

Accretion and feedback in the gas of galaxy nuclei fundamentally shape their hosts on scales from the central supermassive black hole to the bulge. The gas cycling in and out of galaxy centers can alternately promote and disrupt the growth of central black holes and the buildup of stellar populations, driving galaxy evolution. However, our own Galactic center, which has long been the only nucleus we can resolve, has a quiescent central black hole and low star formation, giving limited insight into these processes. Now, with the advances made possible with the Atacama Large Millimeter Array (ALMA), I am leading the first parsec-scale comparisons of the gas in the Galactic center and a nearby starburst galaxy, a project for which I have already secured NSF funding. **As a professor at Bard, I will build the first sample of resolved galaxy cores to directly probe accretion and feedback processes through their impact on gas properties** while continuing to leverage the proximity of our Galactic center to conduct studies impossible in other galaxies.

My research plans for the next five to ten years are focused on three key areas:

1. Combining the information available in my extensive data sets of Galactic center gas to build a self-consistent model of the three-dimensional position and physical, chemical, dynamical properties of the interstellar medium in this region
2. Comparing our relatively quiescent Galactic center with nearby examples of more active galaxies, to determine where it can and cannot be used as a local laboratory for probing the processes that dominate extreme systems like ultraluminous and high-redshift galaxies
3. Using information from comparisons of Galactic and nearby extragalactic systems to determine how to correctly infer the physical, chemical, and dynamical conditions in resolved gas from observations of unresolved gas in distant extragalactic systems.

1. Connecting Data Sets to Model Galactic Center Gas: As the nearest example of a galaxy nucleus, the center of the Milky Way is the best source for probing the details of the physics that shapes these regions. As our Galactic center hosts a quiescent supermassive black hole and little star formation, it is also potentially an ideal environment for isolating how infall processes impact gas properties in the absence of active feedback. The extreme properties of Galactic center gas are unique in our Galaxy, with uniformly complex chemistry¹, and an order of magnitude higher temperatures²⁻⁴, densities^{5,6}, and turbulence^{7,8} than found in the disk. While many studies (including my own work) have aimed to constrain these properties individually, they are fundamentally interconnected. The next frontier in understanding the gas physics in our Galaxy's center is to integrate these studies to build a self-consistent model of the positional, physical, chemical, and dynamical properties of the gas.

Fundamental to understanding the processes that drive the physical, chemical, and dynamical conditions in this gas is knowing where it is, as these conditions are expected to vary with proximity to the central black hole, depth in the gravitational potential, and exposure to stellar radiation and cosmic rays. In building a coherent model of the Galactic center gas, the first step is to establish its 3D layout so that this can be connected with other gas properties.

Linking 3D positions and gas dynamics: Although we have line-of-sight velocity information for Galactic center gas, this does not map in a straightforward way to a line-of-sight positional coordinate. Thus, additional constraints beyond radial velocities are needed for measuring distances. My work focuses on assembling a suite of independent distance constraints

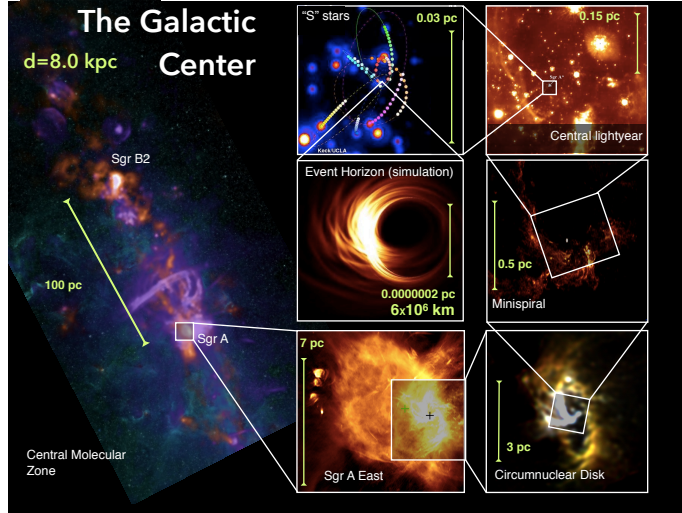


Figure 1: An illustration of the journey that infalling gas takes in the Galactic center.

My research probes the physical, chemical and dynamical properties of gas along this journey, as it flows inward from the hundred parsec scales of the central molecular zone, to the circumnuclear disk: a ring of gas orbiting within a pc of the black hole, to streams of fast-moving ionized and neutral gas even closer in.

