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1. Project Summary

***Overview*:** A key area of investigation identified in the 2010 Decadal Survey is what goes on in galaxy centers: the interactions between stars, black holes and gas. Until recently there has only been one galaxy where we can investigate these interactions in detail: the Milky Way, an inactive and relatively sedate galaxy. Now however, the capabilities offered by ALMA make it possible to conduct detailed comparisons of gas properties and interactions in the Milky Way center with those in other galaxy centers. We will conduct the **first comparison of gas properties on identical, parsec scales in the Milky Way center with those in NGC 253, a nearby starburst galaxy**. This project will lead to advances in our understanding of accretion and feedback processes, and produce new templates for molecular gas properties which can be used to interpret unresolved observations of more distant galaxies.

Intellectual Merit: Using new ALMA data of our Galactic center, the PI and a funded graduate student will conduct detailed studies of gas properties to constrain how accretion itself modifies gas conditions, and not just feedback from processes it drives (e.g., starbursts and AGN, which are absent in our Galactic center). By relating the gas properties on sub-parsec scales determined by this study (scales that can only be probed in our own Galaxy center) to the properties on the parsec and larger scales, this work will test how well global properties probed in other galaxies represent the true properties on smaller scales. Ultimately, we will directly compare the properties on parsec scales with new ALMA observations of the nearby galaxy NGC 253 on identical parsec scales. The synthesis of the Milky Way and NGC 253 data will represent the first 'apples to apples' comparison of detailed gas properties in galaxy nuclei: probing how ISM properties change in the presence of a starburst, and advancing our understanding of our Galaxy center beyond an single case study. Finally, this program will produce a library of templates for the extreme gas properties in these nuclei that can be used to interpret conditions in distant, high redshift galaxies.

***Broader Impacts*:** The PI will partner with the BU Prison Education Program to continue to **teach college-level astronomy courses designed to prepare incarcerated students to be part of a strong and diverse STEM-literate workforce**. Courses will focus specifically on key skills for success including mathematical literacy (numeracy) and quantitative reasoning. Learning goals for these courses will additionally incorporate the Next Generation Science Standards (NGSS) for grades 8-12 to address different levels of student preparation, and build a uniform proficiency in STEM. By centering these courses around topics in astronomy, students will additionally have the opportunity to work with real astronomy data, participating in inquiry and project-based learning designed to reproduce authentic scientific experiences. As a part of this program, the PI will develop and distribute equipment-free labs based on these activities that are suitable for other prison classrooms, and provide funding support for up-to-date educational materials for students.

2. Project Description

At just 8 kpc away (Boehle et al. 2016), the center of our Galaxy is relatively easy to explore in detail. At this distance, we can pick out massive clusters (Clarkson et al. 2012; Hußmann et al. 2012; Lu et al. 2013), and their effects on surrounding gas (Lang et al. 1997; Lang et al. 2001), and can even pinpoint the existence of a largely inactive supermassive black hole (Genzel et al. 1996, 1997; Ghez et al. 1998, 2008). As comprehensive as this view seems, our picture is incomplete: to fully probe this environment, we need to examine the molecular gas, the fuel for all future activity, at comparable, arcsecond resolution. Newly built and upgraded radio/mm interferometers like ALMA and the VLA have finally made this possible (e.g., Mills et al. 2015; Rathborne et al. 2015; Battersby et al. 2017).

However, the problem remains that the Galactic center (GC) is the only galaxy nucleus we can explore in detail, and, cosmically speaking, it is extremely boring. Despite hints of past activity (Ponti et al. 2010; Su et al. 2010; Su & Finkbeiner 2012), the supermassive black hole is currently quiescent, and a sizable central reservoir of molecular gas is producing relatively little star formation (Longmore et al. 2013b). We can examine the molecular gas in the GC with exquisite resolution, but if mechanisms suspected to drive black hole growth (through active accretion from a 'torus'; Lynden-Bell 1969; Netzer 2015), feedback and internal quenching of star formation (either from star formation itself or AGN; Diamond-Stanic et al. 2012; Di Matteo et al. 2005) are not currently present, then this scrutiny will not yield new insight into these phenomena.

We propose to undertake the first detailed comparison of the kinematics and excitation of molecular gas in two galaxy nuclei on identical 2 parsec size scales using identical tracers. While our GC is largely inactive, NGC 253 is a nuclear starburst with more than an order of magnitude more star formation, driving a massive molecular outflow (Bolatto et al. 2013). In comparing the two, the sedate nature of the GC will make it possible to disentangle the feedback effects of a pure starburst (like the GC, the black hole at the center of NGC 253 is believed to be quiescent; Müller-Sánchez et al. 2010; Lehmer et al. 2013) from the initial conditions of heating and turbulence naturally present in gas falling in to the central gravitational potential.

Still, present day galaxies like the Milky Way and NGC 253 are far removed from the epochs of peak star formation, black hole growth, and quenching ($z > 1$; Madau et al. 1998; Hasinger et al. 2005; Whitaker et al. 2012). As we are unlikely to ever be able to study distant populations of galaxies with comparable resolution or sensitivity, one approach to better understand their ISM conditions is to identify local analogs which can then be used as proxies for more detailed study. An outcome of this work will be to produce templates for the range of molecular line emission and gas properties present in these sources that can be compared with newly initiated large surveys of molecular gas in local and distant galaxies (e.g., PHANGS and ASPECS; Walter et al. 2016; Leroy et al. 2016).

2.1. Objectives

(1): Probe gas conditions in the GC over 4 orders of magnitude in size scale

- Quantify how accretion modifies temperature and turbulence in galaxy nuclei, independent of feedback from starbursts or AGN, as these processes are largely absent in our GC
- Measure the extent to which physical conditions on the smallest spatial scales deviate from physical conditions averaged over the entire nucleus

(2): Compare the GC and the nucleus of NGC 253 on identical 2 pc size scales

- Measure enhancement in temperature and turbulence in a starburst over those present in an inactive galaxy nucleus
- Test whether current models for the evolution of gas in the central potential of our Galaxy are more universally applicable

(3): Compile properties of the ensemble of gas in the GC and NGC 253

- Compare properties of NGC 253 and GC clouds to individual case studies of embedded super star clusters, AGN, and high-z galaxies
- Make templates of both sources available for comparison with ongoing surveys of molecular gas in galaxies

2.2. Resolving Physical Conditions of Accreting Gas in the Galactic Center

By measuring sub-parsec gas conditions in the Milky Way center, we will characterize extreme gas properties driven purely by global accretion processes and test the extent to which properties inferred from unresolved galaxy observations are representative of the small-scale gas conditions.

2.2.1. Physical Conditions as a Function of Depth in the Central Potential

Measuring the physical conditions of molecular gas in a galaxy nucleus (e.g., its temperature, density, and turbulence) reveals how the processes in this region (e.g. supernovae, AGN) affect the gas reservoir, regulating and eventually shutting off star formation. Feedback processes– such as radiative heating from different AGN modes (e.g., Xie et al. 2017), winds launched from AGN (e.g., Yuan 2016) and energy input from supernovae (Efstathiou 2000) are expected to increase temperature and turbulence of the gas, increasing its stability against gravitational collapse. However in the GC, gas conditions are notably extreme (T>50-400 K, $\sigma > 10$ km/s on 10 pc size scales; Shetty et al. 2012; Mills & Morris 2013; Ginsburg et al. 2016) in the absence of any obviously dominant feedback mechanism.

It has long been suggested that high gas temperatures in the GC are largely driven by the decay of turbulence (Wilson et al. 1982; Rodríguez-Fernández et al. 2004), however there has been no smoking gun. This may recently have been found in observations that link increases in turbulent line widths with increases in temperature (Immer et al. 2016)– though attributing heating to turbulence still does not address the origin of turbulent energy. However, in a new analysis of pure-rotational H_2 lines toward the GC we have shown that gas closer to the black hole is collisionally heated to higher temperatures (Mills et al. 2017), suggesting that ultimately, energy is drawn from gas falling deeper in the gravitational potential. Unfortunately, the low spectral resolution of the H_2 lines used to measure these high temperatures does not resolve line widths, so a definitive link between increased turbulence, temperature, and depth in the central potential can not yet be made.

