Elisabeth A.C. Mills
PhD candidate at the University of Los Angeles-California
Physics and Astronomy Building
430 Portola Plaza, Box 951547
Los Angeles, CA 90095-1547
millsb@ucla.edu

November 1, 2012

NRAO Headquarters
520 Edgemont Road
Charlottesville, VA 22903-2475

Dear Sir or Madam:

I am applying for the Jansky fellowship program, to be based at the National Radio Astronomy Observatory in Socorro, New Mexico. My curriculum vitae, a list of my publications, a summary of my past and current research, and a proposal for the research I will carry out while a fellow are enclosed for your review. Given my extensive radio and millimeter observing experience and my history of involvement with NRAO, I would appreciate your consideration for this fellowship position. My ongoing research projects to study the Galactic center using NRAO facilities are an ideal match for the resources and research environment of NRAO-Socorro. As a recent participant in the Resident Shared-Risk Observing program in Socorro, I had an opportunity to observe with the cutting-edge capabilities of the Karl G. Jansky Very large Array, and to take advantage of local expertise which greatly increased my productivity and efficiency in analyzing the data. As a Jansky fellow based at the Science Operations Center, I would continue to both assist with the ongoing commissioning activities and to benefit from the opportunities to utilize the latest capabilities of the VLA.

With collaborators at both NRAO and New Mexico Tech, I am leading exciting research projects using NRAO facilities including the detection and characterization of a widespread, hot component of molecular gas in the Galactic center using the Green Bank telescope, and a new high-resolution survey of Galactic center gas using the VLA which is discovering widespread maser activity, and will yield the first resolved temperature maps of Galactic center molecular clouds. I propose to expand on these projects by undertaking complementary surveys with the VLA and the Atacama Large Millimeter Array to study the density structure of Galactic center clouds. Together with my existing work, this will allow me to study the physical processes which cause gas conditions tin the Galactic center to be different than those in the Galactic disk, and to constrain the initial conditions of Galactic center star formation. As a Jansky fellow, I will continue to further my collaborations with NRAO staff and lead independent research projects using the unique capabilities of NRAO facilities including the GBT, VLA and ALMA.

Sincerely,

Elisabeth Mills

Elisabeth A.C. Mills

Contact Information

3-145S Knudsen Hall
UCLA Department of Physics & Astronomy
430 Portola Plaza, Box 95154
Los Angeles, CA 90095-1547

Voice: (310) 825-1618
Fax: (310) 206-2096
E-mail: millsb@astro.ucla.edu
WWW: astro.ucla.edu/∼millsb

Education

University of California, Los Angeles, Los Angeles, California, USA
Ph.D. Track Graduate student **2007- present**

Indiana University, Bloomington, Indiana USA
B.S., Physics, Astronomy **2007**

Research Experience

Graduate Student Researcher **2008 - present**
- Advisor: Prof. Mark Morris, UCLA
- PhD Thesis: Extremes of Temperature and Density in Galactic Center Molecular Clouds

Graduate Student Researcher **2007-2008**
- Advisor: Prof. Andrea Ghez, UCLA
- Wrote pipeline analysis to characterize and remove false stellar detections from Galactic center astrometry data due to the adaptive-optics point spread function

Undergraduate Student researcher **2006**
- Advisor: Prof. Liese Van Zee, Indiana U.
- Determined HI rotation curves for a sample of nearby dwarf galaxies.

Summer researcher, NRAO–Socorro, NM REU program **Summer 2006**
- Advisor: Dr. James Aguirre, U. Colorado-Boulder
- Developed automated routine to detect sources in 1.1 mm survey data
- Compiled and analyzed multiwavelength data of the Galactic center
- Produced preliminary spectral energy diagrams of GC giant molecular clouds.

Summer researcher, NOAO–La Serena, Chile REU program **Winter 2005**
- Advisor: Dr. Hugo Schwarz, NOAO
- Reduced emission spectra of Planetary Nebulae
- Measured Balmer decrement to determine intervening extinction.

