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Isolated massive star formation

Myth or reality?

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Abstract. High-mass stars apparently formed in the field challenge the paradigm of clustered star formation. To understand the conditions that favor isolated massive star formation, we employed the *Hubble Space Telescope* to observe the seven most isolated massive YSOs in the LMC. Our investigation shows that while they are quite remote from any star-forming region, these YSOs are not isolated at all. *HST* revealed a plethora of Pre–Main-Sequence stars, forming compact clusters around the YSOs, and sparsely distributed across the observed regions. Contrary to previous studies, these observations suggest that high-mass stars may not be able to form in clusters smaller than 100 $M_{\odot}$, and that the lack of isolation is at odds with random sampling of the stellar IMF.

Key words. ISM: clouds – Magellanic Clouds – stars: formation – stars: massive

1. Introduction

The formation of massive stars in apparent isolation is a topic that has attracted the interest of the astronomical community for long time. High-mass stars forming in isolation is quite important since this would represent the star formation process under extreme conditions. Investigating the phenomenon, and the search for truly isolated massive stars under formation aims at addressing various issues:

- Can massive stars form alone?
- How to define "isolated star formation"?
- What are the criteria of isolation?
- How can we observe this phenomenon?

Ultimately, what we would like to understand is what the phenomenon of isolated massive star formation tells us about the conditions of the star formation process at its extremes.

Possibly the most important empirical test supporting or contradicting isolated massive star formation is the stellar Initial Mass Function (IMF), i.e., the mass distribution of stars at the time of their formation. Considering that the IMF itself determines how the mass budget of an ensemble of stars is being distributed among them, one would argue that the way the IMF is being populated plays a pivotal role in how stars form. Specifically, if the IMF is being populated in an "optimal" manner, then for every massive star in the ensemble there should be also a few tens of intermediate-mass stars, and for every one of them there should be a corresponding number of low-mass stars.

The optimal IMF sampling scenario predicts a strict relation between the maximum stellar mass in a stellar cluster and the mass of the cluster, with the maximum stellar mass being set by the high-mass end of a fully-populated stellar IMF (e.g., Oey & Clarke 2005). This poses constraints to the very existence of isolated massive star formation. As a consequence the optimal IMF sampling does not allow for isolated massive star formation, specifically excluding O-type stars from forming in clusters with masses $\leq 250\,M_\odot$ (e.g., Weidner & Kroupa 2006).

On the other hand, if the stellar IMF is populated in a stochastic way, i.e., by randomly selecting from a sample of masses, a massive star may form without co-existing with other intermediate- and low-mass companions. This random IMF sampling scenario predicts, thus, isolated massive star formation under certain circumstances. Simulations have shown that the formation of a single O-type star (with no B-type companions) can occur in a $< 100\,M_\odot$ cluster with 1% - 5% chance (e.g., de Wit et al. 2005; Parker & Goodwin 2007).

We present our findings from our recent study (Stephens et al. 2017), focused on testing these scenarios with the use of deep multi-band *Hubble Space Telescope* photometry of seven carefully selected candidates for isolated massive star formation in the Large Magellanic Cloud.

2. Criteria for isolation

The criteria for isolation in massive star formation depend on the very definition of the phenomenon. Probably, the most accurate definition of isolated massive star formation is that stated by Zinnecker & Yorke (2007), i.e., "the monolithic collapse of isolated massive protostellar cores". Nevertheless, the various criteria determined across the literature are ambiguous. As a basis of the most reasonable criteria for isolation we repeat those determined by Bressert et al. (2012), although these authors considered only the last for detecting isolated O-type stars in the Tarantula nebula. In order to be isolated the massive star should ...

- not be forming with other massive stars,
- not be triggered by other massive stars, and
- not be a member of a multiple system.

