A Complete Census of Star Clusters along their Evolutionary Sequence in the Nearby Universe

Intellectual Merit: One of the main questions Astronomers seek to understand is the life cycle of baryons. The cycle follows molecular clouds of gas condensing to form star clusters, the resulting energy and matter ejected once stars die, and the cooling of the ejected gas back down to molecular clouds. This cycle is ripe for a multitude of areas of study across all wavelengths of astronomical observations. Only recently with the Atacama Large Millimeter/Submillimeter Array (ALMA) and JWST have astronomers been able to focus on the heavily embedded star cluster phases of the baryonic cycle. As the name suggests, these phases occur as star clusters are forming using the molecular gas and dust surrounding them. The gas and dust in turn shroud the clusters from optical observation and even in the infrared. My undergraduate research at the University of Kansas has focused on star clusters in this embedded phase, particularly the star clusters in the nuclear starburst NGC 253. The star clusters in NGC 253 are heavily embedded in dust, extremely compact, and are forming stars rapidly. For this galaxy, we've been able to estimate the mass of the clusters and surrounding gas as well as the temperatures for each of the star clusters. With my work using Band 9 (690 GHz continuum) data from ALMA, we've begun to constrain the properties of the dust surrounding these clusters (Donaghue et al. in prep). The next logical step would then be to compare the properties we derive with the properties of star clusters in a representative sample of galaxies in the local universe,

Until recently however, few galaxies, excluding the Milky Way and its satellites, have comprehensive studies of their star clusters and main star-forming regions at high enough spatial resolution to compare the star clusters between galaxies. This means we lack the information necessary to quantify the extent of how environment-dependent star formation truly is. With the onset of the Physics at High Angular resolution in Nearby GalaxieS (PHANGS) survey, we now have the capability to tackle this problem. PHANGS is a multiwavelength astronomy collaboration aimed at helping us understand the interplay between galaxy structure and evolution with small-scale gas physics and star formation through exploring gas cloud-scale physics of nearby galaxies. PHANGS includes data from ALMA, the Hubble Space Telescope (HST), and has recently expanded to include JWST data. Prior to JWST, embedded clusters were identified by observations of their molecular gas and dust using radio or (sub-)millimeter observations[1,2]. With the angular resolution of JWST, we can now resolve the parsec scales necessary to identify clusters in a representative sample of galaxies out to 20 Mpc. The PHANGS-JWST treasury survey targeted 19 galaxies with prior PHANGS-HST and PHANGS-ALMA and is set to cover a range of star formation, gas, and structural properties [3]. Pilot studies from Whitmore et al. 2023 [4] and Rodríguez et al. 2023 [5] have shown the capabilities of identifying star clusters and their properties from early releases of data from this survey. **I plan to use data from the PHANGS-JWST survey to investigate actively forming star clusters in the nearby universe to build population statistics of star clusters and their surrounding environments. I propose to conduct this research with Dr. Adam Leroy of the Ohio State University, A lead member of the PHANGS collaboration and a leading expert in molecular gas, star formation, and young massive star clusters.** My project consists of three main goals:

1. Identify embedded clusters from PHANGS-JWST data and derive luminosity, mass, and age estimates for clusters.
2. Compare star cluster properties to surrounding gas as observed from PHANGS-ALMA including gas vs stellar mass and cluster position.
3. Compare the properties of the star clusters across PHANGS as a function of the environment.

1. <u>PHANGS-JWST cluster identification</u>: Currently 19 galaxies are being imaged as part of the PHANGS-JWST treasury survey. Rodríguez et al. 2023 laid out a cluster identification scheme using the NIRCam F335M filter which provides the highest resolution image that captures Polycyclic aromatic hydrocarbon (PAH) which is key to identifying embedded clusters. From this procedure, they found 67 dust-embedded clusters in NGC 7496. I would follow a similar procedure while including aperture corrections on the photometry for total source flux which Rodríguez et al. chose to forgo in their pilot

study. The identified clusters in each galaxy would be compared with the clusters identified with PHANGS-HST [6] to have a complete census of star clusters across the evolutionary sequence.

