Skyscrapers in a Desert:
Observing Ongoing, Active Star Formation in the Low-Density Wing of the Small Magellanic Cloud

Leah Fulmer[1,2], John S. Gallagher, III[2], Wolf-Rainer Haman[3], Lida Oskinova[3], Varsha Ramachandran[3]

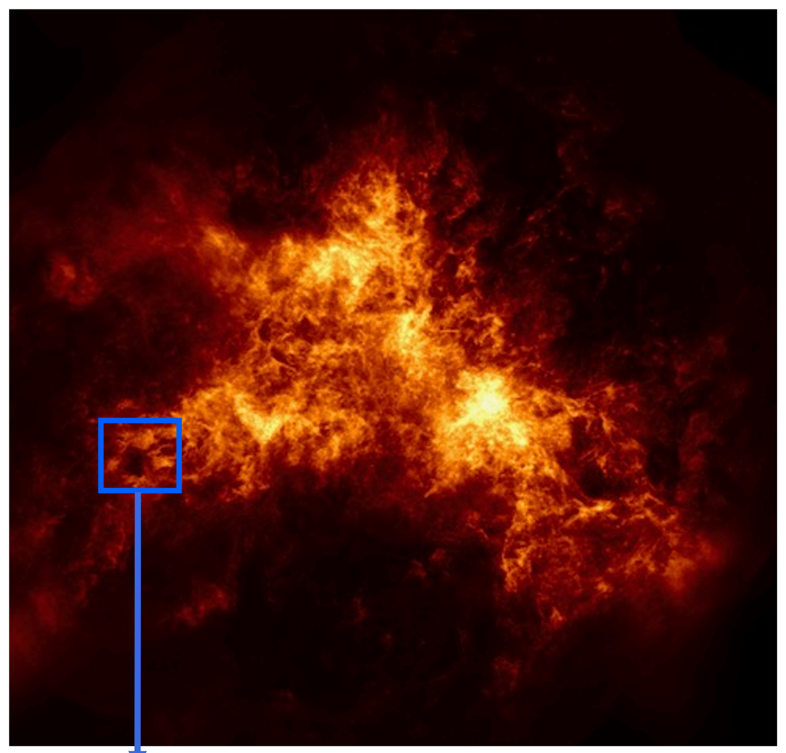
[1]National Optical Astronomy Observatory, [2]University of Wisconsin-Madison, [3]Universität Potsdam

E-mail: lfulmer@noao.edu

Twitter: @leahmfulmer

What's going on here?

The low-density Wing of the Small Magellanic Cloud (SMC) exhibits ongoing, active star formation despite a distinctive lack of dense interstellar matter, or resources from which to form stars[1,2]. The region appears as if you found skyscrapers in an empty desert: there are clear signs of production without an obvious source of materials. Given such paradoxical star formation, the Wing and its most significant star cluster NGC 602 have long been regarded as isolated laboratories in which to study low-density, primordial star formation[3,4]. However, our photometric observations surrounding NGC 602 reveal a far more complex and interconnected star formation history than may have been previously recognized; as though we observe an entire city surrounding these previously isolated "skyscrapers". We seek to more clearly describe this complex history and to ultimately determine if the observed star formation in the greater SMC Wing is indeed connected to that within the well-observed cluster NGC 602. **In other words, is NGC 602 an anomalous skyscraper or part of a larger desert city?**



