

## From Excitation to Physical Conditions in Galactic Center Gas

The Galaxy's central five hundred parsecs (the Galactic center, or GC) contains some of its most extreme molecular gas conditions. GC clouds have wide, turbulent linewidths, (15-50 km s<sup>-1</sup>, Bally et al. 1987), high gas temperatures (50–300 K, Hüttemeister et al. 1993; Mauersberger et al. 1986), and large densities ( $n > 10^4$  cm<sup>-3</sup>, Zylka et al. 1992). Prior observations suggested that the range of conditions in GC clouds have not yet been fully constrained: in one cloud, Sgr B2, the gas is much hotter, with temperatures of up to 700 K (Ceccarelli et al. 2002). In another cloud, densities as high as  $n = 10^8$  cm<sup>-3</sup> are claimed (Montero-Castaño et al. 2009). **My research has shown that hot, 400 K gas is widespread GC clouds (Mills & Morris 2013), and that prior estimates of gas densities as high as  $10^8$  cm<sup>-3</sup> in the GC were overestimates (Mills et al. 2013). The studies that I am now leading are continuing to break new ground in excitation studies of gas in extreme environments, yielding the first measurements of physical conditions on sub-parsec scales in GC clouds.**

### 1. A Very Hot Gas Component in the Galactic Center

Although GC clouds are known to be warmer than those in the disk, one cloud in particular (Sgr B2) is found to host far hotter gas than average ( $\sim 700$  K, Ceccarelli et al. 2002; Wilson et al. 2006). However, prior surveys did not look outside of this cloud to determine whether this hot gas is unique to Sgr B2 or ubiquitous in the GC.

I led a project to survey 13 GC clouds for similarly hot gas with the Green Bank Telescope (Mills & Morris 2013). I observed multiple highly-excited lines of NH<sub>3</sub>, and detected emission from the (9,9) line of NH<sub>3</sub> (excitation energy = 840 K) in 9 of 13 clouds, many of which have no associated star formation. For the three strongest sources, I derived rotation temperatures of 400-500 K, substantially higher than previous measurements of 200-300 K (Mauersberger et al. 1986). My widespread detection of gas with  $T > 400$  K indicated that this hot gas is common and must be heated by global processes in the GC. As these NH<sub>3</sub> lines were observed in emission for the first time in the GC, I also further constrained the hot gas to have densities  $> 10^3 - 10^4$  cm<sup>-3</sup>, suggesting that the heating mechanism may be internal shocks.

**I am PI of an ongoing GBT project (75 hours allocated) to expand my GC survey to search for similarly hot gas in the nuclei of other galaxies.** I am also beginning a project to compare temperatures measured using H<sub>2</sub>CO and NH<sub>3</sub> to determine whether some part of this apparently hot gas might also be an anomalous excitation effect called 'formation excitation' in which NH<sub>3</sub> forms at high energies, and some of it has not yet collisionally relaxed to a thermal distribution.

### 2. Determining Gas Densities Near the Black Hole

Recent studies of the circumnuclear disk (CND), a ring of gas and dust at a radius of 1.5 pc from the central black hole, have yielded discrepant densities. One study assumes the gas is virialized, finding densities that exceed  $10^8$  cm<sup>-3</sup> (e.g., Montero-Castaño et al. 2009). Other studies using low-density tracers such as CO, or dust properties, find lower densities of  $10^4 - 10^5$  cm<sup>-3</sup> (e.g., Etxaluze et al. 2011). Resolving this density discrepancy is necessary to understand the evolution of this structure, as for the gas to be tidally stable and form stars, it must have densities greater than  $10^7$  cm<sup>-3</sup>.

I performed an excitation analysis of HCN and HCO<sup>+</sup> using data from the APEX telescope, a

12m ALMA prototype dish, and found that, with an average density  $\log[n(\text{cm}^{-3})] = 6.5_{-0.7}^{+0.5}$ , this gas is not virialized. I also detect a vibrationally-excited ( $v_2 = 1$ ) line of HCN for the first time in this region, indicating that gas densities may be even lower (Mills et al. 2013). To quantify how radiative excitation indicated by the presence of  $v_2 = 1$  emission affects density measurements, **I have 16 hours of highly-ranked (top 10%) ALMA Cycle 2 observations in progress, observing HCN and other molecules in Bands 3 and 6.** Combined with two other highly-ranked ALMA proposals in Bands 7 and 9 on which I am a co-I, I will use these data to conduct a complete excitation analysis of the gas around the black hole, and determine for the first time its density and temperature structure.

