In Situ Field Massive Star Formation in the Magellanic Cloud

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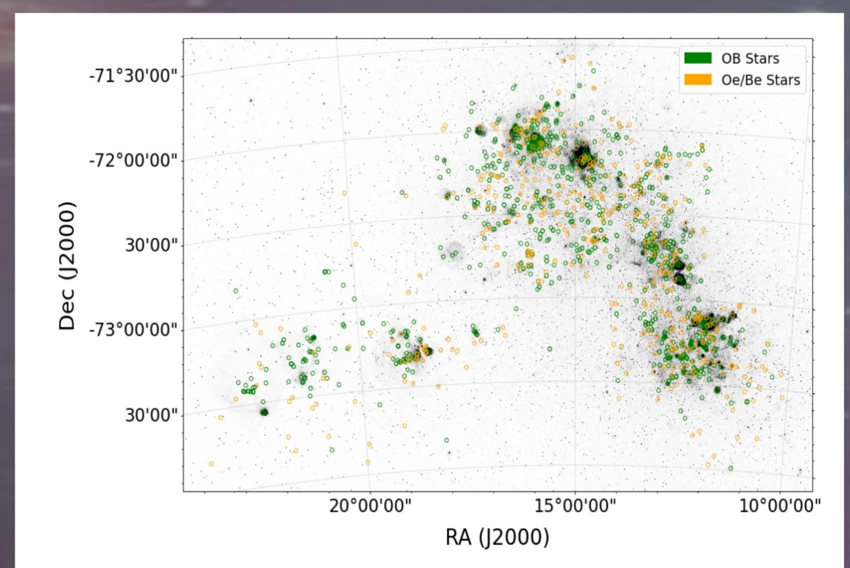
Abstract: A fundamental question for theories of massive star formation is whether OB stars can form in isolation. We assess the contribution of any in-situ OB star formation by using 210 field OB stars in the Small Magellanic Cloud (SMC) from the Runaways and Isolated O-Type Star Spectroscopic Survey of the SMC (RIOTS4). We search for tiny, sparse clusters around our target OB stars using cluster-finding algorithms. Employing statistical tests, we compare these observations with random-field data sets. We find that ~5% of our target fields do show evidence of higher central stellar densities, implying the presence of small clusters. This frequency of small clusters is low, much lower than previous estimates, and within errors, it is also consistent with the field OB population being composed entirely of runaway and walkaway stars. Assuming this small cluster fraction is real, it implies that some OB stars may form in highly isolated conditions. The low frequency could be caused by these clusters evaporating on a short timescale. However, another interpretation is that the low fraction of small clusters is observed because these form rarely, or not at all, implying a higher cluster lower-mass limit and consistent with a relationship between maximum stellar mass (m_{max}) and the cluster mass (M_{cl}). Additionally, we are looking into the binary properties of the runaway stars to provide constraints for the initial properties of the cluster population in future work.

Field stars account for 25-30% of normal OB star population (Oey et al. 2004). Field stars have two different possible origins: runaways, stars that are ejected from their parent cluster; or stars that form in situ in apparent isolation. This could happen, for example, if the stellar IMF and CMF behave as probability density functions, allowing smaller, sparser clusters with a single massive star to form. We call the massive star in such a cluster a Tip-of-the-Iceberg Star (TIB). Simulations (Lamb et al 2010) have shown that these TIB clusters could exist, and observations on field stars (Oey et al. 2013) have found evidence of potential in situ formation. However, the frequency of in situ formed field OB stars has not been well established. Therefore, we use The Runaways and Isolated O-Type Star Spectroscopic Survey of the SMC (RIOTS4; Figure 1; Lamb et al. 2016) and OGLE III photometry (Udalski et al. 2008) to identify a 210 target sample to search for TIB clusters using cluster-finding algorithms to assess the contribution of any in-situ OB star formation in a complete sample of field stars.

