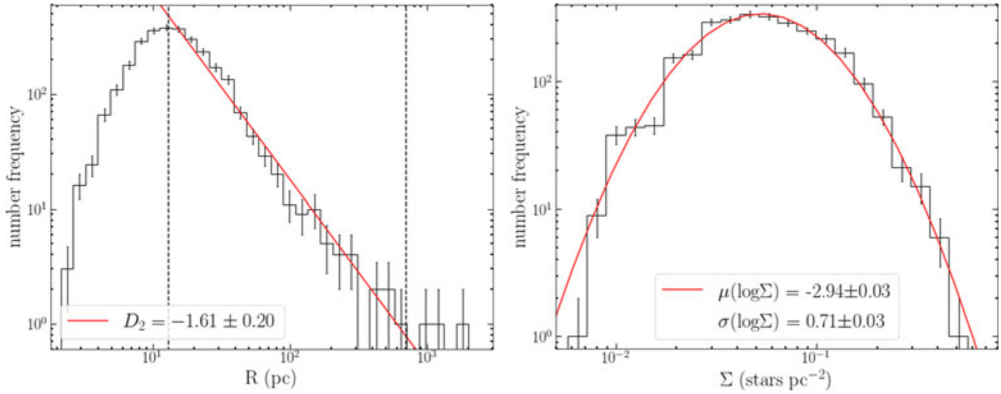

Figure 2. (Left) The size distribution of the young stellar structures. In red, the power-law we fit between 10−700 pc. (Right) The surface density distribution of the structures. In red, the lognormal distribution we fit. After Miller *et al.* (2022).

our size distribution, there is clearly an excess of large structures on the right-hand side. We fit a power-law between the dashed lines at 10 pc and 700 pc. Mathematically, this power–law corresponds to the 2D fractal dimension (D_2). This dimension encodes information about the spatial distribution of the young stellar structures. The one we derive, $\sim$1.6, suggests our structures have a fractal morphology and that there is no preferred scale from 10–700 pc.

The peak of the size distribution is $\sim$13 pc. The peak of a size distribution could be representative of a characteristic size of star formation. However, our structures are incomplete at $R < 10$ pc due to the resolution of our KDE map and due to our two selection criteria. Therefore, it seems the peak is related to the detection limit of our study and is not evidence of a characteristic scale of star formation.

The mass–size relation and the perimeter–area relation follow a power–law (see Figures 7 and 8 in Miller *et al.* 2022). The surface density distribution follows a lognormal shape (see right panel of Figure 3). We summarize LMC results from Miller *et al.* (2022) along with results from Sun *et al.* (2018) in the SMC and compare them to results obtained in studies of gas structures in Table 1. Due to the striking similarities, the young stellar structures in the LMC and SMC might inherit the hierarchical, fractal properties from the interstellar medium from which they form. A further important highlight from this comparison is that the density distribution of the young stellar structures follows the same lognormal shape as probability density functions that are characteristic of supersonic, non–gravitating turbulent gas (Vazquez-Semadeni 1994; Padoan *et al.* 1997; Federrath *et al.* 2010).

4. Conclusion

In Miller *et al.* (2022), we identified $\sim$3000 young stellar structures at 15 significance levels in the LMC using the near–infrared VMC survey. In this article we summarize our findings, and touch on those found in the SMC in Sun *et al.* (2018). We show the young stellar structures have:

- Irregular morphology and hierarchical organization
- Power–law mass–size relation, size distribution, and perimeter–area relation
- Lognormal surface density distribution
- Strong similarities with results in the interstellar medium and simulations of supersonic turbulence

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Table 1. Comparison with results from young stellar structures in the LMC (Miller *et al.* 2022) and SMC (Sun *et al.* 2018) with gas structures in the interstellar medium (references therein).

property	young stellar structures	gas structures
morphology	irregular	irregular[1],[2]
structure	hierarchical	hierarchical[1],[2]
size distribution	power–law	power–law[1]
mass–size relation	power–law	power–law[3]
density distribution	lognormal	lognormal[4]
perimeter-area relation	power–law	power–law[5]
2D fractal dimension	$D_2 \approx 1.6$	$D_2 \approx 1.7$[2]

References: [1] Elmegreen & Falgarone (1996); [2] Sánchez & Alfaro (2008); [3] Sánchez *et al.* (2005); [4] Padoan & Nordlund (2002); [5] Sánchez *et al.* (2007)

Our findings imply that star formation creates a continuum of star–forming structures in the LMC from 10 pc to 700 pc and is scale–free. The findings are consistent with the hypothesis of turbulence–driven hierarchical star formation.

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