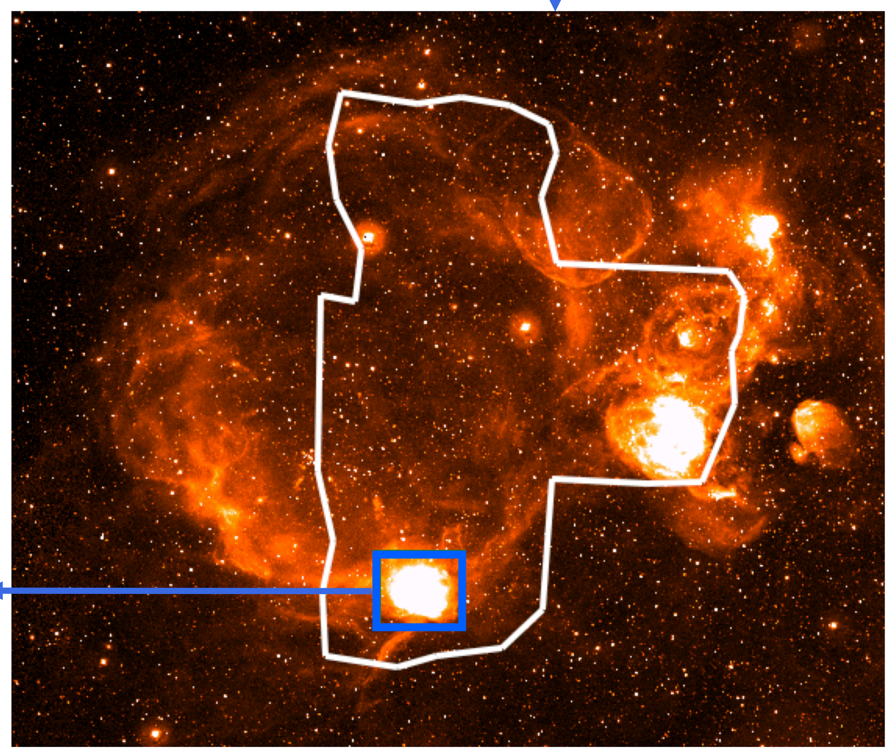


Figure 1 (Right): ***Top:*** HI 21cm image of the SMC from the *Galactic Australian Square Kilometer Array Pathfinder* (image by Helga Denes, Naomi McClure-Griffiths). ***Middle:*** Hα image of NGC 602 and its surroundings in the SMC Wing (hereafter denoted NGC 602+) from the *Magellanic Cloud Emission Line Survey (MCELS)* [5]. The white contour in this image indicates our investigated region. ***Bottom:*** Composite X-ray, optical, and infrared image of NGC 602 (images by Oskinova et al., NASA/STScI, and NASA/JPL-Caltech, respectively).

What can we learn?

- Studying star formation in low-density environments can help us to more clearly define the necessary conditions for stellar birth.
- Given the narrative of NGC 602 as an ideal, isolated laboratory of low-density star formation, an extended study of the SMC Wing will expand our understanding of the environmental conditions that fostered its growth.
- Evidence for a sophisticated stellar history within the SMC Wing may suggest that low-density star formation is driven by interconnected star-forming complexes, rather than isolated, anomalous skyscraper events.

How did we investigate?

Observations

Near-Ultraviolet (NUV):

- **Telescope:** *Galactic Evolution Explorer (GALEX)*
- **Mean wavelength:** 232 nm
- **Resolution:** ~ 5 arcsec
- **Source extraction:** IRAF DAOPHOT
- **Distance correction:** -18.70 : d = 0.055 Mpc
- **Extinction correction:** -0.42 : E(B-V) = 0.052
- **Limitations:** DAOPHOT could not resolve stars in high-density stellar clusters. As a result, they have not been included in this phase of the investigation.

Visible (V):

- **Telescope:** *ESO Danish 1.54m*
- **Mean wavelength:** 550 nm
- **Resolution:** ~ 1.5 arcsec
- **Source extraction:** Braun 2001 [6]
- **Distance correction:** -18.70 : d = 0.055 Mpc
- **Extinction correction:** -0.16 : E(B-V) = 0.052

Additional Information:

- **Source matching:** TOPCAT
- **Faint magnitude cut-off:** NUVo = 1.05 : Applied to avoid high-mass selection biases among dimmer stars.
- **Final stellar count:** ~1100

Photometric Analyses

Color-Magnitude Diagram (CMD): CMDs relate the *observed* temperatures (color) and luminosities (magnitude) of NGC 602+ stars in order to identify their relative ages and evolutionary trends. In ***Figure 2***, blue (NUV-V)o colors and bright NUVo magnitudes reveal significant populations of young, massive stars (skyscrapers), while stars to the right of the main sequence plume give evidence for evolved stars with a range of stellar ages (a desert city).

Isochrone Models: Isochrones describe *simulated* temperatures (color) and luminosities (magnitude) for stars of constant age, quantifying the relative age patterns in CMDs. In ***Figure 2*** we see a significant population of NGC 602+ stars with ages ~30 Myr and a large population of evolved stars. This region most likely experienced a star-forming event ~30 Myr ago, as well as ongoing star formation throughout its recent past.