Figure 1: An image showing the stars from the RIOTS4 survey, the first statistically complete sample of field massive stars in an external galaxy. The targets of this survey were selected to be at least 28pc from other sample OB stars, and it comprises 28% of all SMC OB stars. Image from Dallas & Oey (2022) in prep.



Cluster Finding Algorithms

Friends of Friends (FOF)

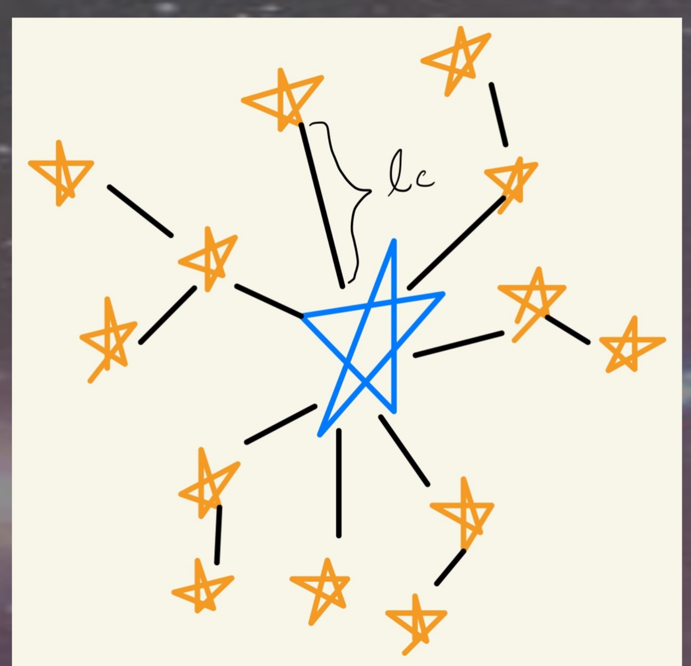


Figure 2a: FOF identifies associated stars ("friends") as those that are within a given clustering length (l_c) of another member. Each l_c is specific to each field of the targets ($l_{c,field}$). Clusters are more likely to be those with greater number of stars (N_*) identified or those with a higher M value:

$$M = \frac{l_{c,SMC}}{l_{c,field}} * N_*$$

Where $l_{c,SMC}$ is the average l_c for all SMC fields. A higher M value corresponds to a larger number of stars closely spaced together.

Nearest Neighbors (NN)

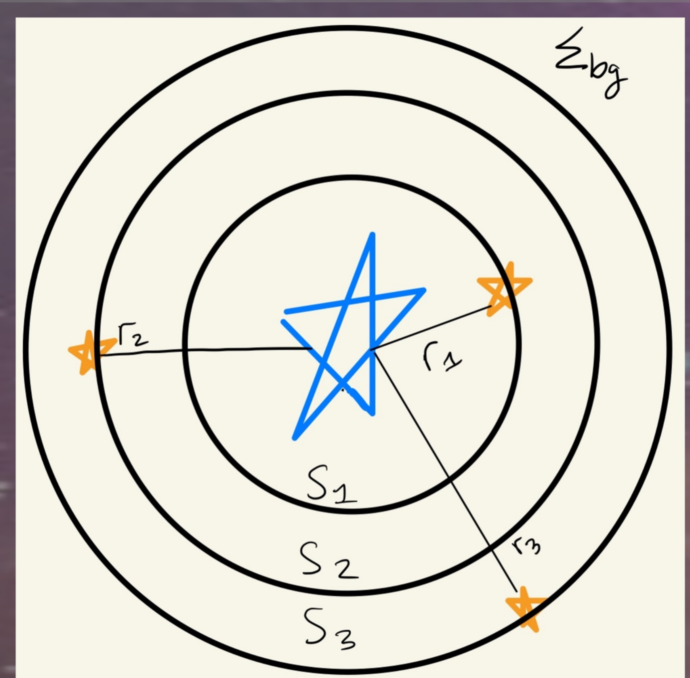


Figure 2b: NN measures the stellar density (Σ_j) associated with a given target star which is calculated by counting the number of stars enclosed within the area (S_j) to its jth nearest neighbor in 2D:

$$\Sigma_j = \frac{j-1}{S_j}$$

We compare the resulting Σ_j with the background density (Σ_{bg}), which were calculated for each target. This is then placed in units of the Poisson error of Σ_{bg} (σ_{bg}): $\frac{\Sigma_j - \Sigma_{bg}}{\sigma_{bg}}$. The higher the difference, the more likely the target belongs to a cluster.