Under the funded program, we propose to establish the relationship between line width, temperature, and depth in the gravitational potential for gas in the GC. Under this program, we will measure temperatures and line widths of molecular gas at a range of depths in the central potential, using data from projects the PI is leading with the VLA and ALMA (Mills et al. 2014, 2015, Casey-Clyde et al. in prep; see Figure 1). Galactocentric distances of individual clouds will be determined based on their position and velocity relative to orbital models (Kruijssen et al. 2015) and models of the central potential (Feldmeier-Krause et al. 2017). This will allow us to place the gas into at least 3 bins for determining its properties: (1) the circumnuclear disk (CND; $R_{GC} = 5$ pc), (2) Gas with large, CND-like velocities but larger projected radii (R_{GC} = 10-30 pc), and (3) clouds on an orbital ring (R_{GC} = 50-100 pc; the majority of GC clouds; Kruijssen et al. 2015). Correlations between temperature and turbulence between these bins would then confirm a connection between the gravitational potential and the properties of gas defined by its accretion into this potential, showing that extreme conditions in galaxy nuclei can be governed not just by feedback processes in the gas, but simply by its infall. The heating profile derived for the GC as a function of its potential would then establish baseline values of temperature and turbulence that must be exceeded in order to show evidence of feedback

By measuring how physical conditions in the gas change as a function of depth in the gravitational potential, this work will be the first to quantify the baseline extreme conditions present in nuclei simply due to energy liberated by accretion.

2.2.2. Inferred Physical Conditions as a Function of Spatial Resolution

Current advances in sensitivity and bandwidth are making it possible not just to probe sub-parsec scales, but to survey large areas simultaneously in more than a dozen lines (e.g., Jones et al. 2012, 2013; Ginsburg et al. 2016; Krieger et al. 2017). With the ability to both survey the multiple square-degree GC region and probe down to the arcsecond scales that dissect individual molecular clouds, we are now poised to probe gas conditions in the GC over nearly 4 orders of magnitude in size scale, from 0.05 to 300 parsec. This allows us to finally quantify gas conditions on the scales of local star formation in the GC and determine how these would appear when averaged over the entire nucleus of our Galaxy (as it would appear when viewed at extragalactic distances).

In addition to the expected hierarchical density structure of gas from clouds to core scales (e.g., Kainulainen et al. 2014), there are many reasons to also expect properties like temperature inferred on different size scales to vary significantly, particularly in extreme environments. Emission on large scales can be dominated by a cloud envelope which may have substantially different excitation conditions (e.g., as in Sgr B2; Hüttemeister et al. 1995; Ceccarelli et al. 2002) or be diminished by absorption against the continuum (as also seen in Sgr B2; Hüttemeister et al. 1993), or can even be preferentially sensitive to probing particular depths if lines are optically thick, especially if there are strong temperature gradients (Juvela et al. 2012). In particular, for the GC, we have recently shown that a simple measurement of the molecular column density can be significantly underestimated if an observation lacks spatial resolution to detect self absorption due to a strong temperature gradient (Mills & Battersby 2017a).

To quantify the amount by which the temperature and density on small scales vary from the values determined by averaging over the entire the whole nucleus, we will combine sub-parsec observations of individual GC cloud complexes with surveys of the entire GC on parsec size scales. We have already assembled the optimal dataset for determining temperature variations over these scales: a VLA NH_3 survey of clouds with 0.1 pc resolution (Mills et al. 2014, 2015) and a lower-resolution ATCA NH_3 survey covering the entire GC (SWAG; Krieger et al. 2017). In addition, the PI is leading two ALMA projects probing individual GC clouds at resolutions of 0.05-0.14 pc, which in conjunction with public (Jones et al. 2012, 2013) and proprietary (HCN and HC_3N from collaborators Tanaka and Ginsburg) surveys of the entire GC, will allow parallel determination of density variations. Using identical molecular line tracers on each scale, we will measure average line intensities on the typical scales of cores, clumps, clouds, and the entire nucleus. These will form the inputs for excitation analyses, which will be conducted for both LTE and non-LTE assumptions using RADEX (van der Tak et al. 2007) and newly updated collisional coefficients where available (e.g., for NH_3 and HC_3N; Faure et al. 2016; Bouhafs et al. 2017).

By measuring the variation in densities and temperatures determined on a range of scales for the relatively extreme gas conditions in the GC, the results of this work will inform statistical inferences of the physical conditions in extreme extragalactic sources where only low-resolution observations are possible. This will allow probabilistic predictions of the true range of gas temperature and densities on the scales relevant for star formation, based on average source properties, and inform radiative transfer modeling that assumes a density or temperature structure on unresolved, sub-beam scales (Leroy et al. 2017).

By comparing the physical conditions inferred on sub-parsec scales to those inferred from integrated gas properties over the entire GC, **this program will make a key measurement of how well bulk physical conditions (like those inferred from low-resolution observations of other galaxies) represent the small scale conditions relevant for star formation.**

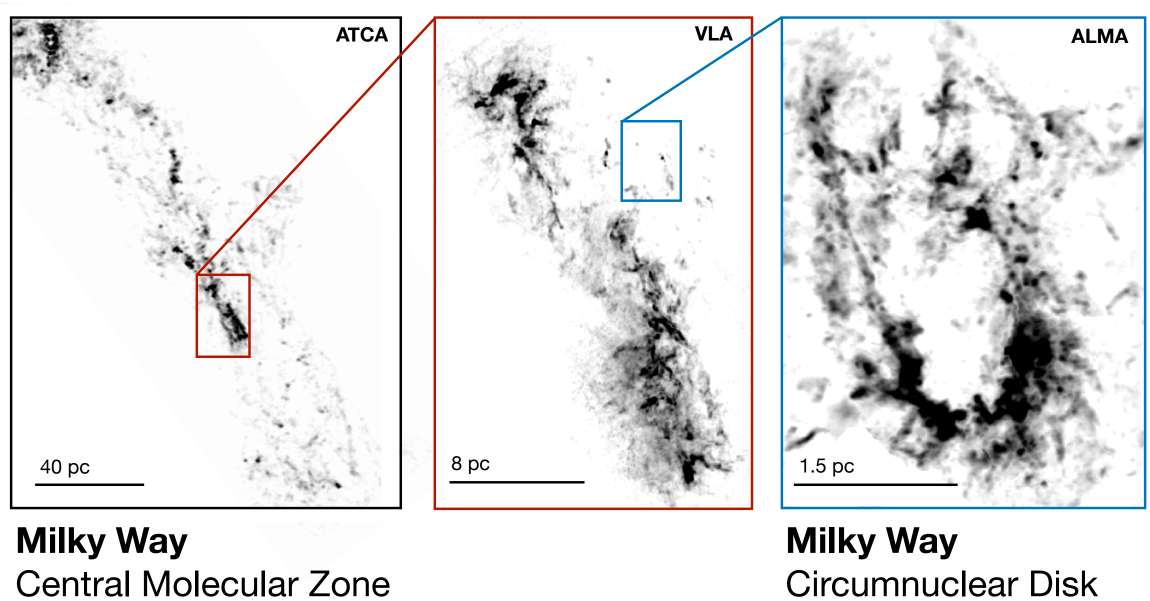

Fig. 1.— An illustration of the data sets to be used in order to probe the variation in physical properties with radius and size scale in the GC. *Left*: SWAG data showing ammonia emission from the entire central 200 pc of the GC. *Center*: VLA data (PI: Mills) showing ammonia emission from a single molecular cloud complex in the GC. *Right*: ALMA data showing HCN emission from the molecular gas surrounding the central supermassive black hole in the GC. Using these data, we will measure how temperature, turbulence, and density vary on sub-cloud scales, and how these properties vary with distance from the black hole and depth into the GC potential.

2.3. Doubling our Sample Size of Resolved Galaxy Nuclei

This work will make the first 'apples to apples' comparison of gas properties in two galaxy nuclei on identical parsec size scales using identical molecular tracers. We will use this to quantify how gas properties vary in the presence of a nuclear starburst and to make direct tests of models predicting the structure and evolution of the central gas concentration.

NGC 253 (3.5 Mpc distant) provides the best opportunity we have to understand how molecular gas feeds intense nuclear activity and subsequently is reshaped by the processes it fuels. Globally, conditions here are unlike anything in our Galaxy. The star formation rate in the central kiloparsec is 3 $M_\odot$/yr (Ott et al. 2005), fueled by a central gas mass of a few 10^8

$M_\odot$ (compare this to a star formation rate of $< 0.1 M_\odot$/year for a few 10^7 $M_\odot$ in the central half-kiloparsec of our own Galaxy; Crocker 2012; Dahmen et al. 1998). Further, as a result of the starburst, there is a massive ($> 10^6$ $M_\odot$) molecular 'superwind' that is expelling gas at a rate equal to or greater than the star formation rate (Bolatto et al. 2013). Using new ALMA observations of the nearby starburst galaxy NGC 253 on subarcsecond size scales (Leroy et al. 2015; Meier et al. 2015, see Figure 2), we can now compare the nucleus of this galaxy with the GC on unprecedentedly small scales.