Spatial Analyses

Brightest Magnitude Bins: We identified three brightest-magnitude bins (***Figure 3: Left***) in order to isolate the youngest NGC 602+ stars and study their relative physical locations. In ***Figure 3: Middle*** the brightest stars (shown in red) cluster toward the left of NGC 602+, whereas stars in fainter magnitude bins (shown in orange and navy) scatter evenly throughout the field. This would indicated that while the youngest stars may have formed in a localized sequential star-forming event, the majority of young stars most likely formed within decentralized star-forming complexes throughout the SMC Wing.

Kernel Density Estimation Clustering: KDE clustering is a non-parametric method for describing density patterns within two-dimensional space. Each point is assigned a value that signifies the degree of local clustering (larger values = higher local density). In ***Figure 3: Right***, two regions of highly-clustered stars (shown in black) emerge as potential areas of localized, sequential star formation.

Defining High-Density Regions: To further investigate these two high-density clumps, we defined their boundaries based on the lowest (least-dense) clustering value at which they split into two distinct regions (threshold clustering value 2.05). ***Figure 4*** shows the locations of the clumps relative to the interstellar gas. As shown, Region I appears to lie in the center of a gaseous supershell, whereas Region II is located at the edge of the same shell and potentially at the intersection of many expanding shells. In ***Figure 5***, Region I appears to encompass brighter, younger stars than Region II. This may be further evidence for sequential star formation or simply expose increased extinction in Region II due to the greater presence of interstellar gas.

What did we find?

Color-Magnitude Diagram and Isochrone Models

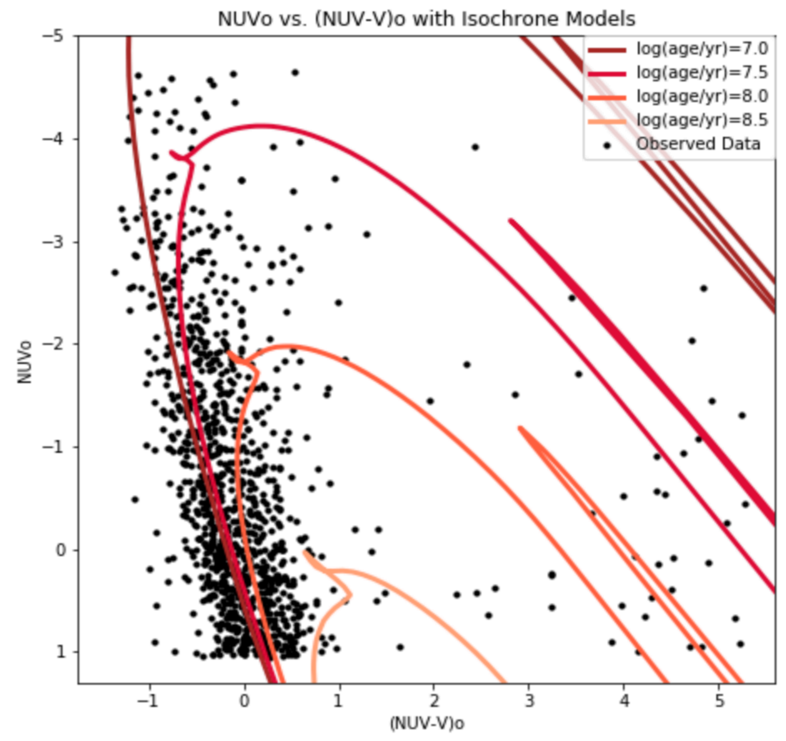
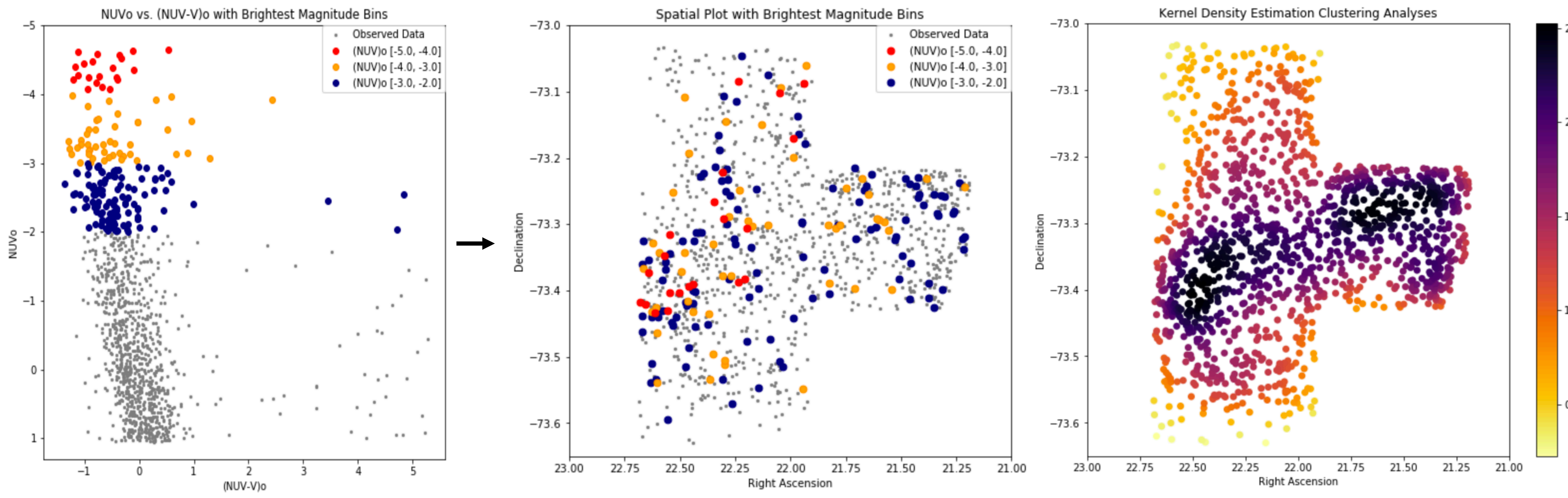