### 3. New High-resolution Probes of Cloud Conditions

In addition to constraining the global extremes of GC gas properties, I am leading projects to determine the variation in physical conditions in the interiors of GC clouds. The properties of these clouds on subparsec scales have not been well studied, which means the dependence of their temperature and density on local processes (e.g. star formation, or supernova-driven shocks) is not known. To begin to characterize the interior conditions of GC clouds, I led an initial VLA study of 5 GC clouds to determine the variation in temperature in these clouds on 0.1 pc scales to ultimately identify their heating sources.

A key discovery of this study has been hundreds of weak, collisionally-excited  $\text{CH}_3\text{OH}$  masers which are detected in all of the clouds we survey. The masers are distributed non-uniformly in the clouds, with concentrations likely indicating regions of shock activity that may be driving the evolution of physical conditions in these clouds (Mills et al., submitted).

**Using data from my VLA survey, I mentored 4 REU students in summer 2014.** Highlights of the results from their work include:

- A study of the excitation of  $\text{HC}_3\text{N}$  in GC clouds identified a new high-column-density, low-excitation component in these clouds. J. Barnes is continuing this project for his senior thesis.
- An analysis of the excitation and distribution of  $\text{NH}_2\text{D}$  in Sgr B2 found a new warm but highly-deuterated core that may represent an early stage of massive star formation (A. Clements, Mills et al. in prep).
- A project to constrain  $\text{NH}_3$  excitation in GC clouds led to a new technique for identifying  $\text{NH}_3$  masers, and a dozen new candidates, more than doubling the number of these sources known in our Galaxy (A. Teachey, Mills et al. in prep).
- An investigation of  $\text{NH}_3$  excitation in the CNB yielded new temperatures that provide further constraints on the gas density, limiting it to  $< 10^{6.5} \text{ cm}^{-3}$  (B. Sun, Mills et al., in prep.).

**Finally, I am also involved in large-scale radio ( $\text{NH}_3$  with ATCA, co-PI) and millimeter ( $\text{H}_2\text{CO}$  with APEX, Ginsburg et al. in prep) surveys of gas excitation over the entire GC which are paving the way for comparisons of the excitation conditions in the GC to those in other Galaxies.**

### References

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## Bootstrapping Gas Properties from Low to High Redshift

Molecular gas is a fundamental building material for structure in our universe: its properties influence where and how many (and possibly what type of) stars will form, governing how galaxies evolve. However, gas in other galaxies is typically observed in only one transition at a time (e.g., Gao and Solomon 2004). ALMA provides sensitivity to not just probe gas over a wider range of environments than was previously possible, but to observe dozens of transitions at once. This means for many sources we no longer have to make assumptions about the gas chemistry and excitation, but can measure them directly. **As an Scientist at NRAO, I will use ALMA to measure excitation in more extreme environments than ever, directly comparing them to well-studied local regions, and better calibrating relationships between observed line brightnesses and physical properties of the gas.**

### 1. The Need to Make Better Assumptions about Molecular Gas Excitation

To continue to use a few bright lines to efficiently derive physical conditions from survey data, the global reliability of standard assumptions about the gas excitation must be assessed with more detailed analyses. New studies are necessary to determine whether these assumptions (e.g., that the observed line is optically thin, that most of the gas is at an expected temperature, or that the abundance of this tracer molecule with respect to  $H_2$  is fixed) are still valid for gas in the apparently more extreme environments of high- $z$  galaxies (e.g., Swinbank et al. 2011)

Nuclei of galaxies are excellent local laboratories for studying extreme environments for molecular gas. In our own Galaxy, the gas in the central 0.5 kpc has an order of magnitude higher temperatures, densities and turbulence than in disk (e.g., Güsten et al. 1985; Bally et al. 1987). Indeed, many assumptions made about the gas in galaxies are believed to break down in extragalactic nuclei compared to disks: from the relationship between gas surface density and star formation rate (Xu et al. 2014), to the typical ratio of CO to  $H_2$  (Sandstrom et al. 2013), to the excitation of CO assumed when determining gas masses (Rosolowsky et al. 2015). These observations indicate that excitation conditions in extreme environments like nuclei are deviant, and must be better characterized.