2.3.1. Comparing Gas Motions

Both the GC and NGC 253 exhibit a nuclear disk of molecular gas in central few hundred parsecs (e.g., Leroy et al. 2015; Launhardt et al. 2002). Like the 100-pc ring of cool dust and dense gas first identified from Herschel observations of our GC (Molinari et al. 2011), NGC 253 also appears to have a central ∼100 pc radius twisted ring of dense gas that can be clearly seen in new images of HCN 4-3 (Figure 2). The dense gas in this ring appears similarly concentrated into compact (∼ 3-10 pc) but massive molecular cloud condensations, the brightest of which appear as intense emission peaks that are co-located with strong dust continuum and radio continuum emission, suggesting that they are embedded protoclusters (Leroy et al. in prep). Initial similarities between the global kinematics of the nuclear star forming ring of NGC 253 and of the Milky Way are striking. Position-velocity plots of both (Figure 2) show a tilted trapezoid structure characteristic of orbits in a bar potential, each having a velocity extent of ±100 km/s around the systemic velocity.

With this work, theoretical predictions that galaxy nuclei go through cycles of episodic star formation based on our own GC (Krumholz & Kruijssen 2015; Krumholz et al. 2017) can be tested by having a second galaxy nucleus observed at comparable resolution to our own. These models predict a characteristic size scale and structure for the nuclear gas, which can be tested by comparing the large-scale kinematic structure of the GC and NGC 253. These same models predict that the mass distribution of nuclear disk gas should be a fundamental discriminant between quiescent and active nuclei. By comparing virial ratios for clouds in both sources, our program will determine whether the observed starburst is consistent with being triggered by global gravitational instability. Further, we will test models of compressional triggering of star formation by comparing the motions of ionized and molecular to search for evidence of an orbital sequence of star formation in this nucleus, as is suggested to exist in the GC (Longmore et al. 2013a; Kruijssen et al. 2015).

These theoretical models also imply that black hole activity and circumnuclear star formation (on < 5 pc scales) and star formation on ∼100 pc scales should not be causally linked. Evidence for this is ambiguous in our own GC, as the young nuclear star cluster around the black hole could be consistent with being coeval with two massive clusters at larger radii (Martins et al. 2008; Liermann et al. 2012; Lu et al. 2013), which Krumholz &

Kruijssen (2015) suggests likely formed in a starburst that ended $\sim$ 5 Myr ago and may also have produced the Fermi bubbles (estimated to be 6-9 million years old; Bordoloi et al. 2017). However, as NGC 253 is currently starbursting, we can more easily test predictions in this source that compact and extended nuclear star formation should not generally be simultaneous. Additionally we will look for kinematic features in the gas connecting embedded star clusters to the nuclear outflow (Bolatto et al. 2013; Walter et al. 2017), testing model predictions that the wind is driven exclusively by the star formation on $\sim$100 pc scales (Krumholz et al. 2017).

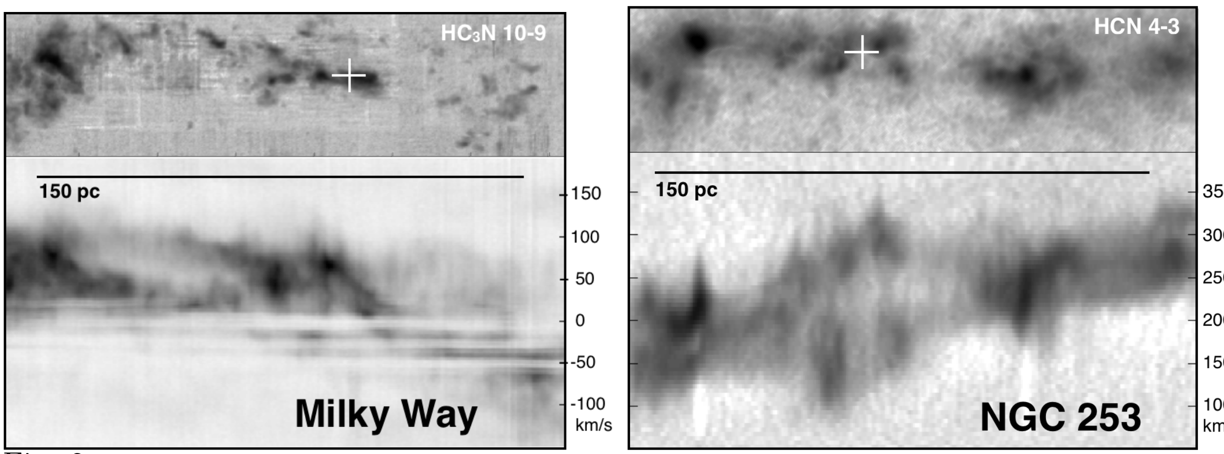

Fig. 2.— A comparison of the kinematics of the GC and NGC 253: *Left*: The molecular gas distribution in the GC. The top panel shows the spatial distribution of gas, seen edge on, as traced by integrated molecular line emission. The bottom panel shows a position-velocity diagram, revealing multiple streams of gas in a bar potential. *Right*: The same information as shown on the left, but now for NGC 253.

2.3.2. Comparing Gas Physical Properties

The nucleus of NGC 253 is more extreme than the GC by at least an order of magnitude in both mass and star formation rate (Ott et al. 2005). However, a superficial comparison of molecular gas tracers shows many general similarities: widespread emission from shock tracers like SiO, hot core tracers like SO, more complex molecules like CH_3SH and NH_2CHO, and dense gas tracers like HC_3N are all seen in both regions (Martin-Pintado et al. 1997; Requena-Torres et al. 2006; Meier et al. 2015; Rathborne et al. 2015). By conducting the first resolved comparison of gas excitation in these sources, this work will go beyond these skin-deep similarities to probe how the temperature, density, and turbulence in these clouds reflect their evolution in the different environments of the GC and NGC 253.

A graduate student funded by this project will conduct robust statistical comparisons of clouds in NGC 253 and the GC by extracting pixel-by-pixel values of mean line intensities, centroid velocities, and velocity dispersions for at least a dozen different molecular tracers. Species for which multiple transitions will be observed in both NGC 253 and the GC include CO, HCN, CS, and HCO^+. We will conduct both LTE analyses and non-LTE RADEX modeling to constrain temperatures on 2-15 pc size scales from H_2CO and CH_3CN in NGC 253, and at a few parsec size scales in the GC from H_2CO, CH_3CN, and NH_3 (Ginsburg et al. 2016; Krieger et al. 2017). Densities will be constrained in the same way on 2-30 pc size scales using HCN, CS, and HCO^+. Here, the temperatures we determine will be used to break the excitation degeneracy between temperature and density which exists for species like HCN, HCO^+, and CS. Cloud masses will additionally be determined from the Band 7 continuum in NGC 253 using the method of Scoville et al. (2016) and from Herschel data in the GC (Mills & Battersby 2017a, Battersby et al. in prep.).

Comparing the temperatures and line widths on identical size scales in both sources, we will investigate the extent to which these properties are elevated in NGC 253, as might be caused by feedback processes unique to the ongoing nuclear starburst here. Comparing the measured masses, we will determine Virial ratios to determine the extent to which clouds in NGC 253 are bound compared to the GC (where all clouds appear bound), or if any of those with embedded star formation may help drive the starburst wind in NGC 253. Finally, with measurements of a wide suite of line ratios in both sources, we will also perform the first search for local analogs for clouds in NGC 253, to see whether any of the most extreme sources seen in the GC (e.g., Sgr B2 or the circumnuclear disk; Lis & Goldsmith 1991; Mills et al. 2013) could be used as proxies for conditions in a nuclear starburst, or whether all of the clouds are wholly different than those seen locally.

In addition to making comparative studies of the two nuclei, with a sample of several dozen resolved compact molecular clouds from both NGC 253 and the GC, we will also make more general inferences about the properties of galaxy nuclei. By comparing the distribution of ionized gas (from recombination lines present in both data sets) and molecular gas, we will measure the existence of evolutionary trends along the orbit (e.g., typical cloud spacings, locations of the most intense star formation, and variations in the amount of shocked gas) to compare with theoretical predictions for gas in a central potential (Kruijssen et al. 2015; Henshaw et al. 2016). Additionally, using measured densities, we will test whether the presence of star formation in each cloud is consistent with a volume-density threshold for star formation in clouds in the strong shearing potential of both of these barred nuclei.

