

My research focuses on the molecular gas in the central five hundred parsecs of the galaxy (the Galactic center, or GC). The GC is a unique laboratory, as it is one of the harshest environments for molecular gas which can be resolved. Gas in this region is markedly different from gas in the Galactic disk: it has higher densities, temperatures, and line widths. My plan is to conduct high-resolution studies of this gas in order to understand the physical processes at work, and their effect on star formation in the GC environment. **My proposed research is an excellent fit with current millimeter and radio studies of ISM properties and the Galactic center at Northwestern University as it will provide important, high-resolution and quantitative studies of cloud properties in this unique environment.** Below, I first describe four related research projects I have already undertaken, before discussing my future research plans to understand the physical processes which regulate the observed extreme conditions in GC gas.

(i) Interactions Between GC Molecular Clouds and their Environment

The interactions between molecular gas and the GC environment may play an important role in its structure and conditions. The M-0.02-0.07 molecular cloud is unique example of a cloud undergoing multiple interactions: it lies just 6 parsecs from the central supermassive black hole (SMBH), is being compressed by a nearby supernova remnant (SNR), and has an embedded group of compact H II regions (Serabyn et al. 1992). I used archival VLA observations and Paschen α images from the Hubble Space telescope to further constrain the interaction between these sources (Figure 1a, Mills et al. 2011). From their extinctions and morphologies, I determined that three of the H II regions formed on the front side of the cloud, and are unaffected by the SNR expansion. The fourth H II region is embedded in the supernova-compressed ridge, and though younger than the other H II regions, is still older than the SNR. In the future, I plan to study other processes that may be responsible for triggering star formation in these clouds.

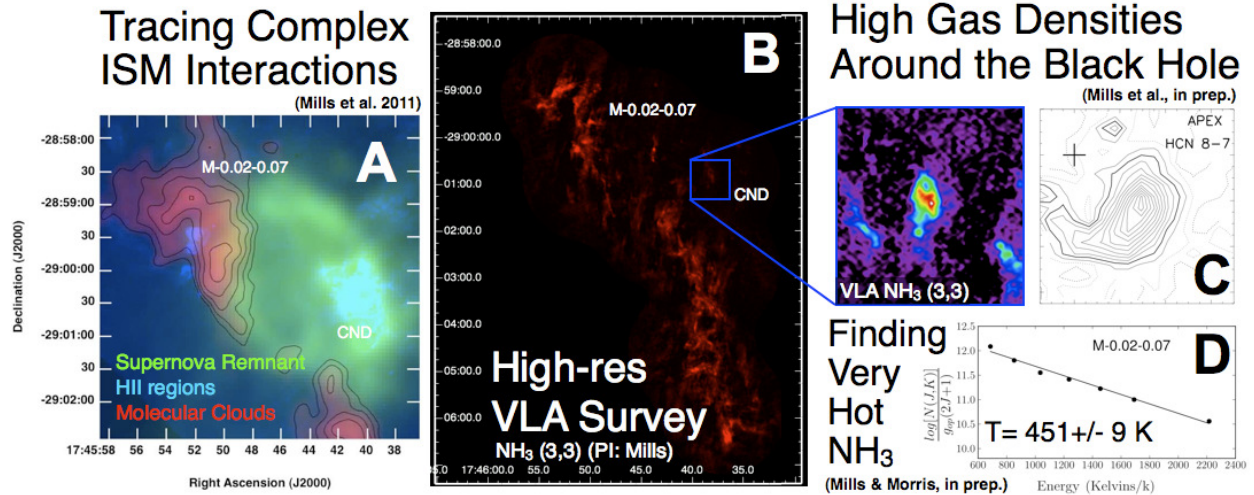


Fig. 1.— From Left to Right: (A) Data from the HST and VLA trace the interaction between an unusual GC cloud and a group of H II regions. (B) A VLA survey yields the first high-resolution images of GC clouds. (C) NH₃ and highly-excited lines of HCN indicate very dense gas in the circumnuclear disk, a massive molecular ring in the central parsec. (D) GBT observations of highly-excited NH₃ find a very high-temperature gas component apparently common to GC clouds.

(ii) Constraining the Extreme GC Physical Conditions

The environment unique to Galactic nuclei leads to elevated temperatures and densities, but the maximum values in quiescent clouds are not well constrained. I have studied highly-excited lines of NH_3 in a sample of GC clouds, deriving rotation temperatures of 400-500 K ((Mills & Morris, in prep.), indicating the widespread presence of hot gas which must be heated by global processes in the GC. I next plan to constrain the processes responsible for heating the gas by increasing my sample size. I was also recently awarded VLA time to study nonmetastable NH_3 in GC clouds, which will identify the distribution of their densest gas ($n > 10^6 \text{ cm}^{-3}$).