A primary goal of my work is to link the three dimensional position of gas in different stages of this journey to its physical and chemical conditions in order to identify the processes that drive extreme gas conditions in this region.

from multiwavelength data sets including X-ray dust echoes⁹, infrared extinction mapping¹⁰, and radio-frequency measurements of the proper motions of masers^{11,12} to break degeneracies in 3D orbital models^{13,14}. Student research topics and senior projects related to this work include:

- Comparing infrared star counts toward individual molecular clouds with models of the 3D stellar distribution in the nuclear bulge to place clouds on the front or back side of gas orbits in the Galactic center.
- Compiling, re-imaging, and cataloging all archival methanol maser data to establish the initial baselines for measuring the 0.05'' per decade Galactic center orbital motions from radio-frequency and ALMA data.
- Searching several of my ALMA data sets for faint molecular gas features that trace gas accretion from the 1 parsec circumnuclear disk inward toward the supermassive black hole.

The research done by my group in this area will determine where the gas is and how it is moving, constraining the rate of gas inflow toward the central parsec (Figure 1), which is a key parameter in determining the future activity of the Galactic center.

Connecting 3D position with physical conditions: Constraining the gas inflow rate also links directly to work I am leading which is connecting the physical conditions in gas clouds to their Galactocentric radius. I am finding that both gas temperature and turbulence increase with proximity to the central supermassive black hole^{3,8}, which suggests that the energy released as clouds move deeper into the Galactic center gravitational potential is driving the extreme conditions observed in this region. As heat in these clouds should quickly dissipate, their temperatures should be defined by rate at which this energy can be injected, or the gas inflow rate. Ultimately, my work is showing that the increase in temperature and turbulence driven by gas inflow must be accounted for when seeking to isolate the effects of feedback on gas properties in more active galaxy cores.

I am also the PI of a 30 hour ALMA program to make the first measurements of gas density structure for a sample of Galactic center clouds. At Bard I will push surveys of temperature and density to the highest resolutions achievable in order to map out the full interconnected thermal structure of gas density, temperature and turbulence in Galactic center gas as a function of scale. Working with me on these projects, students will:

- Investigate data segmentation and clustering algorithms in 2D and 3D to find robust ways to associate different molecular tracers to the same parcel of gas, in order to simultaneously measure its temperature, density, and turbulence.
- Conduct analyses that combine and weight information from multiple different gas tracers to build a multiphase model of Galactic center gas excitation.

Together with my work on the 3D positions of the gas, this research will determine the heating and cooling rates and overall current energy budget of Galactic center gas, which is critical for constraining its potential to form stars.

Matching 3D positions and gas chemistry: The Galactic center has some of the richest chemistry known to exist in the interstellar medium, found in the Sgr B2 star forming cloud¹⁵. However, to understand whether the complex molecules formed in Sgr B2 could exemplify the processes that give rise to the building blocks of life in our own solar system, we need to be able to separate the universal chemistry of star formation from the chemistry unique to its location in the Galactic center. I recently led a study of isotope ratios in the Sgr B2 cloud, finding unusually high ¹⁵N and D abundances that are similar to those found in primitive solar system material^{16,17}. Over the next five years at Bard, my research group will expand Galactic center chemistry studies beyond Sgr B2 to probe the full range of chemistry present in environments with temperature, density and turbulence like high-z galaxies at the peak of star and planet formation¹⁸. Senior projects that will be part of this work include:

- Mining existing archival data to make a radio-frequency chemical inventory of Galactic center gas outside of Sgr B2, focusing on the complex molecules that dominate at these wavelengths
- Measuring rare isotope ratios in Galactic center clouds to determine whether measurements are consistent with the assumption of a constant isotope ratio across this whole region, or show variations due to the infall of less-processed gas.

Joining together all of these pieces, I will construct an interconnected understanding of how gas is inflowing into the Galactic center, undergoing changes in its physical and chemical properties, and contributing to star formation and feeding the central supermassive black hole. This will yield the definitive understanding of the processes of gas inflow in galaxy nuclei. However, the quiescence of the Galactic center means we will have only limited information on processes that drive feedback. To understand the phenomena that govern the more active stages of galaxy evolution, it is then necessary to look to other nearby galaxies.

2. Putting our Galaxy Center in Context: Building a Sample of Galaxy Cores: I am currently constructing a sample of resolved galaxy cores in order to probe how molecular gas conditions change with increased activity. I am leading the first comparison of molecular gas on identical 2 pc size scales in the Galactic center and the nuclear starburst of NGC 253 (see Figure 2; data is in-hand and available for student projects) and I have a 30 hour ALMA PI project to expand this to an additional band to study the excitation. As NGC 253 also lacks an active black hole, these observations will isolate the contribution of the starburst to the gas conditions and directly address the question of whether the processes that set the gas conditions in our own Galactic center are the same as those which dominate in more actively star forming galaxies. Over next five years, the research group I lead will use ALMA and JWST to expand the sample to the cores of a half dozen other major nearby galaxies within 5 Mpc (accessible