This program will be the first to directly compare parsec-scale physical conditions and gas kinematics in the centers of two galaxies, advancing our understanding of detailed gas flows in galaxy nuclei from a single case study of an inactive nucleus toward a sample of resolved nuclei with varying levels of activity.

2.4. Producing Templates for Interpreting Gas in the Distant Universe

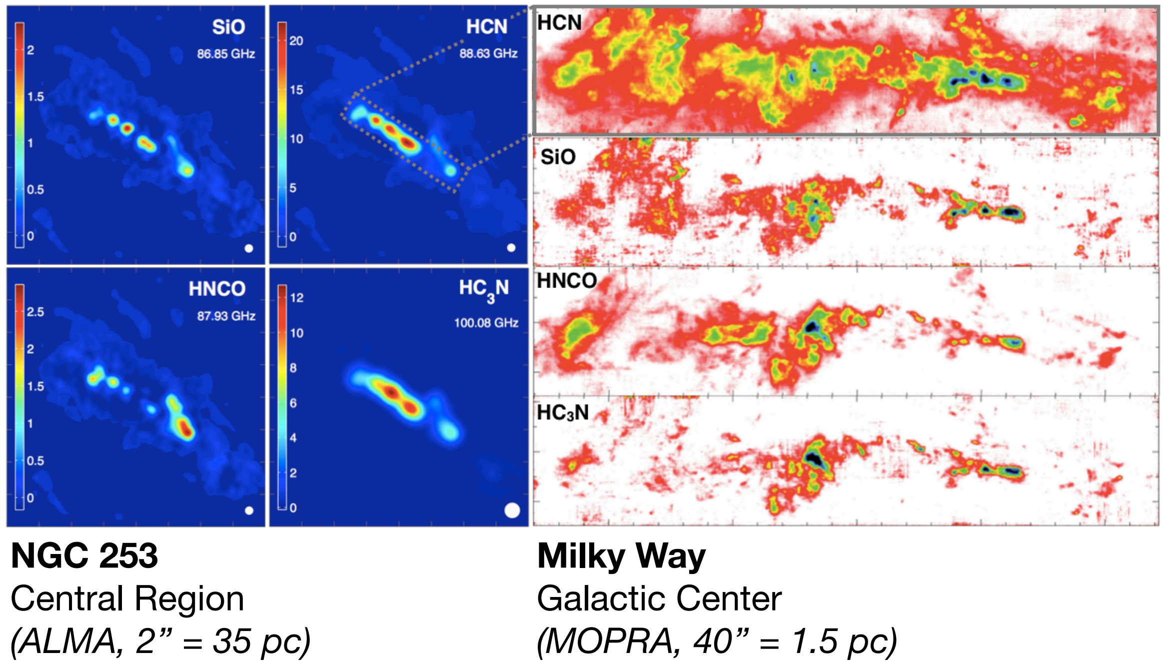

Fig. 3.— Examples of the in-hand data for NGC 253 and the GC. *Left*: A subset of 4 of the 27 lines observed in Band 3 in NGC 253, with 35 pc resolution (Meier et al. 2015). Data from ALMA Cycle 5 proposal would increase this spatial resolution to 2.5 pc, comparable to the GC data *Right*: The same 4 lines (of 20 total) observed in Band 3 toward the GC, from Jones et al. 2013

We will distill the results of these observations into templates (comprised of spectra, line ratios, and representative physical conditions) for NGC 253 and the Galactic center exemplifying both integrated averages and individual exceptional sources, that can be used to identify local analogues to distant sources.

As studies begin to target molecular gas in more and more distant sources, they will preferentially probe gas in extreme environments of luminous sources that are most easily observed at large distances (e.g., submillimeter galaxies, mergers, and ULIRGS). Studying more and more extreme local environments are therefore necessary to correctly interpret observations of individual lines for deriving conditions in more extreme environments of high-z galaxies (e.g., Swinbank et al. 2011). A key deliverable of this project will be the synthesis of all available GC surveys and NGC 253 ALMA data to produce templates of integrated emission in a wide range of lines that are representative of the most locally extreme conditions we can probe.

To construct a template of integrated emission from the GC, we will compile publicly available surveys for spectral lines and continuum, including line surveys at 3 mm and 7 mm (covering 44 transitions from 30 species; Jones et al. 2012, 2013, ; See Figure 3), observations at 350 and 670 μm (3 transitions from CO and [CI]; Martin et al. 2004) and continuum surveys at 1.1 mm (Bally et al. 2010), 450 and 850 μm (Pierce-Price et al. 2000; Csengeri et al. 2016). These will be combined with (currently) proprietary efforts: the 'SWAG' 12 mm line survey for which the PI is a co-lead (covering 20 transitions from 9 species; Ott et al. 2015; Krieger et al. 2017), a 1.4 mm line survey (covering 11 transitions from 9 species, from collaborator Ginsburg; Ginsburg et al. 2016), a Herschel survey of 70-500 μm dust continuum (from collaborator Battersby; Battersby et al. 2011; Mills & Battersby 2017b, ; Battersby et al. in prep.), and maps of individual transitions made available by other collaborators: HCN 4-3 (Collaborator Tanaka; Tanaka et al. 2017), CO 1-0, 2-1 and 3-2 (Collaborator Tanaka; Oka et al. 1998; Oka et al. 1998, 2012), and CS 2-1 and 3-2 (Collaborator Paglione). In all, these data cover multiple transitions of major lines (^{12}CO, ^{13}CO, HCN, CS, SiO, H_2CO, NH_3, and CH_3OH) from 12 mm to 350 μm and thermal continuum from 12 mm to 70 μm.

To construct a template of integrated emission from NGC 253, we will combine existing NGC 253 data in ALMA Bands 3 (3 mm), 6 (1 mm), and 7 (850 μm). These cover continuum emission and at least 95 transitions from > 29 species, including ^{12}CO, ^{13}CO, HCN, CS, SiO, and H_2CO (Bolatto et al. 2013; Leroy et al. 2015; Meier et al. 2015; Krieger et al. 2017, Mills et al. in prep.). Additionally, there are published and archivally-available radio surveys at 8 and 12 mm conducted with the VLA (covering 8 lines of NH_3, H_2O and CH_3OH; Gorski et al. 2017). Unlike the GC, the larger spatial coverage achieved with just a single pointed ALMA or VLA observation of the nucleus of NGC 253 means that for this source, spectra can be integrated on size scales up to the central kiloparsec.

The produced templates will consist of both observational (integrated line intensities, turbulent line widths, and continuum spectral energy distributions), and derived quantities from radiative transfer modeling (temperatures, volume densities, column densities, isotope ratios, and abundances), averaged over the central $\gtrsim$ 300 pc of NGC 253 and the GC. In addition, they will include tables of the same properties derived on 2 pc size scales, as an indication of the range of true small scale properties that these integrated averages represent. These properties will have been already determined in the excitation studies we conduct of both sources; we will focus just on the properties on 2 pc scales averaged over the whole sample of clouds, and the properties of the few most extreme individual sources (e.g., the GC circumnuclear disk, Sgr B2, and protoclusters in NGC 253; Nummelin et al. 2000; Mills et al. 2013, Leroy et al. in prep.)

We will conduct an initial comparison of these different templates to existing sources, quantifying the extent to which, locally or globally, conditions in the GC and NGC 253 can be used as analogs for more extreme galaxies in nearby and distant universe. The produced templates of properties will be compared to observations of e.g., forming globular clusters (e.g., Turner et al. 2003), or deeply buried AGN (e.g., Aalto 2008). to determine where the gas conditions are analogous to those in our own GC or NGC 253, and where we still lack local analogs that can be used as proxies in order to conduct higher-resolution studies of gas properties. Templates will then be made available for comparison with sources in the more distant universe (e.g., ALMA surveys like PHANGS). In particular, they can be used to more probabilistically infer, e.g., gas properties when only a few lines are observed or detected, or the range of resolved, parsec-scale gas properties likely to be present when only low-resolution observations are possible.

This program will connect observations of local galaxies to the distant universe by quantifying the extent to which, locally or globally, the GC and NGC 253 can serve as blueprints for understanding the properties of high redshift galaxies.

3. Methodology & Management

3.1. Overview

- PI Mills has considerable expertise in radio and millimeter interferometry and the study of physical conditions in the GC, and substantial experience supervising undergraduate and graduate students. She will lead the analysis of GC and NGC 253 data sets, focusing on the determination of sub-parsec gas properties in the GC, and the production of integrated template spectra of both objects. PI Mills will additionally supervise and mentor the funded graduate student. As a research professor, she has no teaching or service commitments beyond those described in the broader impacts section of this proposal.
- The funded graduate student will begin working with PI Mills by Summer 2018. They will focus on the comparison of the kinematics and excitation of the GC and NGC 253 data. It is anticipated that they will lead two papers on this work as part of their PhD thesis.