(iii) The Evolution of Gas Around Supermassive Black Holes

The conditions in gas around SMBHs determines its fate: whether it will ultimately accrete, or collapse and form stars. Recent studies of the circumnuclear disk (CND), a ring of gas and dust at a radius of 1.5 pc from our Galaxy's central SMBH, yield discrepant densities of greater than 10^8 cm^{-3} (e.g., Montero-Castaño et al. 2009), and between $10^4 - 10^5 \text{ cm}^{-3}$ (e.g., Etxaluze et al. 2011). For the gas to be tidally stable, it must have densities greater than 10^7 cm^{-3} . Using observations of multiple transitions of HCN and HCO^+ (Figure 1c), I put significantly tighter limits on the density ($n = 10^{5.7} - 10^{7.6} \text{ cm}^{-3}$). However I cannot rule out the possibility that the gas is tidally stable or in virial equilibrium (Mills et al., in prep.).

(iv) High-resolution Studies of Molecular Cloud Structure

In addition to constraining the global extremes of GC gas properties, I am also measuring 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 (including the 'Brick'; Longmore et al. 2012) to determine variations in temperature on 0.1 pc scales and ultimately identify their heating sources (Figures 1b).

What Regulates the Physical Conditions in the Galactic Center?

My work has helped show that Galactic center (GC) molecular clouds are indeed significantly hotter, denser, and more turbulent than disk clouds. But, what causes the gas conditions in the center of our Galaxy to be starkly different than those in the Galactic disk? Are these unique conditions the result of ongoing feedback (e.g., winds and radiation from the central stars or supermassive black hole), which will propagate outward to the surrounding Galaxy? Or, are the properties of GC gas unrelated to feedback, and instead controlled by the shocks, shearing, and release of gravitational energy as gas naturally migrates to the center of the Galaxy?

As a consequence of these extreme properties, it has further been predicted that the resulting stellar initial mass function (IMF) may be top-heavy (Morris 1993). However, a deviant IMF has only been measured in the central parsec (Maness et al. 2007). Are the observed bulk gas properties in the GC really representative of conditions in unresolved star-forming cores?

As a Lindheimer fellow, I will study physical conditions in Galactic Center gas on sub-parsec scales to (1) distinguish between the effects of feedback and processes that fuel gas to the center of the Galaxy and (2) determine whether these extreme conditions persist in the clumpy cloud interiors and modify the resulting star formation process. The observational studies I will undertake are highly complementary to the research being done by Northwestern faculty, including studies of cosmic rays and the magnetic field in the GC, both of which may contribute to the unique physical conditions in GC gas.

1. The Need for A New Study of the Galactic Center Gas Conditions

The low resolution of prior surveys (3–5 pc, e.g., Bally et al. 1987; Hüttemeister et al. 1993), and the limited coverage of recent studies which further constrain the conditions in just a few clouds (e.g, Longmore et al. 2012) are not sufficient to constrain the full variation in physical conditions in the GC gas. To distinguish between different scenarios for the the heating, turbulence, and densities of GC clouds requires a homogenous study of dense gas conditions on both global scales and the small scales most relevant to star formation.

I will conduct the first high-resolution survey of molecular gas on scales as small as thousands of AU, across the central 500 parsecs of our Galaxy, using tracers which are sensitive to both high temperatures and densities. My work will constrain the full range and spatial distribution of density, temperature, and turbulence in GC gas, and will test predictions of models for the processes that control gas conditions in the GC, as well as directly probing the initial conditions of GC star formation.

2. Using Physical Conditions to Test Predictions of Feedback Models

AGN feedback: Feedback from an active galactic nucleus (AGN) can take the form of gas outflows or radiation that expel or heat the central gas (e.g., Silk & Rees 1998). Although the Milky Way’s central black hole is currently quiescent, its recent activity may be traced by gamma-ray lobes (Su et al. 2010) and an X-ray echo from recent outbursts (Ponti et al. 2010). Frequent black hole activity can result in a higher flux of X-ray and cosmic rays in the GC, which would have two main signatures: (1) heating efficiency which increases with density (Glassgold et al. 2012), so that GC clouds are systematically hotter than lower-density gas traced by CO and H_3^+ (Goto et al. 2008), and (2) gas temperatures consistently higher than dust temperatures (Galli et al. 2002).