Figure 2 (Right): ***Black points:*** NUVo vs. (NUV-V)o CMD for ~1100 stars in NGC 602+. ***Red tracks:*** Isochrone models for stars of fixed age (see legend), fixed metallicity (Z=0.004), and varying mass (3.0 < $M_\odot$ < 14.0). Isochrones from the University of Padova (stev.oapd.inaf.it/cgi-bin/cmd)

Spatial Analyses

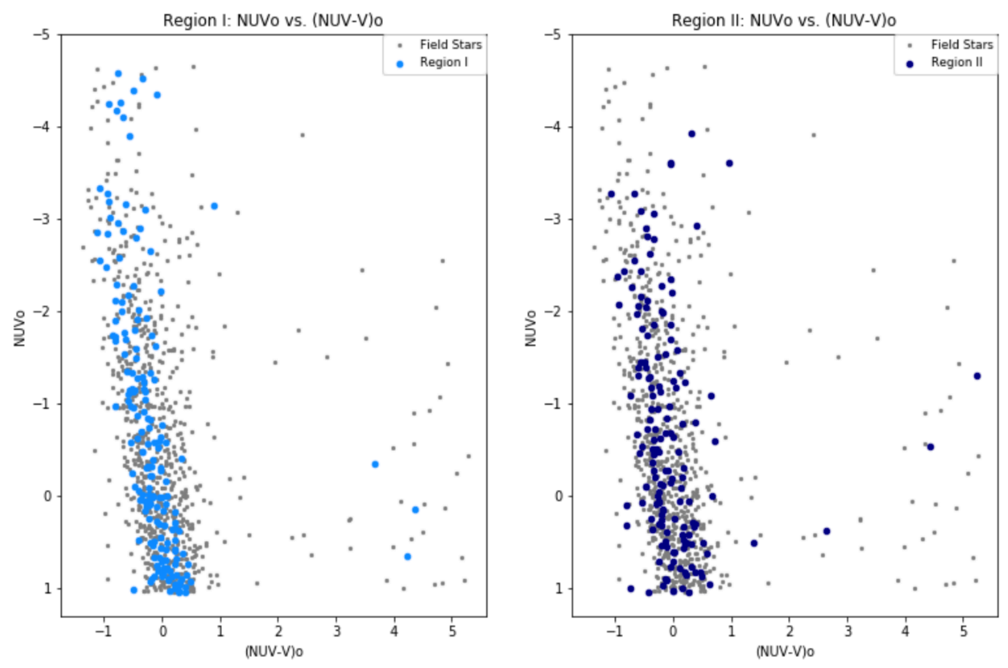
Figure 3 (Below): ***Left:*** NUVo vs. (NUV-V)o CMD highlighting three brightest-magnitude bins (see legend for bin magnitude ranges). ***Middle:*** Spatial plot showing the physical locations of stars according to their assigned bins. ***Right:*** Clustering analyses for all stars within NGC 602+.

