

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 spatially 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 for comparison with models in order to constrain the physical processes which act on this gas, and their effect on star formation. **My proposed research is an excellent complement to the aims of the STARFORM project as it will provide important, high-resolution and quantitative studies of cloud properties in a unique environment within our Galaxy.** Below, I first describe three 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) Constraining the Extreme GC Physical Conditions

The environment of our Galaxy's nucleus leads to elevated gas temperatures and densities, but the maximum values in quiescent GC clouds are not well constrained. By observing highly-excited lines of NH_3 in a sample of GC clouds, I have identified a new, hot gas component with a temperature 400-500 K which is apparently widespread and must be heated by global processes in the GC unrelated to star formation (Mills & Morris, in prep.). I was also recently awarded VLA time to study nonmetastable NH_3 in these clouds, which will further identify the distribution of their densest gas ($n > 10^6 \text{ cm}^{-3}$), as well as better constrain the density of the hot gas component, to determine whether it is diffuse, or a dense, post-shock component.

(ii) The Evolution of Gas Around Supermassive Black Holes

Even closer to the central black hole, the physical conditions in the gas are even more important for its fate: determining 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^+ , I put significantly tighter limits on the density ($n = 10^{5.7} - 10^{7.6} \text{ cm}^{-3}$). However I still cannot rule out the possibility that the gas is tidally stable or in virial equilibrium, and thus capable of forming stars (Mills et al., in prep.).

(iii) High-resolution Studies of Molecular Cloud Structure

In addition to constraining the global extremes of GC gas properties, I am also working to determine the variation in physical conditions on smaller scales, 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. embedded star formation, or supernova-driven shocks) is not known. To begin to characterize the interior conditions of GC clouds, I have begun an initial VLA study of 5 GC clouds (including the 'Brick'; Longmore et al. 2012) to determine the variation in temperature in these clouds on 0.1 pc scales and ultimately identify their heating sources (Figure 1).

Is Galactic Center Star Formation Unusual?

As a consequence of the extreme properties of molecular gas in the GC, it has been predicted that the resulting stellar initial mass function (IMF) may be top-heavy, favoring the formation of high-mass stars (Morris 1993). However, a deviant IMF has only been measured in the central parsec (Maness et al. 2007). This suggests the possibility that, in spite of the higher temperatures in Galactic center gas, star formation proceeds as normal in this region. Is the initial mass function truly unaffected by the extreme environment of the GC, or are the observed bulk gas properties throughout the GC not actually representative of the conditions on the smallest scales, in unresolved star-forming cores?

As a STARFORM fellow, I will study the physical conditions in Galactic Center gas on sub-parsec scales to test whether these extreme conditions persist in the clumpy cloud interiors and modify the resulting star formation process, as measured by the clump mass function of these clouds. By closely comparing these observations to STARFORM models, I will further be able to consider the evolution of these structures, and test for differences in the low-mass end of the resulting IMF, which is not directly measurable in the GC.

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) do not completely constrain the range of physical conditions which exist in GC molecular clouds. To study the range of initial conditions for star formation in the nucleus of our Galaxy requires a homogenous study of dense gas conditions on both global scales and the small scales most relevant to star formation.

Using the new capabilities of the Very Large Array (VLA) and ALMA, 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 directly probe the initial conditions of GC star formation.

2. Complementary VLA and ALMA Observations of the Galactic Center

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 1; Longmore et al. 2012), which I will use to measure the internal temperature structure of GC clouds.

To complement these data, I next plan to conduct a large-area, high-resolution ($8''=0.5$ pc) C and Ku-band survey of dense gas in the GC, observing the 4.8 and 14 GHz lines of the optically-thin density-tracer formaldehyde (H_2CO) simultaneously with the shock-tracing 6.6 and 12.2 GHz methanol (CH_3OH) lines. Excitation analyses of H_2CO will tightly constrain the gas density (e.g., Mangum et al. 2008), especially when combined with temperatures determined using NH_3 . Additionally, CH_3OH lines which appear in enhanced absorption coincident with collisionally-excited masers (Menten 1991) can be used to probe the kinematics and excitation conditions of shocked gas in these clouds (Cragg et al. 1992). By observing multiple lines of all of these species, I will be sensitive to multiple temperature and density components throughout the spatially-resolved GC clouds, allowing me to clearly separate the properties of dense clumps and interclump gas. Given the improved sensitivity of the VLA and a $4'-7'$ field of view, this survey will be a medium-sized project (~ 70 hours).