Tracers of dense gas are more incompletely studied than CO. The fundamental transition of HCN has been shown to be a linear star formation tracer over multiple decades of star formation rate (e.g., Gao and Solomon 2004). However, in the center of our galaxy there is brighter HCN 1-0 in a cloud forming just 4 OB stars, than in Sgr B2, which is forming hundreds of O stars (Jones et al. 2012). While it is true star formation ‘laws’ may become invalid below a certain size scale (Kruijssen and Longmore 2014), the case of Sgr B2 indicates that HCN is no longer a reliable tracer when lines are extremely optically thick. HCN excitation may also not reliably measure gas densities in systems with strong IR fields like ULIRGS, as the radiative excitation can cause line ratios to mimic what is expected from collisional excitation (e.g., Ziurys and Turner 1986; Sakamoto et al. 2010; Mills et al. 2013)

### 2. Making Improved Measurements of Gas in Extreme Environments

Ultimately, to measure the physical conditions in extreme environments such as the nuclei of other galaxies, we need to be able to understand when and where standard assumptions about the typical gas excitation will fail. **I will measure excitation conditions for a wider variety of extragalactic environments than has previously been possible. My work will constrain the range of excitation conditions present in these environments and allow gas properties to be inferred in more distant systems even when only a few bright lines can be observed.**

Determining accurate physical conditions for molecular gas requires measuring how energy levels in observed molecules are populated (e.g., whether or not they are in LTE). With ALMA’s exquisite sensitivity we can now constrain the excitation in distant sources as never before: measuring faint isotopologues in order to assess the optical depth, and detecting weak vibrationally-excited transitions that may indicate a molecule is excited by infrared radiation and not high densities.

For sufficiently nearby sources, ALMA also provides the high spatial and velocity resolution necessary to measure column densities, abundances, local velocity gradients, and the 3D structure of the emitting gas on sub-parsec scales in order to accurately model emission from molecules in non-LTE conditions. ALMA’s high resolution is also necessary to compare the physical conditions inferred from multiple molecular tracers, e.g. determining whether you are seeing a range of densities and temperatures present in the same gas (purely an excitation effect) or whether different molecules are present in distinct regions of temperature/density (an effect of the chemistry).

Ultimately, we need to be able to both make the highest resolution observations possible (typically, in our Galaxy) but also to sample the most extreme conditions (typically, outside of it). At present the fundamental missing step to connect these two is identically-high-resolution local and extragalactic datasets. **At NRAO I would bridge this gap by using ALMA to conduct the first parsec-scale, multi-frequency observations of the molecular gas excitation in extragalactic nuclei, which can be directly compared to single dish studies of the molecular gas excitation in our own Galactic center, one of the most extreme environments in our own Galaxy.** Effectively, my research will “bootstrap” the calibration of typical excitation conditions from more quiescent local sources to more distant extreme sources.

### 3. A Bootstrap Method for Calibrating Gas Properties Inferred from Excitation

By characterizing the small-scale ( $<0.1$  pc) excitation and physical conditions of the hottest and densest gas in our Galaxy, I will first determine how well these conditions are represented by coarser (parsec-scale) observations of the same regions. I will then use this comparison to inform the interpretation of conditions from parsec-scale observations in more distant and extreme galaxies. Ultimately, I will identify the fewest lines capable of effectively discriminating between physical conditions in extreme environments that can be used to more efficiently survey large number of galaxies at low resolutions.

#### *Rung #1: Characterizing Sub-Parsec Resolution Galactic Center Gas*

In the center of our Galaxy (GC), I am currently conducting several high-resolution molecular excitation studies. The first is a VLA  $\text{NH}_3$  project, observing GC clouds at 0.1 pc resolution. I am already finding deviations from prior lower-resolution results (e.g., Hüttemeister et al. 1993; Ott et al. 2014), including extremely large opacities, and masers, changing the previously inferred excitation properties. A detailed comparison with  $\sim 1$  pc scale ATCA data of the central 500 pc (Co-PI: Mills, Figure 1, right) will show whether temperatures derived on larger scales are consistent with those at smaller scales.

