

Origins of Mass Segregation in Stellar Clusters within the STARFORGE Simulations

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[Research Notes of the AAS, Volume 4, Number 9](#)

Citation Carleen Markey *et al* 2020 *Res. Notes AAS* **4** 163

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Dates

- 1. Received September 2020
- 2. Accepted September 2020
- 3. Published September 2020

DOI

<https://doi.org/10.3847/2515-5172/abba78>

Keywords

[Star formation](#); [Stellar physics](#); [Computational astronomy](#); [Star clusters](#)

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Abstract

Stellar clusters formed within Giant Molecular Clouds are mass segregated. This is either because massive stars are born at the center of the clusters, or because they migrate to the center due to gravitational interactions. We analyze a run from the STARFORGE simulation suite to identify what role the above processes play in determining mass segregation. We find that clusters begin as inversely- or non-mass segregated but contain separate mass-segregated star formation sites. As the cluster evolves, these substructures merge, and the overall cluster becomes more mass segregated due to gravitational interactions.

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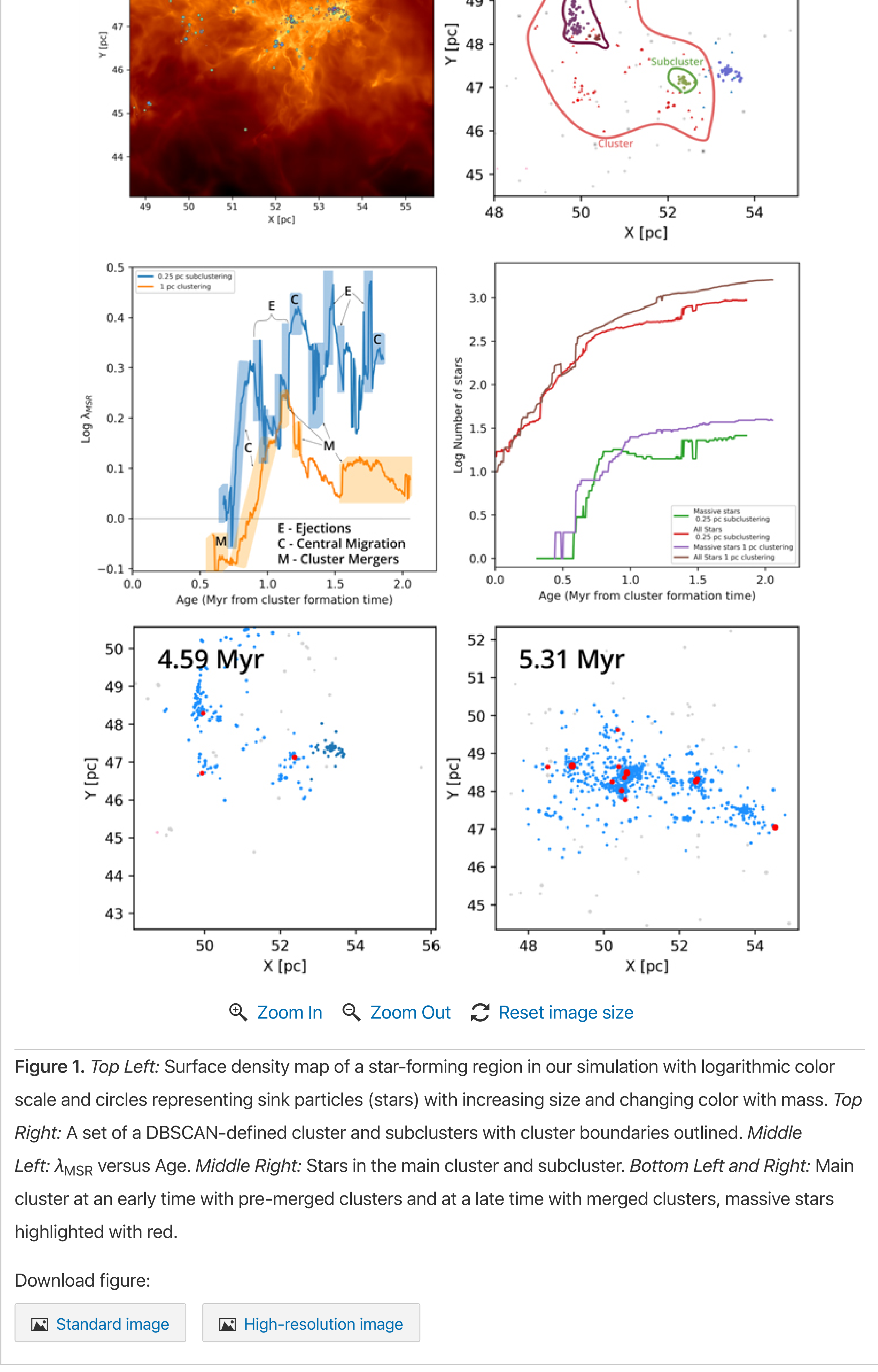
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1. Introduction

Star formation primarily occurs in Giant Molecular Clouds (GMCs), which produce clusters of stars (Lada & Lada 2003). In observed clusters, massive stars are often found in the centers of these clusters (Hillenbrand & Hartmann 1998; Kirk & Myers 2010). The source of this mass segregation is unknown. It is possible that gravitational N -body interactions cause more massive stars to migrate to the center of the cluster, leading to mass segregation (Spitzer 1969). Alternatively, massive stars may simply be born at the centers of stellar clusters, leading to inherent mass segregation (Bonnell & Bate 2006).