The PI has access to state of the art, ground-based radio and millimeter facilities, with substantial data in hand from both the VLA and ALMA and a demonstrated track record of securing considerable observing time on these telescopes.

3.2. Detailed Work Plan

Table 1 outlines the plan of attack for this project, which is described in detail below.

Year 1: Initial analysis of Galactic center and NGC 253 datasets. Work during this period will focus on the initial analysis of data in hand (described in Facilities, Equipment and Other Resources), and training of a graduate student. The PI will conduct any necessary data calibration and imaging, and will focus on the analysis of all GC data, producing a study of how physical conditions vary with size and position in the nucleus. In parallel, the graduate student funded by this project will focus on data from just a single line (HCN 4-3) in both the GC and NGC 253 to conduct a comparison of their kinematics on 2 pc size scales, and make an initial presentation of results at a Winter AAS meeting. The following papers are to be written in Year 1:

- *Paper 1:* Variation of physical conditions in GC gas as a function of depth in the central potential, and how the derived physical conditions change when viewed at different resolutions.
- *Paper 2 (letter):* Comparison of kinematics in NGC 253 and the GC (Led by graduate student)

Year 2: Detailed synthesis and comparison of datasets. In the second year, the emphasis will be on conducting radiative transfer modeling to derive physical conditions from gas excitation parameters in both NGC 253 and the Galactic center. The PI will focus on compiling observational and model results into a series of templates for public distribution, while the graduate student will focus on the detailed comparison of gas properties in these two sources. At the end of the year, both the PI and graduate student will present results from this project at an international conference. The following papers are to be written in Year 2:

- *Paper 3:* Comparison of excitation in NGC 253 and the GC (Led by graduate student)
- *Paper 4:* Templates for the extreme gas properties in NGC 253 and the GC, exemplifying both integrated average molecular line properties and those for individual exceptional sources

Table 1: Timeline & Work Plan

	2018–2019	**2019–2020**
Summer	Imaging of Cycle 5 ALMA observations Begin working with Graduate Student Prepare paper on resolved GC gas conditions Broader Impacts (BI): Develop lab activities	Prepare proprietary imaging data for public release Imaging of Cycle 6 and archival ALMA observations Analysis of GC excitation data BI: Refine Astronomy lab activities
Fall	Analysis of GC / NGC 253 kinematics **Publish paper on resolved GC gas conditions** BI: Teach Astronomy at MCI Norfolk	Analysis of GC temperature, turbulence, density gradients Analysis of NGC 253 excitation data BI: Teach Astronomy at MCI Norfolk
Winter	Prepare letter on NGC 253 physical conditions Prepare letter on GC / NGC 253 kinematics Present initial results at Winter AAS BI: Rework Astronomy lab activities	Release proprietary imaging data from ALMA campaigns Prepare paper on GC / NGC 253 excitation Prepare paper on GC / NGC 253 template spectra BI: Publicly release Astronomy lab activities
Spring	**Publish letter on GC / NGC 253 kinematics** **Publish letter on NGC 253 physical conditions** BI: Teach Astronomy at MCI Norfolk	**Publish paper on GC / NGC 253 template spectra** **Publish paper on GC / NGC 253 excitation** Present results at an International Conference BI: Teach Astronomy at MCI Norfolk

3.3. Perceived Impact

1) **Accretion in Galaxy Nuclei:** This work will address the *New Worlds, New Horizons* question of how baryons cycle in to galaxies by making the first comparison of molecular gas on identical 2 pc size scales using identical tracers in two galaxy nuclei: the Milky Way and NGC 253. As the first 'apples-to-apples' comparison of nuclei on these size scales, this work will provide a critical test of whether current models (e.g., Krumholz & Kruijssen 2015; Krumholz et al. 2017) for the flow of gas in the central potential of our Galaxy are more universally applicable to the evolution of nuclei in general. Additionally, we will quantify for the first time how the accretion process enhances temperature and turbulence in galaxy nuclei, independent of feedback from starbursts or AGN, providing a key baseline for the interpretation of more active sources.

2) **Feedback in Galaxy Nuclei:** Complementary to our studies of accretion, this work will address the *New Worlds, New Horizons* question of how baryons cycle out of galaxies by comparing gas properties in the currently quiescent (Milky Way) and actively starbursting (NGC 253) nucleus. As both galaxies lack an active black hole, this comparison will isolate the unique effects of star formation feedback by quantifying enhancement in temperature and turbulence in the starburst nucleus of NGC 253 compared to the Milky Way. With the first high-resolution look at gas in a nearby starburst, we will also isolate individual sources driving the molecular outflow, and compare this to theoretical models of wind launching (Krumholz et al. 2017).

3) **High Redshift Galaxies:** Telescopes like ALMA are allowing for molecular tracers to be used at greater cosmological distances, probing ever more extreme sources (e.g., at z=3 in SDP.81, Rybak et al. 2015). This work will address the important challenge of determining how average gas properties, derived from low-resolution observations of a few bright lines, are related to the true physical conditions in these environments As a key deliverable of this project, we will compile observed and derived properties of NGC 253 and the GC to make available templates for extreme gas that will be an important touchstone for interpreting surveys of gas in distant galaxies.

4. Broader Impacts: Prison Education

To **increase public scientific literacy, public engagement with science and technology, and contribute to a diverse and well-educated STEM workforce**, The PI will continue a program of teaching through the Boston University Prison Education Program (BU-PEP). This program will:

- ***Design and teach math/physics-intensive introductory astronomy courses;***
- ***Provide students with modern textbooks; and***
- ***Develop and distribute a series of equipment-free astronomy lab activities.***

4.1. The Importance of STEM in Prison Education

In the United States, it is estimated that there are nearly 2.3 million people incarcerated - 0.7% of the US population (The Prison Policy Initiative), with more than half of these (1.3 million) in state prisons. The educational attainment of the incarcerated population is significantly below the average level in this country: according to Harlow 2003 in a Bureau of Justics Statistics study, 68% of State prison inmates had not previously received a high school diploma (compared to an overall rate of 12% among adult respondents in the 2015 US census). As of 2017, 95% of those incarcerated in state facilities will eventually be reintegrated into society (Hughes and Wilson, Bureau of Justice Statistics), and studies have shown providing them with educational opportunities has transformative effect: reducing recidivism, and increasing post-release employment (Davis et al. 2013; Rand Research Report).

STEM literacy plays a major role in current job opportunities. As an example, nearly half of the current job openings in Massachusetts require a college degree, and nearly half of those jobs require strong STEM knowledge and skills (Massachusetts plan for Excellence in STEM Education). Providing college-level STEM education in prisons can be an important part of building a strong and diverse STEM workforce.

4.2. Using Astronomy to Teach Students Math and Physics

Through this grant, the PI will make Astronomy courses a consistent presence in BU-PEP, using these courses as a medium for reinforcing math skills and teaching introductory physics concepts. Given the limited instructional time available (2 hours once a week, for 11-12 weeks), the PI will design two stand-alone courses, each covering a different aspect of introductory astronomy. These courses will provide consistent STEM opportunities for students, as currently, college-level math and physics courses are only offered intermittently.

The first course will cover topics from stars to cosmology, focusing on the scale, structure, and history of the universe. Topics will be chosen to reinforce key mathematics skills each week, including fractions (e.g., using the Drake equation to determine the possible number of advanced civilizations in our Galaxy), calculating with time (placing events on the timeline of our universe), percentages (e.g., the mass/energy makeup of the universe), and estimates and approximations (e.g., how long would it take to send a camera outside of our Galaxy?). The PI will adapt the QUARCS survey of numeracy (Follette et al. 2015) to assess student learning outcomes.

The second course will cover the nature, formation, and exploration of our solar system. It will primarily be designed to emphasize introductory physics topics, including gravity (shaping solar system objects and guiding their motion), angular momentum (the formation of the solar system), projectile motion (launching spacecraft for exploration), and thermodynamics (the effects of atmospheres and the greenhouse effect on planetary temperatures). A key goal will be to make connections between these concepts and real-life experiences.