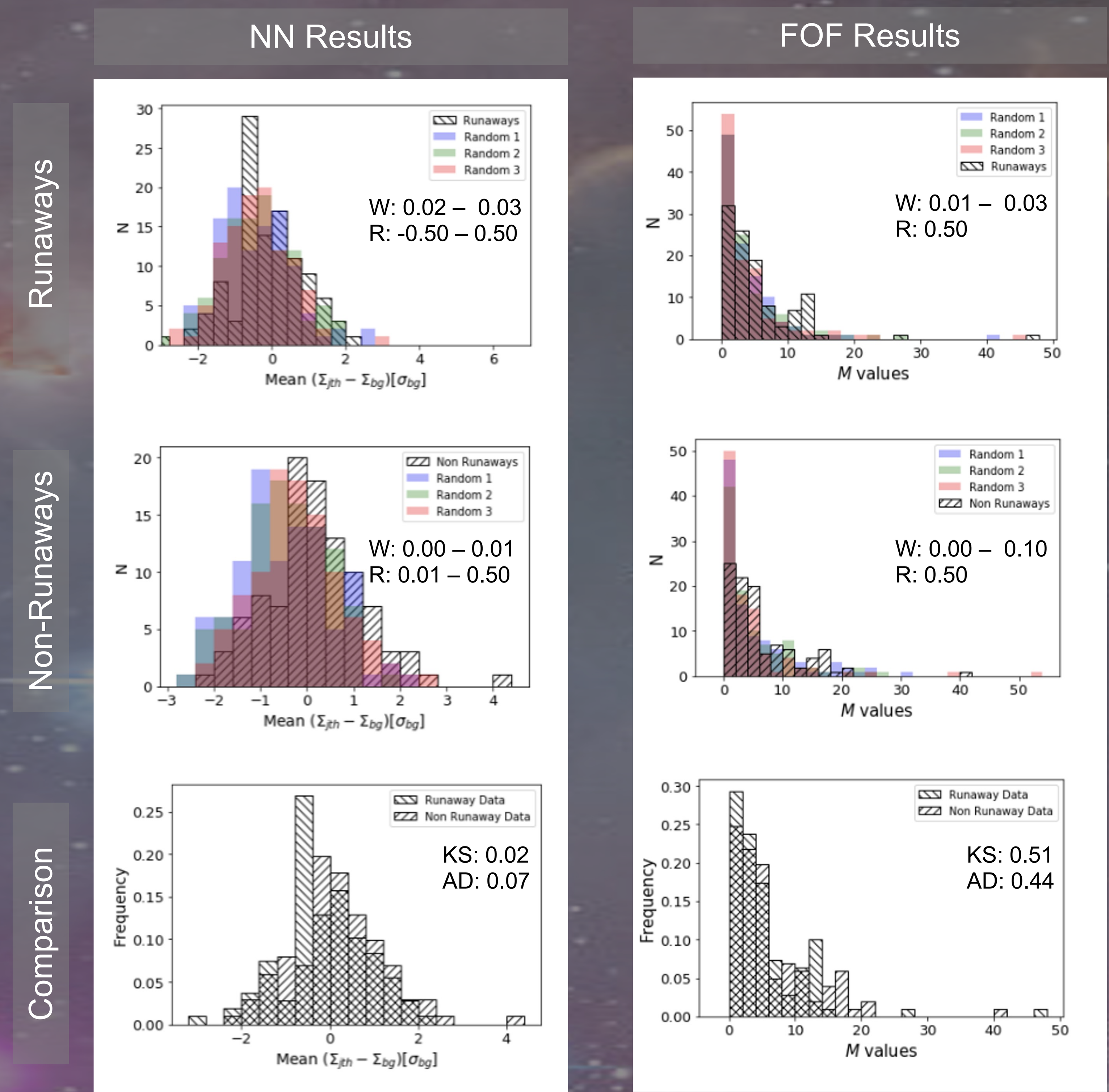


Figure 3: results from NN showing the mean values of the stellar density results (left) and the results from FOF for the M values (right) of different subsamples of our survey against the results from random fields (colored bars). The comparison between the results of the two samples is at the bottom. To confirm our results, we employed four statistical tests: the Wilcoxon (W) and Rosenbaum (R) tests when comparing our results to the random fields, and the KS and Anderson-Darling (AD) tests when comparing the sub-samples to each other. These results are displayed above with the p-value ranges displayed to the side (or bottom) of the plots.

Table 4
Estimated Percentage of TIB Clusters[a]