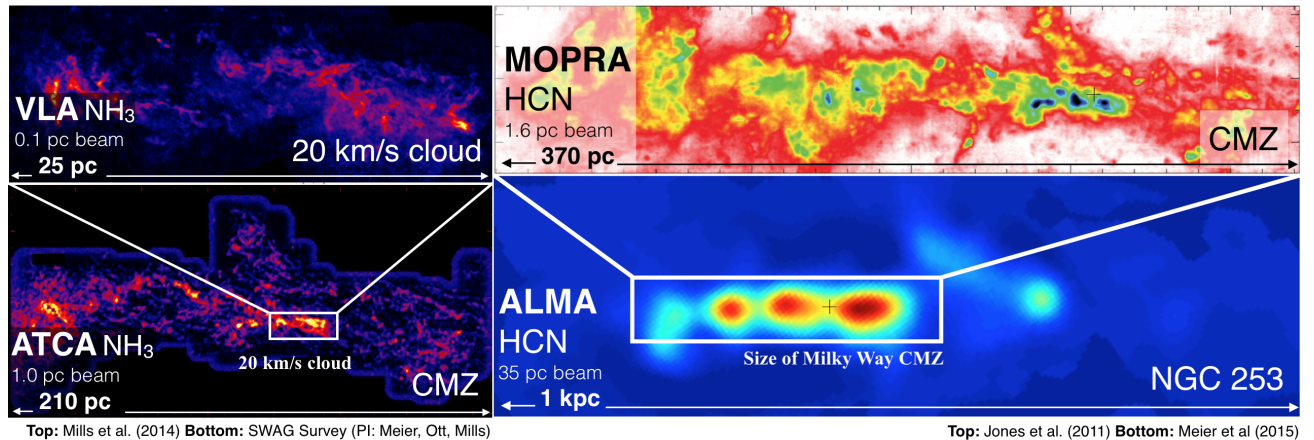


Fig. 1.— Illustration of the rungs in the “excitation ladder” I will use to calibrate the excitation of distant galaxies to that observed locally. **Left:** VLA  $\text{NH}_3$  observations of a GC cloud on 0.1 pc scales are compared to a lower-resolution  $\text{NH}_3$  map of the entire GC at parsec-scale resolution, revealing excitation features such as 3,3 masers that are not apparent in the lower-resolution observations. **Right:** A 1.5 pc resolution map of the GC is compared to an ALMA map of the center of NGC 253 with 35 pc resolution, highlighting the current inability to pinpoint the scales on which extragalactic molecular emission occurs and the substructure of the emission. Centers of both galaxies are marked with crosses.

I also have an in-progress ALMA project (1'' resolution, <0.1 parsec) looking at gas within a few parsecs of the central supermassive black hole in our Galaxy. I am detecting and localizing weak vibration-line emission to reassess densities previously determined using single dish observations (Mills et al. 2013). At NRAO I will continue to use ALMA to conduct excitation analyses of GC clouds to determine how widely the excitation and the resulting inferred physical conditions vary as a function of environment.

### ***Rung #2 Mapping the Galactic Central Kiloparsec at Parsec Scales***

I will use the physical conditions measured from the excitation of GC gas on small scales to calibrate those inferred from coarser observations. In this way, accurate physical conditions can be determined over the entire GC. At NRAO I will continue to work with a network of European collaborators to build upon existing 3 mm maps of the central 400 pc of the GC made by Jones et al. (2012), and survey more highly-excited lines with the APEX single-dish telescope. Focal plane arrays on APEX are optimized for mapping large areas at 345 GHz (ALMA band 7) and 650/800 GHz (ALMA band 9). Using these, I will be able to map the entire central 500 pc in multiple bands to constrain the gas excitation for optimal comparison to the nuclei of other galaxies.

### ***Rung #3 Making the First Parsec-Scale Map of an Extragalactic Nucleus***

Within 4 Mpc, there are at least half a dozen well-studied galaxies whose central 500 parsecs can be observed with <1.5 K km/s sensitivity at parsec resolution with 20 hours on source at ALMA Band 7. Within this sample are galaxies having 100× the star formation rate (NGC 253, NGC 4945), or 1/10 the metallicity (M33, NGC 300) of our own Galactic center, and potentially entirely different excitation conditions. ALMA observations are already underway toward many of these sources, including NGC 253 (Leroy et al. 2014; Meier et al. 2015, See Figure 1, left). These observations demonstrate the wealth of molecules that can be measured, as well as indicating properties that could not previously be inferred from lower-resolution observations (e.g., sizable optical depths). I propose to resolve these galaxies at parsec scales in multiple ALMA bands, to deconstruct individual clouds and measure the excitation in sources that may be analogous to those in our own Galaxy (e.g., the chemically-rich star forming cloud Sgr B2, or highly-excited gas near our black hole) and potentially sources that may have no local analogues, e.g. forming globular clusters (e.g., Turner et al. 2003), or deeply buried AGN (e.g., Aalto 2008). My groundbreaking high-resolution observations will determine typical excitation conditions and their variation in some of the most extreme sources in the local universe.