The high frequencies and long baselines of ALMA allow for the highest resolution picture of GC gas yet obtained. However, the much smaller FOV of ALMA makes it less ideal for a large-area survey. Therefore I will use the previously-described VLA survey to identify a sample of 20-30 especially dense clumps for high-resolution (10^3 - 10^4 AU) ALMA followup in order to measure the density structure, kinematics, and potentially the fragmentation in their interiors. With the sensitivity of ALMA, observing a sample of this size will be a medium-sized project ($\sim 40 - 50$ hours).

3. Constraining the Initial Physical Conditions for GC Star Formation

The planned study will yield a detailed picture of GC cloud properties on scales down to individual clumps resolved on thousand AU scales, which will provide many measurable quantities which can be directly compared with simulations. These observations will facilitate the construction of multiphase models of molecular clouds in an extreme environment: studies of their organization and dynamic structure will help constrain their future evolution, and the distribution of individual dense cores will be a probe of the first seeds of star formation in these clouds.

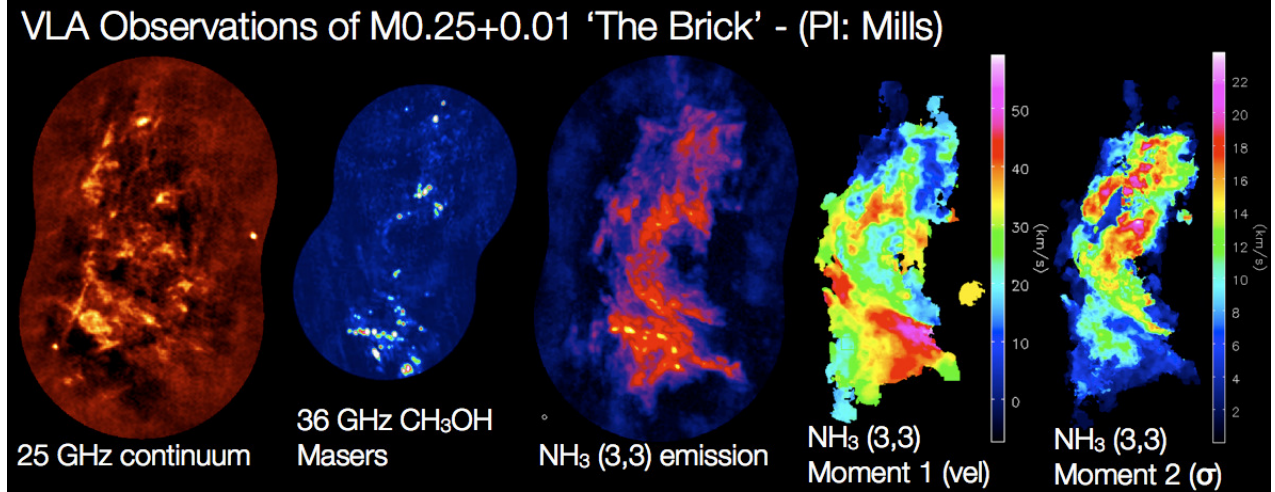


Fig. 1.— *Example VLA data (PI: Mills, Spatial resolution: 0.1 pc) which I will use to characterize a sample of GC clouds. The cloud, shown here, the ‘Brick’, is the most massive cloud in the GC, next to Sgr B2. However unlike Sgr B2, it is not actively forming stars. Its large mass ($M \sim 10^5 M_\odot$) and column density make it a candidate for eventually forming a massive star cluster (Longmore et al. 2012).*

Detailed Structure: By constraining the temperature and density structure in cloud interiors, I will test whether cooler and denser, potentially thermal, clumps exist in these clouds. By measuring the temperature profiles of individual clumps I will further constrain the dominant heating source in cloud interiors, as well as measure the Jeans mass in these clouds. Finally, by correlating density structure with shocks, I will search for regions of shock-enhanced density in these clouds, to understand whether shocks help drive the evolution of clouds towards star formation in this environment.

Virialization vs. Turbulence: GC clouds are known to have large line widths, on the order of $25\text{--}50 \text{ km s}^{-1}$, 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 determine the turbulent pressure in individual clumps, and compare this 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 on scales as small as 1000 AU, 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.

As a STARFORM fellow, I will use these high-resolution observations of the prestellar gas conditions in GC clouds to make a detailed comparison of their physical properties and those predicted by the models developed by the STARFORM project. My observations of conditions in these clouds and the processes which control them can also be used to inform the initial conditions of simulations of clouds in the Galactic center environment. **Altogether, my work will 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 behind its properties and quantify the initial conditions for GC star formation.**

References

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