	Full Sample %	Nonrunaways %	Runaways %	Full Data Subtracted[b]	Nonrunaways Subtracted[b]
NN Average vs. Random 1	15 ± 2.9	22 ± 5.1	11 ± 3.4	4 ± 4.5	11 ± 6.1
NN Average vs. Random 2	12 ± 2.6	21 ± 5.0	8.3 ± 2.9	3.7 ± 3.9	1 3± 5.8
NN Average vs. Random 3	12 ± 2.6	18 ± 4.6	8.3 ± 2.9	3.7 ± 3.9	9.7 ± 5.4
NN Median vs. Random 1	17 ± 3.1	23 ± 5.3	13 ± 3.7	4.0 ± 4.8	10 ± 6.5
NN Median vs. Random 2	15 ± 2.9	22 ± 5.1	12 ± 3.5	3.0 ± 4.5	10 ± 6.2
NN Median vs. Random 3	11 ± 2.4	16 ± 4.3	10 ± 3.2	1.0 ± 4.0	6.0 ± 5.4

Table 1: The final estimated TIB cluster fractions from our NN tests. Since runaways are unlikely to originate in TIB clusters, we consider this to be our false positive hit rate. When subtracting these from the full data set, we get an estimated fraction of ~4-5% of field stars identified as small clusters.