2.1. Issues with the search for isolation

Various studies are dedicated to the search for isolated massive star formation, based on criteria like those stated above. However, the definition of Zinnecker & Yorke (2007) implies that the isolated massive stars should have formed in-situ, which poses various issues for studies focused on field O-type stars. First, runaway or walkaway O-stars, kicked out of their clusters due to dynamical interactions, may be confused with O-stars formed in isolation (e.g., Gvaramadze et al. 2012). Second, studies that reproduce through simulations the observed fraction of field O-stars in true isolation, set as a precondition that the IMF is stochastically populated, proving a one-way argument (random IMF sampling supports isolated massive star formation, but not the opposite). Finally,

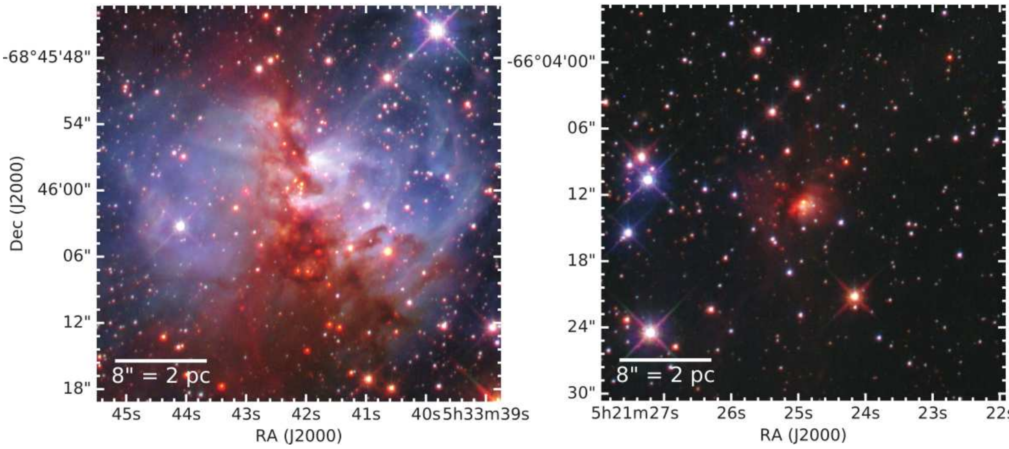

Fig. 1. Three-color images from our *Hubble* observations zoomed on two of the MYSOs. The colors in red, green, and blue correspond to the F160W, F814W, and F555W ($\sim$1.5, 0.80, and 0.53 μm) filters, respectively. Both panels are centered on the brightest photometric sources of the high-mass star-forming regions. Each color is on an arcsinh scale, and colors were adjusted in each panel to best show the stellar content. Adapted from Figs. 4 – 10 in Stephens et al. (2017).

and most importantly, field O-type stars (e.g., Lamb et al. 2010; Oey et al. 2013) are no longer embedded, with any memory of the conditions at the time of their formation being erased through ionization and winds.

2.2. The new paradigm

Considering that field O-type stars have already erased the signs of their formation, it becomes more obvious that if there is massive star formation happening, it should be "caught in the act", i.e., it should be observed at an evolutionary stage as close to the initial conditions as possible. This stage would be that of a massive radiative source, which is still embedded in its parental core, i.e., a massive young stellar object (MYSO). This hypothesis was tested for a compact HII region in the Small Magellanic Cloud by Selier et al. (2011), who resolved the related high-excitation blob into separate components, i.e., there was no isolation.

Building on this hypothesis we developed a program for the search for isolated MYSOs in the LMC with the use of *Hubble* imaging (Stephens et al. 2017). In order, however, to select the best possible candidate MYSOs for isolation we determined a set of strict criteria. Specifically, the YSO should be . . .

- spectroscopically confirmed as a MYSO,
- massive enough to ionize hydrogen,
- farther than 80 pc from any known GMC,
- farther than 80 pc from any OB association,
- farther than 80 pc from another MYSO.

We selected our best candidates from the complete sample of 248 MYSOs across the whole extend of the LMC (Gruendl & Chu 2009), from the sample of YSOs previously identified in Chu & Gruendl (2008). The objects were confirmed to be massive with the use of ground-based narrow-band imaging and spectroscopy from Spitzer/IRS (Seale et al. 2009). For verifying the remoteness of the candidate from any known GMC and association, we used the catalogs of GMCs constructed with NANTEN (Fukui et al. 2008) and MAGMA (Wong et al. 2011) surveys, and the OB associations census from Lucke & Hodge (1970).