Stellar feedback: In contrast, feedback from massive stars takes the form of UV heating, or shocks from stellar winds and supernovae (e.g., McKee & Ostriker 1977). Simulations of stellar feedback (Hopkins et al. 2012) predict distributions of cloud densities that decrease with increasing feedback strength, which can be directly compared to the observed gas density distribution in GC clouds (Figure 1, right). The signatures of radiative heating also differ from AGN heating, as (1) gas temperatures in shielded cloud interiors will be cooler than dust temperatures (Figure 1, right; Tielens & Hollenbach 1985), and (2) the global distribution of cloud temperatures will follow the asymmetry of young stars in the GC (predominately located at positive Galactic longitudes).

Feedback or Fueling? Although feedback processes may be one explanation for the extreme physical conditions in GC gas, processes which fuel gas to the center of the Galaxy may also be responsible. Tidal shearing will both heat and disrupt GC clouds, and as the shearing strength scales inversely with distance to the center, so too should cloud temperatures and the incidence of shocks (Wilson et al. 1982). Alternatively, if large-scale shocks at the edge of the GC where HI becomes H_2 (Binney et al. 1991) are primarily responsible for heating the gas, temperature and shocks should decrease toward the center.

With measurements of the detailed density, temperature, and shock structure of the molecular gas in the GC, I will then be able to determine whether the observed extreme gas conditions are the result of feedback processes, which may shape the evolution of the surrounding Galaxy, or fueling processes, the effects of which will remain confined to the GC.

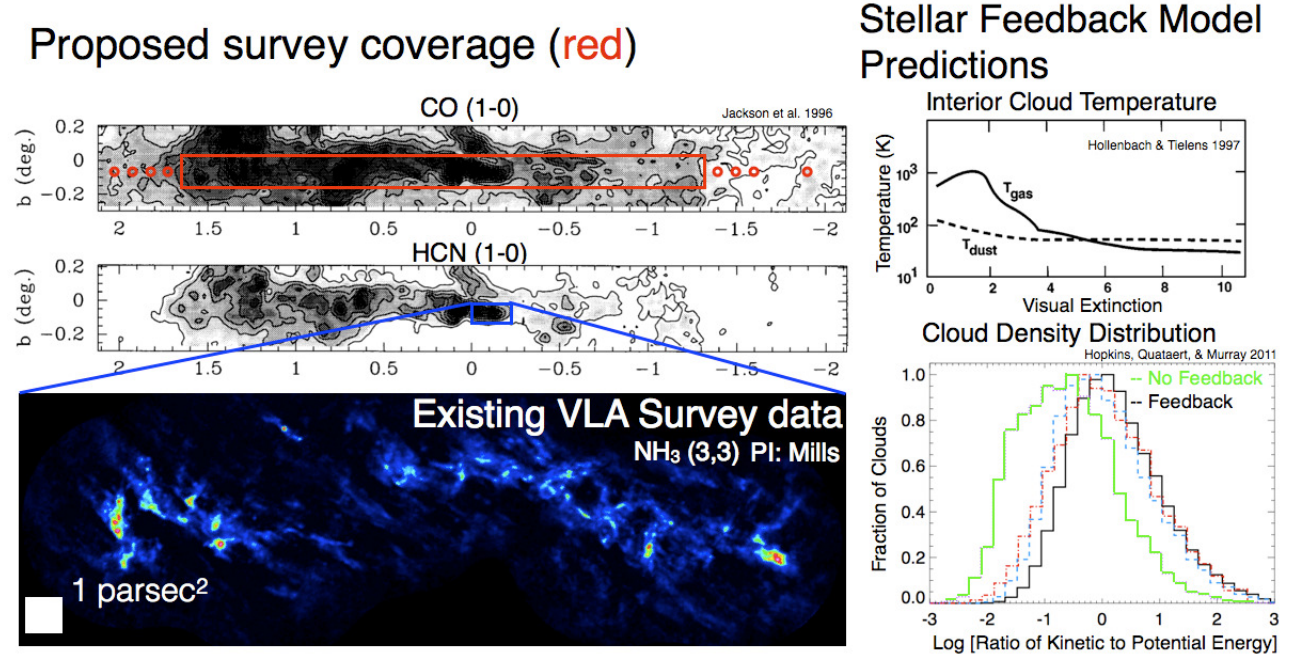


Fig. 2.— **Top Left:** The distribution of molecular gas in the Galactic center, showing the region I propose to survey in red. **Bottom Left:** A completed study of a sample of clouds, illustrating the resolution and sensitivity attainable with the VLA. **Right:** Global and local predictions of feedback models which can only be tested with large-area, high-resolution survey of the Galactic center gas like that which I propose.