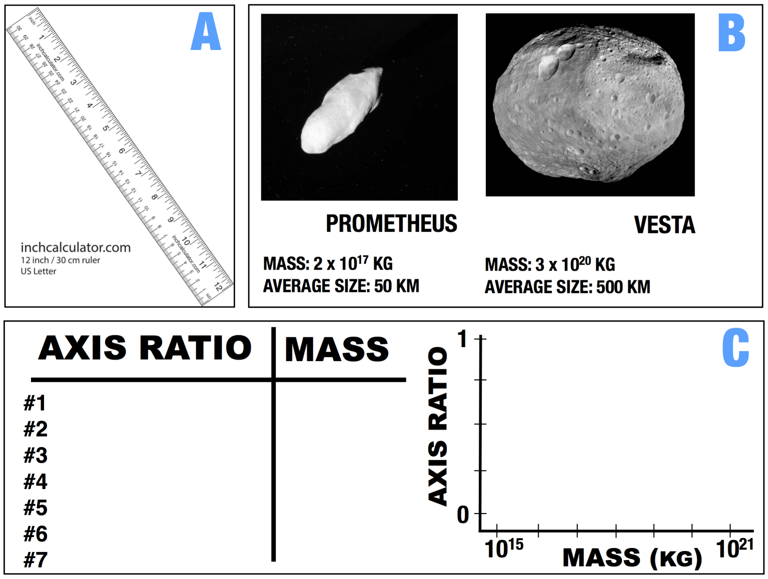

Figure 4 **Sample from an astronomy lab investigating the scales on which gravity shapes objects in the solar system**, showing the components of typical content to be developed under this award **A:** Any required equipment can be included in the printed materials of the activity; **B:** Students will work with actual astronomical images and data; **C:** Activities will progressively develop student skills in the interpretation and analysis of quantitative data.

Basing these courses around astronomy is a choice that not only gives students an approachable introduction to STEM: a topic full of unknowns to speculate about, but also offers the unifying experience for students to participate in its investigations in much the same way as scientists do: studying distant objects from anywhere on earth. I plan to emphasize this aspect by bringing in current data (e.g. survey images from this project) for students to explore and participate in qualitative analysis of trends and patterns.

4.3. Providing Students with Modern Textbooks and Library Materials

From the discovery of potentially habitable exoplanets to the detection of gravitational waves, astronomy is quickly changing. This necessitates up-to-date educational materials, especially given the limitations placed on access to outside information for incarcerated students. At MCI-Norfolk, the facility where the PI currently teaches, students have no internet access. Their primary access to current science is magazines and newspapers. Through this grant, students at MCI-Norfolk will be provided with modern astronomy textbooks. It will also provide current, popular science books to prison libraries in the Massachusetts State Correctional System, enabling independent student learning.

4.4. Developing and Distributing a Series of Equipment-Free Lab Activities

As part of this grant, the PI will design and distribute a series of lab-style activities to bring interaction and inquiry into classrooms where it is not possible to have a traditional lab setup. Development of these materials will build on the PI's past experience developing inquiry-based classroom activities. To allow for maximal distribution of these materials, they will not require equipment beyond the printed materials (See Figure 4).

5. Results from Prior NSF Work

N/A

REFERENCES

Aalto, S. 2008, Ap&SS, 313, 273

Bally, J., Aguirre, J., Battersby, C., et al. 2010, ApJ, 721, 137

Battersby, C., Bally, J., Ginsburg, A., et al. 2011, A&A, 535, A128

Battersby, C., Keto, E., Zhang, Q., et al. 2017, in IAU Symposium, Vol. 322, The Multi-Messenger Astrophysics of the Galactic Centre, ed. R. M. Crocker, S. N. Longmore, & G. V. Bicknell, 90–94

Boehle, A., Ghez, A. M., Schödel, R., et al. 2016, ApJ, 830, 1

Bolatto, A. D., Warren, S. R., Leroy, A. K., et al. 2013, Nature, 499, 450

Bordoloi, R., Fox, A. J., Lockman, F. J., et al. 2017, ApJ, 834, 191

Bouhafs, N., Rist, C., Daniel, F., et al. 2017, MNRAS, 470, 2204

Ceccarelli, C., Baluteau, J.-P., Walmsley, M., et al. 2002, Astronomy and Astrophysics, 383, 603

Clarkson, W. I., Ghez, A. M., Morris, M. R., et al. 2012, The Astrophysical Journal, 751, 132

Crocker, R. M. 2012, in IAU Symposium, Vol. 284, IAU Symposium, ed. R. J. Tuffs & C. C. Popescu, 371–378

Csengeri, T., Weiss, A., Wyrowski, F., et al. 2016, A&A, 585, A104

Dahmen, G., Huttemeister, S., Wilson, T. L., & Mauersberger, R. 1998, A&A, 331, 959

Di Matteo, T., Springel, V., & Hernquist, L. 2005, Nature, 433, 604

Diamond-Stanic, A. M., Moustakas, J., Tremonti, C. A., et al. 2012, ApJ, 755, L26

Efstathiou, G. 2000, MNRAS, 317, 697

Faure, A., Lique, F., & Wiesenfeld, L. 2016, MNRAS, 460, 2103

Feldmeier-Krause, A., Zhu, L., Neumayer, N., et al. 2017, MNRAS, 466, 4040

Follette, K. B., McCarthy, D. W., Dokter, E., Buxner, S., & Prather, E. 2015, ArXiv e-prints, arXiv:1507.03997

Genzel, R., Eckart, A., Ott, T., & Eisenhauer, F. 1997, MNRAS, 291, 219

Genzel, R., Thatte, N., Krabbe, A., Kroker, H., & Tacconi-Garman, L. E. 1996, ApJ, 472, 153

Ghez, A. M., Klein, B. L., Morris, M., & Becklin, E. E. 1998, ApJ, 509, 678

Ghez, A. M., et al. 2008, ApJ, 689, 1044

Ginsburg, A., Henkel, C., Ao, Y., et al. 2016, A&A, 586, A50

Gorski, M., Ott, J., Rand, R., et al. 2017, ApJ, 842, 124

Hasinger, G., Miyaji, T., & Schmidt, M. 2005, A&A, 441, 417

Henshaw, J. D., Longmore, S. N., & Kruijssen, J. M. D. 2016, MNRAS, 463, L122

Hußmann, B., Stolte, A., Brandner, W., Gennaro, M., & Liermann, A. 2012, Astronomy and Astrophysics, 540, A57

Hüttemeister, S., Wilson, T. L., Henkel, C., & Mauersberger, R. 1993, A&A, 276, 445

Hüttemeister, S., Wilson, T. L., Mauersberger, R., et al. 1995, Astronomy and Astrophysics (ISSN 0004-6361), 294, 667

Immer, K., Kauffmann, J., Pillai, T., Ginsburg, A., & Menten, K. M. 2016, A&A, 595, A94

Jones, P. A., Burton, M. G., Cunningham, M. R., Tothill, N. F. H., & Walsh, A. J. 2013, MNRAS, 433, 221

Jones, P. A., Burton, M. G., Cunningham, M. R., et al. 2012, MNRAS, 419, 2961

Juvela, M., Harju, J., Ysard, N., & Lunttila, T. 2012, A&A, 538, A133

Kainulainen, J., Federrath, C., & Henning, T. 2014, Science, 344, 183

Krieger, N., Ott, J., Beuther, H., et al. 2017, ArXiv e-prints, arXiv:1710.06902

Kruijssen, J. M. D., Dale, J. E., & Longmore, S. N. 2015, MNRAS, 447, 1059

Krumholz, M. R., & Kruijssen, J. M. D. 2015, MNRAS, 453, 739

Krumholz, M. R., Kruijssen, J. M. D., & Crocker, R. M. 2017, MNRAS, 466, 1213

Lang, C. C., Goss, W. M., & Morris, M. 2001, AJ, 121, 2681

Lang, C. C., Goss, W. M., & Wood, D. O. S. 1997, Astrophysical Journal v.474, 474, 275

Launhardt, R., Zylka, R., & Mezger, P. G. 2002, A&A, 384, 112

Lehmer, B. D., Wik, D. R., Hornschemeier, A. E., et al. 2013, ApJ, 771, 134

Leroy, A. K., Bolatto, A. D., Ostriker, E. C., et al. 2015, ApJ, 801, 25

Leroy, A. K., Hughes, A., Schruba, A., et al. 2016, ApJ, 831, 16

Leroy, A. K., Usero, A., Schruba, A., et al. 2017, ApJ, 835, 217

Liermann, A., Hamann, W.-R., & Oskinova, L. M. 2012, A&A, 540, A14

Lis, D. C., & Goldsmith, P. F. 1991, ApJ, 369, 157

Longmore, S. N., Kruijssen, J. M. D., Bally, J., et al. 2013a, ArXiv e-prints, arXiv:1304.2397