## **4. Improving Future Measurements of Gas Properties**

With a better calibration of which lines best characterize the average excitation conditions in more extreme systems and how these relate to the physical conditions, my research will allow gas conditions in large samples of distant, high-redshift systems to be efficiently constrained. The ultimate goal is to be able to take a standard plot of star formation rate as a function of cosmic time (e.g., Madau et al. 1998) and compare it to plots of the gas conditions in the same eras: tracing the quantity, temperature, and density of molecular gas in these systems as a function of cosmic time. **By measuring the excitation properties of the most extreme gas in the local universe, the research I will do as an NRAO Scientist will lead to an unprecedented understanding of the relationship between gas conditions and star formation over the history of our universe.**

## **References**

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**As a member of the observatory staff I will bring with me five years of experience observing with NRAO facilities and a comprehensive practical knowledge of the calibration, imaging, and analysis of these data products.**

**I have extensive observing experience using both the Green Bank Telescope (GBT) and the Karl G. Jansky Very Large Array (VLA).** Over the last five years, I have been the PI of 6 successful proposals for 2 survey projects using these telescopes, totaling over 100 hours. As described in my statement of past research, the first program is a survey for highly-excited lines of ammonia in the Galactic center, which constrained a previously unknown high-temperature molecular gas component in this region (Mills et al. 2013a). As a followup to this project, I have an ongoing 70 hour project on the GBT to search for these lines in the centers of other nearby galaxies. As a result of this work, I am expert in single-dish observing techniques and procedures, particularly at high radio frequencies ( $\nu > 20$  GHz). The second program is a high-resolution VLA survey of molecular gas in a sample of Galactic center molecular clouds to constrain their interior temperature structure (Mills et al. 2014, Mills et al. submitted). For this project I spent 3 months in summer 2012 at NRAO-Socorro assisting with ongoing commissioning activities for the VLA. As a result of this work, I am an expert in current calibration techniques and procedures for utilizing the wide-bandwidth capabilities of the VLA correlator.

**I am also skilled in the calibration of single-dish millimeter and submillimeter data** from a multi-frequency APEX study of circumnuclear gas in our Galaxy, yielding important new constraints on its density (Mills et al. 2013b). Finally, I have 6 ongoing ALMA projects, including a 16 hour PI project to continue to observe gas near the central black hole of our Galaxy in Bands 3 and 6. Combined with 2 other successful projects in bands 8 and 9 to observe this source, and Cycle 1 Band 7 data, I plan to conduct an excitation analysis of this gas in 5 ALMA bands to more fully constrain its excitation, as detailed in my description of my future research plans.

**I am an authority on a wide variety of data calibration and reduction software** including AIPS, CASA, GILDAS-CLASS, and GBTIDL for the processing of interferometric and single-dish radio, millimeter, and submillimeter data. I routinely use CASA to reduce data from multiple VLA projects, and I am an expert in the calibration and imaging of radio data, particularly high frequency spectral-line data, utilizing complex correlator setups. I am also skilled at using AIPS to calibrate and image archival VLA data observed with the old correlator. In addition to working with interferometric data, I regularly use GBTIDL to calibrate single-dish GBT spectral line observations and on-the-fly maps. I also use GILDAS for single-dish millimeter and submillimeter calibration and the processing of data from the APEX telescope (200-800 GHz). I am a specialist in the analysis of spectral line data, including performing excitation analyses using codes such as RADEX and RATRAN. I am also experienced in a variety of scripting languages and tools for data visualization, including IDL, Python, C++, Fortran, DS9, CASA, and GREG.

**I am also at the forefront of efforts to address new challenges in visualizing data products from NRAO facilities.** I co-PI'd a proposal detailing current barriers to the visualization and analysis of line-dense spectral line data cubes that was submitted to computer scientists at the Scientific Computing and Imaging Institute at the University of Utah to As a result of my involvement in this proposal and a visit to pitch our problem to researchers at this institute, we have begun a collaboration to develop new computational approaches to this problem.