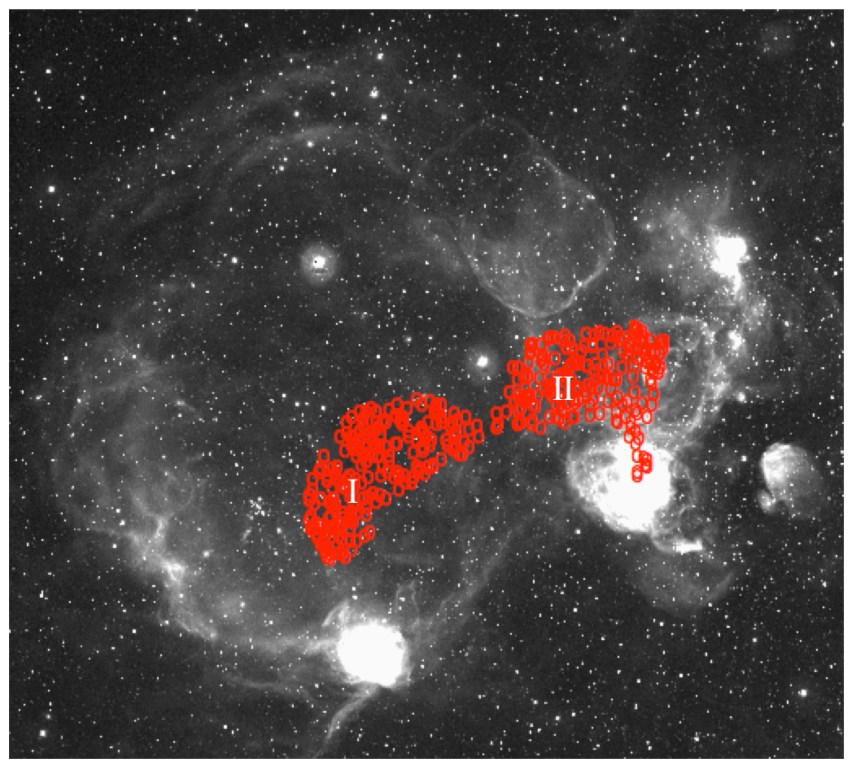


High-Density Regions

Figure 4 (Most Right): ***Image:*** MCELS Hα image of NGC 602+. ***Red circles:*** The two high-density clumps exhibited in Figure 3: *Right*, defined by a threshold clustering value of 2.05 (labeled Regions I and II).

Figure 5 (Immediate Right): NUVo vs. (NUV-V)o CMDs highlighting Region I ***(Left)*** and Region II ***(Right)*** as defined in Figure 4.





What does this mean?

- **Our study reveals a far more extended, complex, and interconnected star formation history than has previously been assumed for the greater SMC Wing.**
- Evidence for massive star formation throughout the SMC Wing and specifically beyond the star cluster NGC 602 encourages us to question the roles of both sequential and decentralized star formation in driving low-density stellar birth.

What's next?

- Further define the relationship between the stellar and gaseous components within this region. Did shell-shell collisions spark the trend of massive star formation in NGC 602+? What initiated shell expansion?
- Understand the impact that high-density star clusters have on our extended study (those too dense for our NUV source extractor to detect). Would inclusion of these clusters change our core results?
- Compare our photometric analysis with spectroscopic investigations of NGC 602+ (Ramachandran+ in preparation).

References:

[1] Westerlund, 1964, MNRAS, 127, 429.
[2] Courtes et. al., 1995, A&A, 297, 338.
[3] Cignoni et. al., 2009, AJ, 137, 3668.
[4] Carlson et.al., 2011, ApJ, 730, 78.
[5] Smith and the MCELS Team, 1998, PASA, 15, 163.
[6] Braun, 2001, yCat, 2232, 0.

Acknowledgements:

We respectfully acknowledge that during the 231st AAS Meeting we are situated on traditional lands of the Pamunkey Indian Tribe and Piscataway Indian Nation. We would like to thank the Universität Potsdam Institut für Physik und Astronomie for supporting a visit to Potsdam, Robert Gruendl and You-Hua Chu for their help with early imaging.