3. Results

We employed *Hubble* to follow up on seven of the sources identified with this selection as the best candidate MYSOs for isolation. We

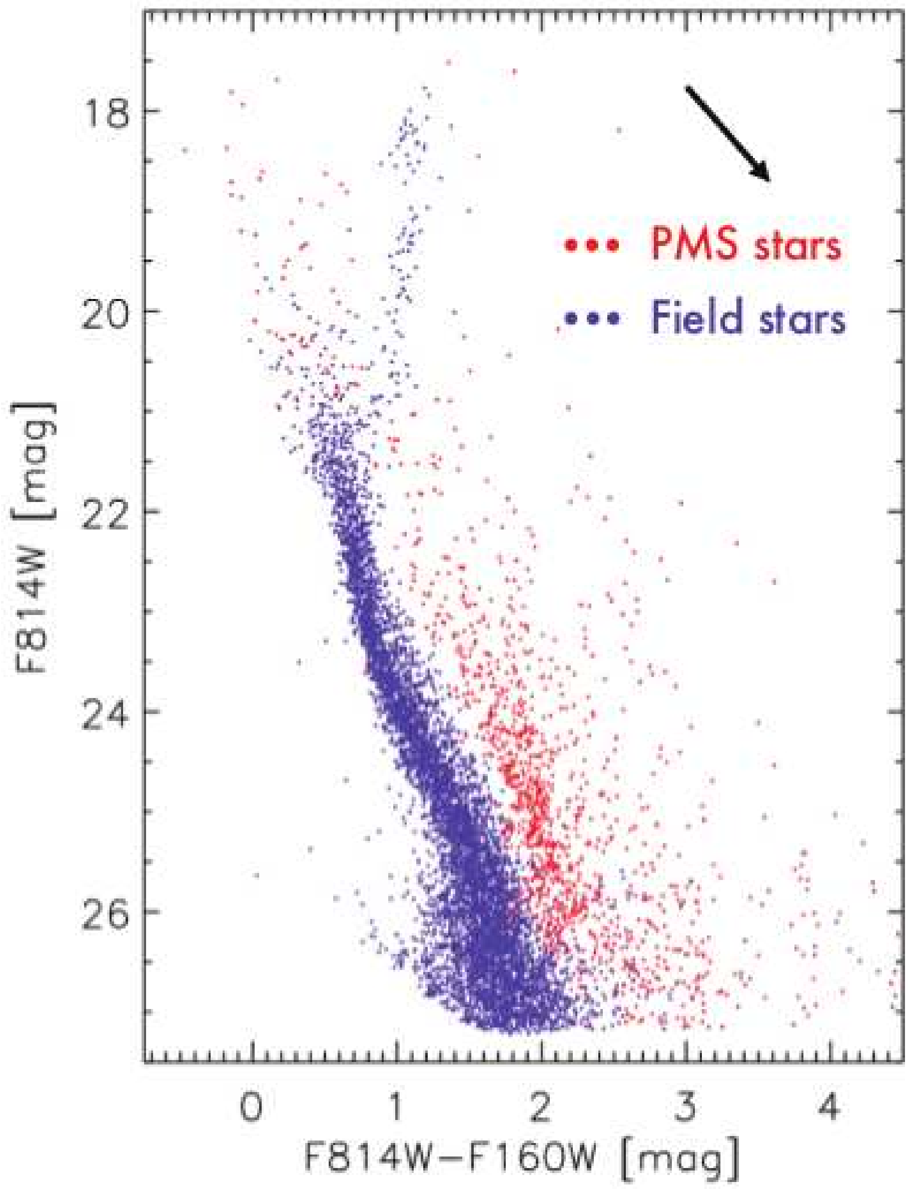

Fig. 2. Color-Magnitude Diagram for one of the candidate isolated MYSOs using the F814W and F160W filters. Typical stellar populations of the nearby LMC field are plotted with blue symbols. The young PMS stellar sources of each region, determined by statistically decontaminating the complete observed CMDs from the field contribution, are plotted in red. They represent the recent star formation events for each region. An indicative reddening vector for $A_V = 2$ mag is shown only to demonstrate the effect of extinction; the length of the vector does not correspond to the actual interstellar extinction in the region, which is much lower. Adapted from Fig. 12 in Stephens et al. (2017).