3. Constraining the Initial Physical Conditions for GC Star Formation

By characterizing the temperatures, turbulence, and densities on the smallest spatial scales, my work will also constrain the initial conditions of future star formation in this gas.

Virialization vs. Turbulence: GC clouds are known to have large line widths, on the order of 25-50 km s⁻¹, but the relative line width contributions from inter-clump kinematics and intra-clump microturbulence is not well constrained. By measuring the detailed structure of the velocity field and its dispersion, I will compare the turbulent pressure in individual clumps to their density, thus testing whether these clumps are virialized pre-stellar cores, or merely transient features.

Clump Mass Function: Using spatially-resolved measurements of the density structure within GC clouds, I will also make the first clump mass function (CMF) measurements in the GC. Observations suggest that the CMF translates directly to the stellar IMF (e.g., Lada et al. 2008). By comparing the slope and characteristic mass of the CMF in a sample of GC clouds to those derived in Galactic disk environments, I will perform a unique test of existing hypotheses that the GC environment causes the IMF to differ from that in the disk.

4. Determining Physical Conditions from Molecular Line Observations

Temperatures: To discriminate between types of feedback, I will use multiple NH₃ lines to measure the internal temperature structure of GC clouds and map the distribution of the hottest gas ($T > 400$ K) across the GC. As such hot gas has a cooling time of only $\sim 10^3$ years, it should be tightly correlated with the location of the sources responsible for heating the gas.

Shocks: Along with highly-excited NH_3 , methanol (CH_3OH) also traces the locations and kinematics of shocks related to feedback or fueling. Collisionally-excited CH_3OH masers arise in shocks, and radiatively-excited CH_3OH masers also appear in enhanced absorption coincident with the collisionally-excited masers (Menten 1991). The presence or absence of masering in multiple transitions will probe of the excitation conditions in the shocked gas (Cragg et al. 1992).

Densities: Excitation analyses of optically-thin species such as formaldehyde (H_2CO) and cyanoacetylene (HC_3N) will tightly constrain the gas density (e.g., Mangum et al. 2008), especially when combined with temperatures determined using NH_3 . By observing multiple lines of each species, I will be sensitive to multiple density components throughout the spatially-resolved GC clouds, allowing me to clearly separate the properties of dense clumps and interclump gas.

5. Facilities I Will Use in This Study

Karl G. Jansky Very Large Array: Using the new capabilities of the VLA, I will conduct a large-area, high-resolution ($8''=0.5$ pc) C and Ku-band survey of dense gas in the GC (Figure 1, left). I will observe the 4.8 and 14 GHz lines of the density-tracer H_2CO simultaneously with the shock-tracing 6.6 and 12.2 GHz CH_3OH lines. With a $4'-7'$ field of view, this is a medium-sized project (~ 70 hours). I already have data from a 0.1 pc resolution VLA study of NH_3 in five of the most massive GC clouds (PI: Mills), including the ‘Brick’ (Figure 2; Longmore et al. 2012).

Green Bank Telescope : I will also make sensitive single-dish observations of a large sample of clouds across the GC in two fainter, higher-excitation lines of ammonia (9,9 and 12,12), the ratio of which can be used to constrain gas temperatures in excess of 300 K. This study will improve upon a pilot study of GC clouds (PI: Mills) which indicates that the highly-excited (9,9) line is widespread (Mills & Morris, in prep.), and determine the fraction of high-temperature gas across the GC and its distribution.

Atacama Large Millimeter Array: I also propose to conduct high-resolution (10^3 - 10^4 AU) ALMA observations for a sample of 20-30 especially dense clumps identified by the VLA survey to measure the density structure and kinematics in their interiors. With the sensitivity of ALMA, observing a sample of this size will be a medium-sized project ($\sim 40 - 50$ hours).

Altogether, my work as a Lindheimer Fellow will combine radio and millimeter observations to build a picture of the conditions in Galactic center gas from the largest (600 pc) to the smallest (10^3 AU) scales in order to identify the mechanisms which determine its properties and to quantify the initial conditions for GC star formation.

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