Longmore, S. N., Bally, J., Testi, L., et al. 2013b, MNRAS, 429, 987

Lu, J. R., Do, T., Ghez, A. M., et al. 2013, ApJ, 764, 155

Lynden-Bell, D. 1969, Nature, 223, 690

Madau, P., Pozzetti, L., & Dickinson, M. 1998, ApJ, 498, 106

Martin, C. L., Walsh, W. M., Xiao, K., et al. 2004, ApJS, 150, 239

Martin-Pintado, J., de Vicente, P., Fuente, A., & Planesas, P. 1997, ApJ, 482, L45+

Martins, F., Hillier, D. J., Paumard, T., et al. 2008, A&A, 478, 219

Meier, D. S., Walter, F., Bolatto, A. D., et al. 2015, ApJ, 801, 63

Mills, E. A. C., & Battersby, C. 2017a, ApJ, 835, 76

—. 2017b, ApJ, 835, 76

Mills, E. A. C., Butterfield, N., Ludovici, D. A., et al. 2015, ApJ, 805, 72

Mills, E. A. C., Güsten, R., Requena-Torres, M. A., & Morris, M. R. 2013, The Astrophysical Journal, 779, 47

Mills, E. A. C., Lang, C. C., Morris, M. R., et al. 2014, in IAU Symposium, Vol. 303, IAU Symposium, ed. L. O. Sjouwerman, C. C. Lang, & J. Ott, 139–143

Mills, E. A. C., & Morris, M. R. 2013, ApJ, 772, 105

Mills, E. A. C., Togi, A., & Kaufman, M. 2017, ArXiv e-prints, arXiv:1701.04826

Molinari, S., Bally, J., Noriega-Crespo, A., et al. 2011, ApJ, 735, L33

Müller-Sánchez, F., González-Martín, O., Fernández-Ontiveros, J. A., Acosta-Pulido, J. A., & Prieto, M. A. 2010, ApJ, 716, 1166

Netzer, H. 2015, ARA&A, 53, 365

Nummelin, A., Bergman, P., Hjalmarson, Å., et al. 2000, ApJS, 128, 213

Oka, T., Hasegawa, T., Hayashi, M., Handa, T., & Sakamoto, S. 1998, Astrophysical Journal v.493, 493, 730

Oka, T., Hasegawa, T., Sato, F., Tsuboi, M., & Miyazaki, A. 1998, ApJS, 118, 455

Oka, T., Onodera, Y., Nagai, M., et al. 2012, ApJS, 201, 14

Ott, J., Meier, D., & Mills, E. 2015, IAU General Assembly, 22, 57227

Ott, J., Weiss, A., Henkel, C., & Walter, F. 2005, ApJ, 629, 767

Pierce-Price, D., et al. 2000, The Astrophysical Journal, 545, L121

Ponti, G., Terrier, R., Goldwurm, A., Belanger, G., & Trap, G. 2010, ApJ, 714, 732

Rathborne, J. M., Longmore, S. N., Jackson, J. M., et al. 2015, ApJ, 802, 125

Requena-Torres, M. A., Martin-Pintado, J., Rodríguez-Franco, A., et al. 2006, Astronomy and Astrophysics, 455, 971

Rodríguez-Fernández, N. J., Martín-Pintado, J., Fuente, A., & Wilson, T. L. 2004, A&A, 427, 217

Rybak, M., Vegetti, S., McKean, J. P., Andreani, P., & White, S. D. M. 2015, MNRAS, 453, L26

Scoville, N., Sheth, K., Aussel, H., et al. 2016, ApJ, 820, 83

Shetty, R., Beaumont, C. N., Burton, M. G., Kelly, B. C., & Klessen, R. S. 2012, MNRAS, 425, 720

Su, M., & Finkbeiner, D. P. 2012, ApJ, 753, 61

Su, M., Slatyer, T. R., & Finkbeiner, D. P. 2010, ApJ, 724, 1044

Swinbank, A. M., Papadopoulos, P. P., Cox, P., et al. 2011, ApJ, 742, 11

Turner, J. L., Beck, S. C., Crosthwaite, L. P., et al. 2003, Nature, 423, 621

van der Tak, F. F. S., Black, J. H., Schöier, F. L., Jansen, D. J., & van Dishoeck, E. F. 2007, A&A, 468, 627

Walter, F., Decarli, R., Aravena, M., et al. 2016, ApJ, 833, 67

Walter, F., Bolatto, A. D., Leroy, A. K., et al. 2017, ApJ, 835, 265

Whitaker, K. E., Kriek, M., van Dokkum, P. G., et al. 2012, ApJ, 745, 179

Wilson, T. L., Ruf, K., Walmsley, C. M., et al. 1982, A&A, 115, 185

Xie, F.-G., Yuan, F., & Ho, L. C. 2017, ApJ, 844, 42

Yuan, F. 2016, in Astrophysics and Space Science Library, Vol. 440, Astrophysics of Black Holes: From Fundamental Aspects to Latest Developments, ed. C. Bambi, 153

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BIOGRAPHICAL SKETCH

Elisabeth A. C. Mills

Professional Preparation:

Indiana University: Physics, Astronomy B.S. – 2007
University of California, Los Angeles: Astronomy M.S. – 2009
University of California, Los Angeles: Astronomy Ph.D. – 2013

Appointments:

National Radio Astronomy Observatory: Jansky Postdoctoral Fellow 2013- 2016
San Jose State University: Assistant Professor 2016- 2017
Boston University: Assistant Research Professor 2017-Present

Selected Awards and Honors:

2017 SJSU Research, Scholarship, and Creative Activity Award
2010 NSF GK-12 Fellowship
2007 UCLA Chancellor's Prize

Related Publications:

1. Mills, E.A.C. and Battersby, C *Origins of Scatter in the Relationship Between HCN 1-0 and Dense Gas Mass in the Galactic Center* 2017, ApJ, 835:76-89

2. Mills, E.A.C., Güsten, R., Requena-Torres, M.A., Morris, M.R. *The Excitation of HCN and HCO^+ in the Galactic Center Circumnuclear Disk.* 2013, ApJ, 779:47-67

3. Krieger, N., Ott, J., Beuther, H., Walter, F., Kruijssen, J.M.D., Meier, D.S., **Mills, E.A.C.**, Contreras, Y., Edwards, P., Ginsburg, A., Henkel, C., Henshaw, J., Jackson, J., Kauffmann, J., Longmore, S., Martín, S., Morris, M.R., Pillai, T., Rickert, M., Rosolowsky, E., Shinnaga, H., Walsh, A., Yusef-Zadeh, F., Zhang, Q. *"The Survey of Water and Ammonia in the Galactic Center (SWAG): Molecular Cloud Evolution in the Central Molecular Zone"*. ApJ Accepted.

4. Mills, E.A.C., Morris, M.R. *Detection of Widespread Hot Ammonia in the Galactic Center.* 2013, ApJ, 772:105-124

5. Henshaw, J.D., Longmore, S.N., Kruijssen, J.M.D., Battersby, C., Moore, T.J.T., Burton, M., Ott, J., Dale, J., Pillai, T., Ginsburg, A., Schmiedeke, A., Davies, B., Kendrew, S., **Mills, E.A.C.**, Walker, D., Barnes, A., Immer, K., Zhang, Q. *Molecular gas kinematics within the central 250 pc of the Milky Way* 2016 MNRAS, 457:2675-2702

Other Significant Publications:

1. Mills, E.A.C., Togi, A., Kaufman, M. *Hot Molecular Gas in the Circumnuclear Disk.* ApJ Accepted.

2. Mills, E.A.C., Lang, C.C., Butterfield, N., Ludovici, D.A., Schmitz, S., Ott, J., Morris, M.R. *Abundant CH_3OH Masers but no New Evidence for Star Formation in GCM0.253+0.016.* 2015, ApJ, 805:72-97

3. Mills, E.A., Morris, M.R., Lang, C.C., Cotera, A., Dong, H., Wang, Q.D., Stolovy, S.*Properties of the Compact H II Regions G-0.02-0.07.* 2011, ApJ, 735:84-96

4. Ginsburg, A., Ao, Y., Riquelme, D., Kauffmann, J., Pillai, T., **Mills, E.A.C.**, Requena-Torres, M.A., Immer, K.,Testi, L., Ott, J., Bally, J., Battersby, C., Darling, J., Aalto, S., Stanke, T., Kendrew, S., Kruijssen, J.M.D., Longmore, S., Dale, J., Guesten, R., Menten, K.M. *Dense gas in the Galactic central molecular zone is warm and heated by turbulence* 2016 A&A, 586:50-81

5. Butterfield, N., Lang, C.C., Morris, M.R., **Mills, E.A.C.**, Ott, J. *GCM-0.20+0.033: An Expanding Molecular Shell in the Galactic Center Radio Arc.* ApJ Accepted.