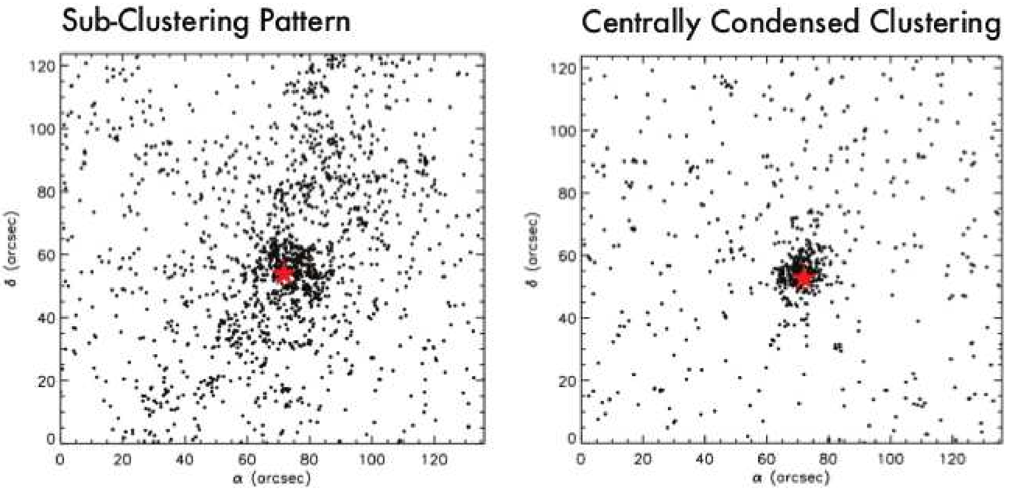

Fig. 3. Two extreme examples, showing the clustering pattern of PMS stars around the apparently isolated MYSOs. In the example on the left, PMS stars are widely distributed around the MYSO (indicated with the red star), showing significant sub-structure that depicts the extent of the parental molecular cloud. The example on the right exhibits the unique case of a single compact populous PMS cluster forming centered around one of the candidate isolated MYSOs (also indicated with the red star). Adapted from Fig. 15 in Stephens et al. (2017).

acquired WFC3 observations in the F656N, F555W, F814W, F110W, and F160W bands to examine the interstellar environment and determine the surrounding stellar populations down to ~ 0.7 $M_\odot$ (Fig. 1). These observations clearly demonstrated that while these MYSOs appear to be in isolated environments, they are actually surrounded by a plethora of low- and intermediate-mass Pre–Main-Sequence (PMS) stars (Fig. 2). Significant numbers of such T Tauri equivalent stars are known to populate star-forming regions of the Magellanic Clouds (Gouliermis 2012).

We performed a clustering analysis of these stars based on the method demonstrated by Gouliermis et al. (2014). Our analysis showed that all MYSOs are members of compact clusters. The regions around the MYSOs showed significant substructure, with the PMS stars being both sparsely distributed (Fig. 3, left) and in compact clusters (Fig. 3, right). These stellar alignments appear to be the signatures of the parental molecular cloud, which is currently undetected by CO surveys. Only one of the analyzed MYSOs was found to be surrounded by a single isolated compact low-mass stellar cluster with no other stellar distribution being associated with it. This indicates that the parental cloud of this object did not produce stars in a dispersed fashion. The fact that there are no other known clusters within the region around it, makes this isolated cluster around a single O-star a very rare occurrence in the context of high-mass star formation, and therefore a unique case of star formation (Fig. 3, right).

3.1. How the IMF is populated

These observations provide a basis for testing both optimal and random sampling of the IMF. For the estimation of the total mass of the clusters around the MYSOs, we considered all stars found within the borders of each cluster and determined their masses from their CMD positions based on evolutionary models for ages of 1 and 2.5 Myr. We added the undetected stellar mass, based on the mass of our photometric detection limit, which we extrapolated to lower masses assuming that the IMF of the clusters behaves according to Kroupa (2001). We then estimated the total mass of cluster that would

Table 1. Spectral types of the investigated MYSOs and masses of their surrounding compact clusters. Columns 1 and 2 provide the spectral type and the corresponding mass of the YSOs. In column 3 the approximate embedded cluster mass ($M_{\rm cl}$) is given, assuming a stellar age of 2.5 Myr. Columns 4 and 5 show the cluster mass expected analytically from the stellar IMF, and from the empirical $m_{\rm max} - M_{\rm cl}$ relation, respectively. Extracted from Table 6 in Stephens et al. (2017).