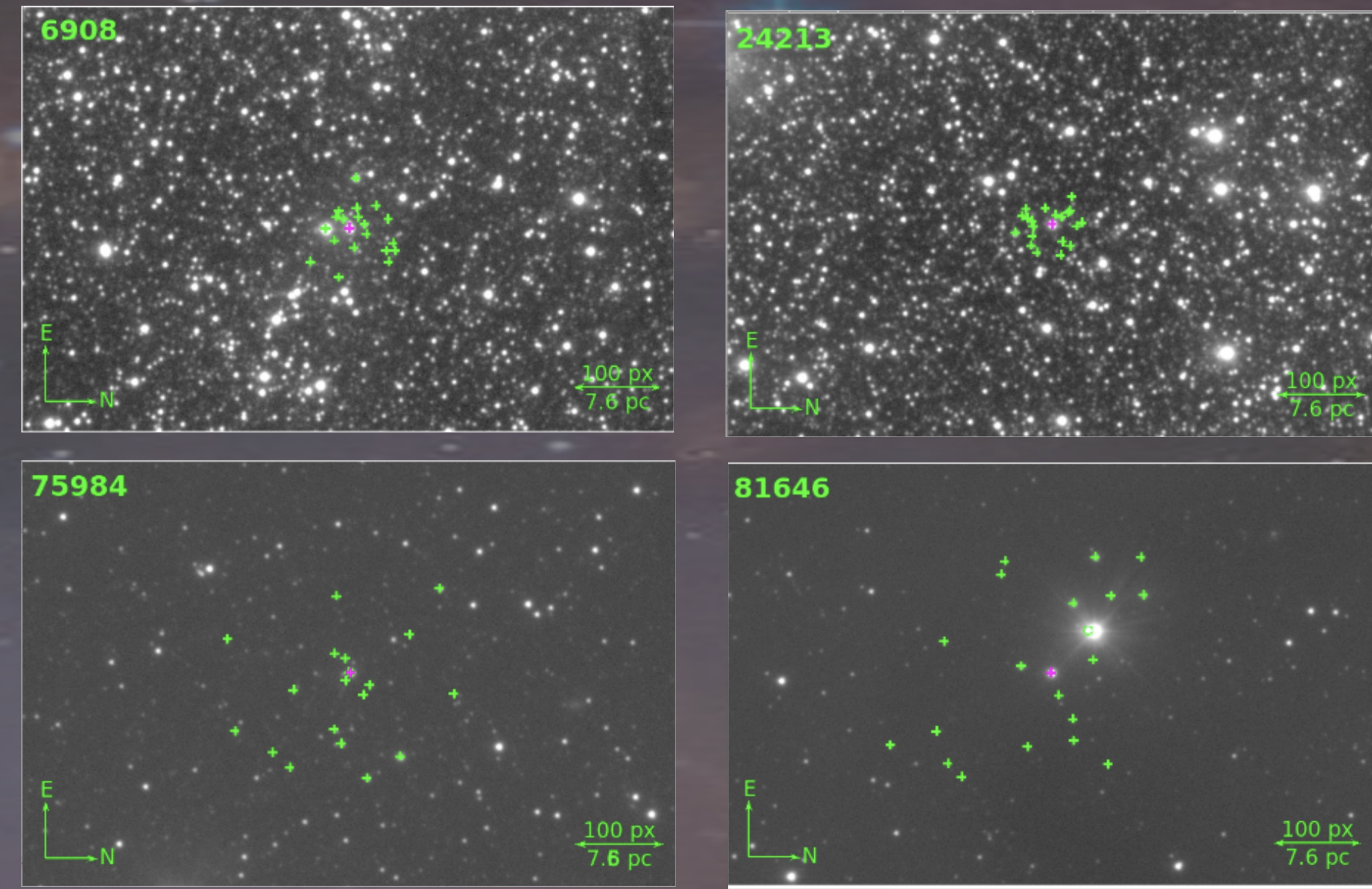


Figure 5: Four of our top cluster candidates from NN in our non-runaway sample. North is to the right and East is up. 100 px corresponds to 26″ in angular scale. Each target is shown in magenta with its 20 jth nearest neighbors in green.

Our two cluster finding algorithms are Friends of Friends (FOF) and Nearest Neighbors (NN, Figure 2). Figure 3 shows the results for identifying potential TIB clusters of two sub-samples of our data: known runaway stars, which should not show TIB clusters; and the rest of our targets, the non-runaways. We use statistical tests to determine the significance of our results. Both our FOF and NN results show a very small presence of positive detections. However, the statistical significance of the FOF results is lower. NN results present more centrally concentrated stellar densities for the non-runaway sub-sample (Figure 5), and a greater significant difference between this sub-sample and the others, which is expected of real detections. Some statistical tests do not confirm this detection, thus these ambiguous results could also indicate a regime where TIB clusters are marginally detected. Overall, we estimate a percentage of TIB clusters of ~4% (Table 1).

Final result: There is evidence that ~4% of field stars do form in situ in TIB clusters. The rest is overwhelmingly composed of runaways. There are three possible scenarios for this result:

1) TIB clusters usually do not contain OB stars.
2) A higher cluster lower-mass limit is required.
3) Clusters evaporate quickly. Our detections are clusters that haven't evaporated yet.

Our results place stringent constraints on the formation of OB stars in isolation.

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