The STARFORGE simulation suite is a set of magneto-hydrodynamic simulations that follow the evolution of a GMC while resolving individual stars (Guszejnov et al. 2020; D. Guszejnov et al. 2020, in preparation). These simulations provide a unique opportunity to follow the formation of star clusters as new stars form, accrete, and gravitationally interact with each other and the gas present. In this note, we analyze the evolution of mass segregation in newly formed star clusters. For our analysis we choose a simulation that has stellar feedback in the form of protostellar jets (see Figure 1, top left), which are necessary to produce a realistic stellar initial mass function (see D. Guszejnov et al. 2020, in preparation).



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2. Methods

We define clusters in each snapshot using the DBscan (Density-based spatial clustering of applications with noise) clustering algorithm from scikit-learn (Pedregosa et al. 2011). We identify *clusters* with characteristic maximum distance of 1pc between stars (and also require at least 10 stars per cluster). Visual inspection of the stellar distribution, however, shows another, smaller scale of of clustering. Figure 1, top right, shows sub-groupings of stars within our defined clusters, which we hereby denote as *subclusters*. These subclusters are primarily present at early times before merging to form larger clusters, and they have a characteristic maximum distance of 0.25pc between stars and a minimum 15 stars per subcluster. We explicitly choose a higher minimum for the number of stars to exclude incorrectly identifying small unbound groupings of stars as subclusters. These definitions allow us to examine mass segregation on two separate scales, where the smaller scales are not influenced by the large distances between star formation sites. An important caveat of our method is that DBSCAN may combine subclusters that pass near one another but are not bound gravitationally. This temporarily enhances the mass segregation ratio due to the drastic increase in the typical distance between massive stars or the average distance between cluster members.

As a measure of mass segregation we adopt the λ_{MSR} mass segregation ratio from Allison et al. (2009). This is derived from a minimum spanning tree (MST), a graph connecting a set of points with the smallest possible total path length. To find λ_{MSR} , we find l_{massive} , which is the average path length of the MST of massive stars above $5 M_{\odot}$ within a single cluster or subcluster. We additionally require a minimum of 5 massive stars to calculate l_{massive} in order to exclude the effect of early massive binaries that artificially decrease the massive star path length and highly skew λ_{MSR} . We then repeat the above process 500 times with N_{MST} random stars to obtain l_{random} , which is the average length between stars in all 500 MSTs. We also compute σ_{random} , which we define as the error in l_{random} . Therefore $\lambda_{\text{MSR}} \equiv \frac{l_{\text{random}}}{l_{\text{massive}}} \pm \frac{\sigma_{\text{random}}}{l_{\text{massive}}}$ similar to Allison et al. (2009).

Beginning with the final simulation snapshot, we apply DBSCAN to identify the clusters and subclusters. We then track each cluster backwards through its evolution until the cluster or subcluster forms. For each snapshot, we record λ_{MSR} , l_{massive} , l_{random} , the number of massive stars, and total number of stars in each cluster and subcluster.

3. Results and Discussion

We show the evolution of these metrics through the cluster lifetime in the middle panels of Figure 1. First, we see that the subcluster and cluster begin as non-mass segregated ($\lambda_{\text{MSR}} \approx 1$) and inversely mass segregated ($\lambda_{\text{MSR}} < 1$), respectively. The lack of mass segregation ($\lambda_{\text{MSR}} > 1$) is likely because of the initial presence of separate mass-segregated star formation sites (see bottom left of Figure 1) and large distance between these sites dominates l_{massive} and λ_{MSR} . In inspecting simulation snapshots in the beginning of the cluster and subcluster lifetimes, we find that these sites initially contain single or binary massive stars, and future massive stars form nearby. This discovery supports that early mass segregation is created by massive stars simply forming closer to each other in stellar clusters than a random star. However, we find variations in λ_{MSR} that cannot be explained by the addition of stars or massive stars alone, as we would expect if this was the sole explanation. Examining simulation snapshots at later times, there is evidence for gravitational interactions leading to mass segregation as the subclusters and clusters evolve. The first dynamical mass segregation process is the gravitational migration of massive stars toward the center in both subclusters and clusters. This causes lambda to increase in the the highlighted central migration periods in Figure 1, middle left. Both subcluster mergers and the ejection of stars then interrupt this central migration. In the bottom left. Row of Figure 1, we show snapshots before and after a merger of subclusters. As these objects merge, gravitational interactions can halt or even reverse central migration and cause ejections, flinging massive stars outward from their clustered configurations. During these mergers, also highlighted in Figure 1, λ_{MSR} decreases.

Additionally, ejections resulting from cluster mergers and N -body interactions lead to the slow drops and spikes seen in the subcluster λ_{MSR} evolution in Figure 1. Ultimately, ejections do not have a detectable long-term impact on the evolution of λ_{MSR} , as central migration steadily increases mass segregation.

To conclude, we propose a third hypothesis to explain the evolution of mass segregation: massive stars form at the centers of mass-segregated subcluster star formation sites, which move into larger mass-segregated cluster configurations through gravitational N -body interactions. Future analysis of simulation runs with alternate physics is required to verify this hypothesis.

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Abstract

1. Introduction

2. Methods

3. Results and Discussion

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