Undergraduate Student researcher **2002 - 2005**
- Advisor: Prof. Constantine Deliyannis, Indiana U.
- Processed and reduced multiple nights of open star cluster photometric data
- Determined cluster metallicity, reddening, distance and age

Awards

- NSF GK-12 Fellowship (*$30,000 + fees*) **2010-2011**
- Chancellor's Prize Graduate Summer Research Mentorship Award (*$5000*) **2008**
- Honorable mention, NSF Graduate Research Fellowship **2008**
- Chancellor's Prize (*$5000*) **2007-2008**
- Honorable mention, NSF Graduate Research Fellowship **2007**
- Outstanding Undergraduate Physics Major, IU Physics Dept. **2007**
- Honorable Mention, AAS Chambliss Award **2007**
- Johnson Award for Excellence in Student Research, IU Astronomy Dept. **2006**
- Alumni Award for Overall Academic Excellence, IU Astronomy Dept. **2006**
- Sigma Xi Grant-in-Aid of Research Award(*$500*) **2005**
- Elected to Phi Beta Kappa **2005**
- Indiana University Science, Technology, and Research Scholar **2002-2007**

Grants

- NRAO Student Observing Support Program (*$35,000*) **2010**

Accepted Observing Proposals

- Very Large Array: **PI for an exploratory proposal using Director's Discretionary Time**. 1.5 hours allocated to an observation of an unusual molecular cloud in the Galactic center.
- Very Large Array: **PI of project 'What is Heating Galactic Center Molecular Clouds?'** in semester 2011B. 24 hours allocated for a survey of continuum and molecular line emission from four molecular cloud complexes in the Galactic center
- Green Bank Telescope: **PI of project 'How Hot is Galactic Center Molecular Gas?'** in 2011B. 5 hours allocated to search for hot ammonia in an additional sample of clouds.
- Green Bank Telescope: **PI of project 'Probing extremes of density and temperature in Galactic center molecular clouds'** in semester 2010C. 9 hours allocated for a survey of very hot ammonia in a sample of Galactic center molecular clouds to constrain their temperatures.

Professional Experience

8th IRAM Interferometry School *(Grenoble, France)* — **October 14-19, 2012**

NRAO Resident Shared-Risk Observing Program *(Socorro, NM)* — **June - August 2012**

- Tested and documented new tools for VLA proposal preparation
- Redesigned the user interface for the CASA software webpage

13th NRAO Synthesis Imaging Workshop *(Socorro, NM)* — **May 29 - Jun 5, 2012**

- Assisted with observing preparation tutorials

12th NRAO Synthesis Imaging Workshop *(Socorro, NM)* — **June 8 - 15, 2010**

10th NRAO Synthesis Imaging Workshop *(Socorro, NM)* — **June 13 - 20, 2006**

Oral Presentations

Mills E.A., et al. *Star Formation Past and Future at the Center of our Galaxy*
Lunch Talk, National Radio Astronomy Observatory, Socorro, NM, July 2012

Mills E.A., et al. *Tidally-stable Gas in the Galactic Center Circumnuclear Disk?*
220th Meeting of the American Astronomical Society, Anchorage, AK, June 2012

Mills E.A., et al. *Hot clouds in the center of the Galaxy: Highly excited ammonia*
Lunch Talk, National Radio Astronomy Observatory, Socorro, NM, March 2011

Mills E.A. and Morris, M.R. *Extremely Hot Ammonia in the Galactic Center*
Star Formation Under Extreme Conditions: the Galactic Center, Besançon, France, December 2010

Poster Presentations

Mills E.A., et al. *Properties of G-0.02-0.07, the Sgr A East Complex of H II regions Within 10 Parsecs of the Galactic Center.*
215th Meeting of the American Astronomical Society, Washington, D.C., January 2010

Mills, E.A., et al. *Extinction toward the Compact HII Regions G-0.02-0.07.*
Galactic Center Workshop, Shanghai, October 2009

Mills, E.A., et al. *Characterizing Filamentary Structure in Images from an HST-NICMOS Paschen Alpha Survey of the Galactic Center.*
213th Meeting of the American Astronomical Society, Long Beach, CA, January 2009

Mills, E.A., et al. *Preliminary results from an HST-NICMOS Paschen alpha survey of the Galactic center* . International Summer School on the Galactic Center, Nagoya, Japan, September 2008

Teaching Experience

Culver City Middle School, Culver City, CA **2010-2011**
As a UCLA NSF GK-12 Fellow, spent two days a week partnered with a local teacher co-teaching and enhancing the science curriculum by developing new lesson materials.