Sp.	$m_{\rm max}$	$M_{\rm cl}$ ($M_\odot$)		
Type	($M_\odot$)	Measured	$m_{\rm max}$	$- M_{\rm cl}$
B0V	14	170	210	200
O9.5V	16	360	240	280
O8V	21	510	360	490
B0V	14	140	210	200
B0V	14	250	210	200
O6V	31	610	670	1220
B0V	14	350	210	200

be expected in the optimal sampling scenario according to the mass of the most massive star in each cluster. We made this calculation both analytically from the IMF (Weidner & Kroupa 2004) and from the empirical relation between the maximum stellar mass and the total mass of a cluster (Weidner et al. 2013). The derived cluster masses are very similar to those estimated from our data (Table 1), indicating that, at least for the clusters found around the selected MYSOs, the IMF may be optimally populated.

4. Concluding remarks

We investigate isolated high-mass star formation at a much earlier stage, i.e., the embedded MYSO stage. Based on our selection criteria, we have selected the best candidates for in situ, isolated high-mass star formation in the LMC. Our investigation showed that none of them are actually isolated, being members of compact clusters, most of which are part of extended stellar constellations. We recover the total masses of the compact clusters surrounding these MYSOs, under the assumption of optimal sampling of the stellar IMF. We find these clusters to be larger than 100 $M_\odot$, suggesting that these MYSOs are not as isolated as typical field O-stars.

Considering that our results are based on only few candidates, we estimate the chances our search not to detect a truly isolated MYSO that may exist in our complete sample. If 1%–5% of MYSOs form in isolation, then assuming that we randomly selected seven candidates from a subset of 25 best candidates, we estimate that the chances of not random selecting an isolated MYSO from this subset are 43% and 0.2% respectively. Given these probabilities, it is unlikely that 5% of all MYSOs in the LMC are isolated; however, it is certainly possible to expect 1% of the sources to be isolated. In summary, while we cannot entirely rule out neither the random nor the optimal sampling of the IMF, we suggest that if our selection criteria increased our chances of finding isolated MYSOs and the IMF is randomly sampled, the LMC likely has significantly fewer than 5% of its MYSOs forming in isolation.

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APLpy, an open-source plotting package for Python hosted at `http://aplpy.github.com`.

References

Bressert, E., Bastian, N., Evans, C. J., et al. 2012, A&A, 542, A49
Chu, Y.-H., & Gruendl, R. A. 2008, in Massive Star Formation: Observations Confront Theory, ed H. Beuther, H. Linz and T. Henning (ASP, San Francisco), ASP Conf. Ser., 387, 415
de Wit, W. J., et al. 2004, A&A, 425, 937
de Wit, W. J., et al. 2005, A&A, 437, 247
Fukui, Y., Kawamura, A., Minamidani, T., et al. 2008, ApJS, 178, 56
Gouliermis, D. A. 2012, Space Sci. Rev., 169, 1
Gouliermis, D. A., Hony, S., & Klessen, R. S. 2014, MNRAS, 439, 3775
Gruendl, R. A., & Chu, Y.-H. 2009, ApJS, 184, 172
Gvaramadze, V. V., et al. 2012, MNRAS, 424, 3037
Kroupa, P. 2001, MNRAS, 322, 231
Lamb, J. B., et al. 2010, ApJ, 725, 1886
Lucke, P. B., & Hodge, P. W. 1970, AJ, 75, 171
Oey, M. S., & Clarke, C. J. 2005, ApJ, 620, L43
Oey, M. S., et al. 2013, ApJ, 768, 66
Parker, R. J., & Goodwin, S. P. 2007, MNRAS, 380, 1271
Seale, J. P., Looney, L. W., Chu, Y.-H., et al. 2009, ApJ, 699, 150
Selier, R., Heydari-Malayeri, M., & Gouliermis, D. A. 2011, A&A, 529, A40
Stephens, I. W., Gouliermis, D., Looney, L. W., et al. 2017, ApJ, 834, 94
Weidner, C., & Kroupa, P. 2004, MNRAS, 348, 187
Weidner, C., & Kroupa, P. 2006, MNRAS, 365, 1333
Weidner, C., Kroupa, P., & Pflamm-Altenburg, J. 2013, MNRAS, 434, 84
Wong, T., Hughes, A., Ott, J., et al. 2011, ApJS, 197, 16
Zinnecker, H., & Yorke, H. W. 2007, ARA&A, 45, 481