Synergistic Activities:

2017-2020 Member, FIR Science Interest Group Leadership Council

2017–2019 Science Review Panelist for ALMA proposals

2017–Present Instructor, BU Prison Education Program

- Co-teaching an introductory astronomy course for students at MCI-Norfolk

2010–2011 NSF GK-12 Fellow at Culver City Middle School, Culver City, CA

- Taught in the classroom two days a week with a local teacher
- Created new lesson materials to enhance the classroom science curriculum

2007–2009 Center for Adaptive Optics (now ISEE), Santa Cruz, CA

- Developed and taught inquiry-based astronomy programs
- Participated in workshops on inquiry in science, engineering, learning and teaching

6. Data Management

Raw data

The data in-hand and proposed for from the National Radio Astronomy Observatory's facilities – the Karl G. Jansky Very Large Array (VLA) and the Atacama Large Millimeter Array (ALMA) – have a one-year proprietary period. After this time, both the raw data and the imaged data are automatically made publicly accessible via a web-based archive.

The raw data obtained as part of the SWAG survey using the Australia Telescope Compact Array (ATCA) are also automatically made available in a web-based archive after a proprietary period.

Processed products

For SWAG and other proprietary survey data used in this work, our team will make the processed maps available on the CDS data hosting service by the start of 2020, at which point initial team publications (including Papers 1 and 5 from this work) will be published or submitted.

Additional images from the ALMA and VLA data that we process beyond the standard pipelines (e.g., imaging of all spectral lines in the data, and combination of data obtained at multiple resolutions) will be made available on the CDS data hosting service in FITS format. As hosting at CDS requires an associated refereed publication, the processed products will be made available after an initial paper describing each data set (e.g., Papers 1 and 3) have been refereed and accepted.

7. Facilities, Equipment, and Other Resources

The PI has a demonstrated track record of securing considerable observing time on ALMA, which will maximize the science to be accomplished in this program.

The minimal data necessary to conduct the proposed projects is already in hand:

- PI Mills has access to millimeter spectral line data from the archival public survey data at 3 mm and 7 mm presented in Jones et al. (2012) and Jones et al. (2013) and Martin et al. (2004), as well as 12 mm spectral line data from the SWAG survey (Krieger et al. 2017, as co-PI)). The PI also has access to a number of proprietary survey data sets: maps of individual CO and HCN transitions from collaborator Tanaka, maps of individual CS transitions from collaborator Paglione, a 1.4 mm survey from collaborator Ginsburg, and Herschel dust emission maps from collaborator Battersby. All together, these data will be used to construct a template of molecular line and continuum emission from the GC (Paper 4)
- PI Mills also has millimeter spectral line data of ALMA NGC 253 from an ALMA project in Band 7 (as a project co-I). A graduate student will use the CO and HCN data from this project and the GC data of the same lines from Tanaka to conduct a comparison of the kinematics in the GC and NGC 253 on identical 2 pc size scales (Paper 2).
- Through other proposals, the PI additionally have access to ALMA data of NGC 253 in Bands 3 and 6. These data (and additional data publicly available in the ALMA archive) will be used to create a template spectrum of integrated emission from the central region of NGC 253 (Paper 4). In parallel, a graduate student will also use these data to make a comparison of excitation of NGC 253 and the GC on identical 35 pc size scales (Paper 3).
- Finally, the PI has data in hand from leading other projects observing selected GC clouds in radio and millimeter spectral lines with the VLA and ALMA. In conjunction with the SWAG survey, these data sets will be used to probe the variation in physical conditions (temperature, turbulence, and where possible, density) as a function of size scale and radius in the GC (Paper 1).

In addition, the PI is leading two approved (C-ranked) ALMA proposals for Cycle 5. These are both sizable (30-hour) programs; one to conduct 2 pc-scale imaging of NGC 253 in lower-excitation lines complementary to the Band 7 data in hand, and one to conduct imaging of selected GC clouds in higher-excitation lines, complementary to existing archival data. The prospects for obtaining these data during the funded period are good. The NGC 253 observations will be conducted in Band 3, which has the least stringent weather requirements (and so typically the largest amount of observing time available), though they will require relatively long baselines. The GC observations will be conducted using ALMA's relatively more undersubscribed Atacama Compact Array, though better weather conditions will be required in order to execute these Band 7 observations. The current completion rate for C-ranked projects in Cycle 5 is 70%. It is anticipated, planning for resubmission of these proposals in Cycle 6 if necessary, that by Year 2 there will be at least partial data in hand for both projects.

While not required in order to meet the goals of this proposed projects, completion of the approved NGC 253 ALMA observations will allow higher spatial resolution measurements of the gas excitation, allowing the properties of the GC and NGC 253 to be compared on sub-cloud size scales. Completion of the approved ALMA GC observations will allow for a more complete comparison of the variation of physical conditions (particularly the density) as a function of size scale and Galactocentric radius.

8. Statements of Support

8.1. Current and Pending Support

CURRENT AND PENDING SUPPORT

Elisabeth A. C. Mills

Current Support:

1. Assistant Research Professor Salary (at Boston University)

Role:	N/A
Source of Support:	MIT
Total Award Amount:	$255,000
Starting Date:	09/01/17
Ending Date:	08/31/20
Person months committed:	9.0

Pending Support:

1. REU Site: Magnetic Fields on Planetary to Cosmic Scales- a Joint Program in Astronomy and Space Science at Boston University

Role:	Co-PI
Source of Support:	NSF REU Site Proposal
Total Award Amount:	$197,155
Starting Date:	01/01/18
Ending Date:	12/31/20
Person months committed:	1.0

2. Apples to Apples: Comparing the Cores of Nearby Galaxies

Role:	PI
Source of Support:	NSF AAG Proposal
Total Award Amount:	$331,920
Starting Date:	07/01/18
Ending Date:	06/30/20
Person months committed:	1.0

8.2. Letters of Commitment and Collaboration

Matesanz, James

Sun 11/12/2017 9:25 PM

To: Mills, Elisabeth <eacmills@bu.edu>;

Dear Dr Mills,

If the proposal submitted by Dr. Elisabeth Mills entitled " Apples to Apples: Comparing the Cores of Nearby Galaxies" is elected for funding by the NSF, it is my intent to provide the support and resources of the BU PEP in order to support this initiative. Additional details may be found in the Project Description or the Facilities, Equipment or other Resources section of the proposal.

Sincerely,

James Matesanz

James Matesanz, M.Ed.
Field Coordinator
Lecturer
Prison Education Program

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Japan
ktanaka@phys.keio.ac.jp

November 10th, 2017

To Whom it May Concern,

If the proposal submitted by Dr. Elisabeth Mills entitled “Apples to Apples: Comparing the Cores of Nearby Galaxies” is selected for funding by NSF, it is my intent to collaborate as detailed in the Project Description section of the proposal.

Sincerely,

Kunihiko Tanaka
Faculty of Science and Engineering
Keio University

YORK COLLEGE
The City University of New York
Jamaica, NY 11451
718 262-2650
718 262-2652 (FAX)

Department of Earth & Physics Sciences

November 8, 2017

To Whom It May Concern:

If the proposal submitted by Dr. Elisabeth Mills entitled “Apples to Apples: Comparing the Cores of Nearby Galaxies” is selected for funding by NSF, it is my intent to collaborate as detailed in the Project Description section of the proposal.

Sincerely,

Timothy A. D. Paglione
Professor of Physics & Astronomy

UCONN
UNIVERSITY OF CONNECTICUT
College of Liberal Arts & Sciences

University of Connecticut
Department of Physics

Dr. Cara Battersby
Assistant Professor
University of Connecticut
(303) 960-7148
cara.battersby@uconn.edu
http://physics.uconn.edu/cara-battersby/

13 November, 2017

To Whom it May Concern,

If the proposal submitted by Dr. Elisabeth Mills entitled "Apples to Apples: Comparing the Cores of Nearby Galaxies" is selected for funding by NSF, it is my intent to collaborate as detailed in the Project Description section of the proposal.

Sincerely,

Cara Battersby

An Equal Opportunity Employer

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National Radio Astronomy Observatory
P O Box O, 1003 Lopezville Road
Socorro, NM 87801 USA
575.835.7000 Fax 575.835.7027
www.nrao.edu

To Whom it May Concern,

If the proposal submitted by Dr. Elisabeth Mills entitled "Apples to Apples: Comparing the Cores of Nearby Galaxies" is selected for funding by NSF, it is my intent to collaborate as detailed in the Project Description section of the proposal.

Sincerely,

Adam Ginsburg