With the clusters identified, I would follow the methods laid out by Rodriguez et al. 2023 and Whitmore et al. 2023, another pilot paper focusing on NGC 1365, to measure the luminosities, stellar masses, and ages of these clusters. With a larger sample, the assumptions made in prior work, such as the power law indices, will be better constrained leading to more accurate measurements of the cluster properties. These properties will provide the basis for which we compare clusters that reside in similar environments.

2. Relation to PHANGS-ALMA: Currently the PHANGS-ALMA survey has a sample of roughly 90 galaxies [7] including the 19 galaxies observed in JWST Cycle 1. The ALMA data specifically measures molecular gas through the CO 2-1 transition which can be used to approximate the gas masses corresponding to the star clusters within the 19 PHANG-JWST galaxies. These measurements along with measurements of the gas cloud structure will allow us to compare and categorize star clusters within the local environment they reside in. Specifically, we can directly compare the mass of the clusters to the mass of the gas surrounding the cluster to test the correlation of the two as a function of age.

3. Compare the properties of the star clusters as a function of the environment: With a comprehensive sample of star clusters in the nearby universe, I will compare the measured properties highlighted above across the sample for similar environments. For initial environment distinctions, I would use current literature classifications such as nuclear starburst, active galactic nuclei, dwarf, etc. With this analysis, we can identify typical vs atypical clusters within given the environment they reside in. This further applies to categorizing clusters not currently a part of PHANGS, i.e. the clusters in NGC 253.

Future Directions: In the coming years, more data will come in to flesh out the population statistics. Observations of an additional 55 galaxies at high resolution are expected to arrive in the next few years as part of the PHANGS-JWST Cycle 2 Treasury program. With these observations, we will not only be able to increase our sample size but will be able to incorporate a wider range of galaxy environments to compare to. A follow-on/expansion to this project would be specifically focusing on galaxies with extreme environments (i.e. undergoing a nuclear starburst or have active galactic nuclei) to see how well JWST observes star clusters in such regions as well as to compare that subsample with the main sample.

Broader Impacts: Having done outreach with the Society of Physics students, I've seen the impact science outreach can have on enthusiasm in STEM fields. As I go into grad school, I intend to continue with outreach for both youth and adults. At Ohio State University, graduate students run an undergraduate mentoring program called Polaris which allows grad students to mentor undergraduates on short projects. I want to expand this to middle school and high schoolers. This would be a summer astronomy camp where middle and high schoolers would apply to the program through a short personal statement of interest and would be selected by a committee of grad students running the program. This camp would follow all youth activity and program policies defined by OSU. Selected students would attend the camp in person, or virtually and would learn basic coding and astronomy, get experience doing simple astronomy research, and have an opportunity to share their work at the end of the summer. All seminars and "lecture" parts of the program would be available to anyone to join virtually. This will help build early interest in STEM and will give youth the opportunity to experience the sense of discovery that makes research so enjoyable. To measure the success of this program, I would include anonymous pre and post-surveys measuring student satisfaction with the program and their growth in coding and in doing research. The results from these surveys would be presented at a professional conference. As a natural extension of the Polaris program, this camp would be handed off to the leadership of this program after I receive my PhD. For adults, I want to push citizen science programs for the larger involvement of the general public. Ohio State also hosts the Arne Slettebak Planetarium, which would allow me to host and run planetarium shows and would pair well with my idea of a youth astronomy camp. The NSF GRFP will help provide me with the resources I need to focus on this research project and to develop my proposed outreach program.

[1] Johnson et al. 2015 [2] Levy et al. 2021 [3] Lee et al. 2023 [4] Whitmore et al. 2023
[5] Rodríguez et al. 2023 [6] Hannon et al. 2023 [7] Leroy et al. 2021