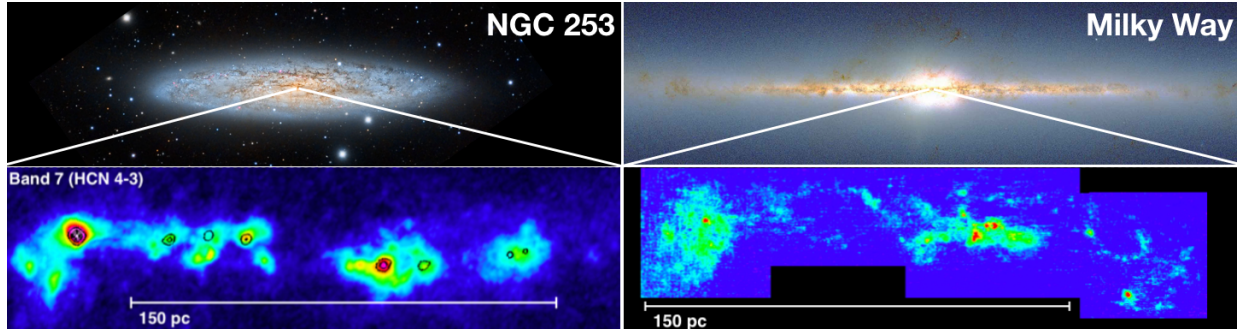


Fig. 2.—: Parsec-scale gas structure in the center of NGC 253 (ALMA) and the Milky Way (ASTE). At Bard, I will use ALMA to lead the the first survey of resolved gas in the cores of spiral galaxies within 5 Mpc

with ALMA) and begin to isolate the effects of AGN, a bar potential, and metallicity. However, as even extreme local galaxies still do not sample the most intense AGN or star formation activity, I will expand this sample over the next ten years, using an identical observational setup comprising multi-band observations of dense gas tracers beyond CO, to include galaxies more representative of high redshift populations.

3. Inferring Gas Properties in Unresolved, Distant Galaxies: As I expand the sample of galaxy cores to more distant sources, one goal will be to identify local regions in more nearby sources (e.g., individual star forming regions, or gas very close to a low-level AGN) that are representative of global conditions in more distant and extreme sources. I will conduct detailed characterization of their chemical and physical conditions that will serve as templates for interpreting progressively less resolved galaxy cores, in order to characterize the most likely conditions of the small scale gas in these objects. However, for these templates to be accurately compared to distant sources, it will be critical to determine how low spatial resolution biases the determination of the physical and chemical conditions¹⁹. My primary goal with this work over the next ten years will be to quantify how accurately the true gas conditions revealed by my sub-parsec scale investigations are reflected in properties inferred from ‘unresolved’ averages over the entire galaxy nucleus. The studies my group will lead will constrain the magnitude of scatter or systematic bias by which the small-scale properties indicative of star formation conditions deviate from the conditions inferred on larger scales. My work will yield the most accurate interpretation of conditions in the star forming gas for galaxies in the early universe. As our own Galactic center will allow the highest resolution probes of star forming gas conditions for comparison with the nucleus-averaged properties, the surveys that I will continue to lead for this region will be critical for accurately interpreting observations of the most distant sources.

- [1] Requena Torres, M.A. et al. 2006, A&A, 455, 971
- [2] Mills & Morris, M.R. 2013, ApJ, 772, 105
- [3] Mills, Togi, A & Kaufman, M. 2017 ApJ 850, 192
- [4] Krieger, N., et al. incl. Mills. 2017 ApJ 850, 77
- [5] Mills, Güsten, R., et al. 2013, ApJ, 779, 47
- [6] Mills, Ginsburg, A., et al. ApJ Accepted
- [7] Shetty, R., et al. MNRAS 2012 425, 720
- [8] Mills, Liu, H-Y. B., et al. In Preparation
- [9] Corrales, L.R., et al. 2017, ApJ, 839, 76
- [10] Mills, Morris, M.R., et al. 2011, ApJ, 735, 84
- [11] Mills, Butterfield, N., et al. 2015, ApJ, 805, 72
- [12] Mills, Ginsburg, A., et al. ApJ submitted
- [13] Kruijssen, J., et al. 2015 MNRAS 447, 1059
- [14] Kruijssen, J. et al. incl. Mills. MNRAS submitted
- [15] Belloche, A. et al. 2008, A&A 482, 179
- [16] Aléon, J. 2010, ApJ 722, 1342
- [17] Mills, Corby, J., et al. ApJ Submitted
- [18] Kruijssen, J. & Longmore 2013 MNRAS 435, 2598
- [19] Mills & Battersby 2017 ApJ 835, 76