University of California, Los Angeles, Los Angeles, CA
- *Teaching Assistant,'Astrophysics II: Stellar Evolution, Galaxies, and Cosmology'* **Spring 2010**
- *Teaching Assistant, 'Life in Universe'* **Summer 2009**
- *Teaching Assistant, 'Cosmology: Our Changing Concepts of the Universe'* **Spring 2009**
- *Teaching Assistant, 'Nature of Universe' lab* **Spring 2009**
- *Teaching Assistant, 'Stellar Atmospheres, Interiors, and Evolution'* **Winter 2008**

Center for Adaptive Optics Professional Development Program

Workshops:
- *Re-Thinking Science & Engineering Learning & Teaching*, Santa Cruz, CA **Nov. 30, 2007**
- *Inquiry in Science & Engineering Learning & Teaching*, Maui, HI **March 13-17, 2008**
- *Advancing Inquiry & the PDP Community* , Santa Cruz, CA **April 4, 2009**
- *Inquiry in Science & Engineering Learning & Teaching*, Maui, HI **May 8-12, 2009**

Teaching:
- *Po'okela program for Native Hawaiian high school students*, Maui, HI **July 2008**
  Helped develop, co-teach a week-long program of inquiry-based astronomy to encourage students to pursue science & technical careers in Hawaii.
- *Akamai Internship program for Hawaiian college students*, Big Island, HI **June 2009**
  Led a team to develop & co-teach a week-long program of inquiry-based astronomy to prepare students for a 10-week internship at the Mauna Kea Observatories.

Service

UCLA Astronomy Outreach Co-Coordinator **2010-2011**
UCLA Astronomy Journal Club Coordinator **2008-2009**

List of Publications

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

Mills, E.A., Morris, M.R., Lang, C.C., Cotera, A., Dong, H., Wang, Q.D., Stolovy, S. *Extinction toward the Compact HII Regions G-0.02-0.07* 2011, PASP, 439:125-127

Dong. H. , Wang, Q.D., Cotera, A., Stolovy, S., Morris, M.R., Mauerhan, J., **Mills, E.A.**, Schneider, G., Calzetti, D., Lang, C. *Hubble Space Telescope Paschen α survey of the Galactic Centre: data reduction and products.* 2011, MNRAS, 417:114-135

Stolte, A., Ghez, A.M., Morris, M.R., Do, T., Ballard, C., **Mills, E.A.**, Lu, J.R., Matthews, K. *L-band sources in the Arches cluster.* 2010, ApJ, 718:810-831

Bally, J., Aguirre, J., Battersby, C., Bradley, E.T., Cyganowski, C., Dowell, D., Drosback, M., Dunham, M.K., Evans, N.J. II, Ginsburg, A., Glenn, J., Harvey, P., **Mills, E.**, Merello, M., Rosolowsky, E., Shirley, Y.L., Schlingman, W., Stringfellow,G., Walawender, J., Williams, J. *The Bolocam Galactic Plane Survey: Dust Continuum Emission in the Galactic Center Region.* 2010, ApJ, 721:137-163

Rafelski, M., Foley, M., Graves, G. J., Kretke, K. A., **Mills, E.**, Nassir, M., Patel, S. *Teaching Astronomy with an Inquiry Activity on Stellar Populations.* 2010, PASP, 436, 108-119

Sonnet, S., **Mills, B.**, Hamilton, J.C., Kaluna, H. *The 2009 Akamai Observatory Short Course Inquiry Activity: "Design and Build a Telescope"* 2010, PASP, 436, 131-137

Beers, T.C., Flynn, C., Rossi, S., Sommer-Larsen, J., Wilhelm, R., Marsteller, B., Lee, Y.S., De Lee, N., Krugler, J., Deliyannis, C.P., Simmons, A.T., **Mills, E.**, Zickgraf, F.J., Holmberg, J., nehag, A, Eriksson, A., Terndrup, D., Salim, S., Andersen, J., Nordström, B., Christlieb, N., Frebel, A., Rhee, J. *Broadband UBVRCIC Photometry of Horizontal-Branch and Metal-poor Candidates from the HK and Hamburg/ESO Surveys. I.* 2007, ApJS, 168:128-139

Constraining the Physical Conditions in Galactic Center Molecular Clouds

The central five hundred parsecs of the galaxy (the Galactic center, or GC) is a harsh environment for molecular gas. GC molecular clouds experience strong tidal shear, especially when in close proximity to the central supermassive black hole. The clouds are subject to winds and intense ultraviolet radiation from multiple young, massive star clusters and isolated massive stars (Figer & Morris 2002; Mauerhan et al. 2007). Further, there is evidence that GC clouds experienced a strong X-ray burst from the SMBH as recently as 100 years ago (Ponti et al. 2010). That this environment has an effect upon the molecular gas seems apparent: the properties of GC gas are markedly different from those of gas in the Galactic disk. It is not yet clear which environmental factor is primarily responsible, but what is clear is that GC clouds are characterized by large, turbulent linewidths, (15-50 km s^{-1}, Bally et al. 1987), high gas temperatures (50−300 K, Hüttemeister et al. 1993; Mauersberger et al. 1986), and substantial densities ($n > 10^4$ cm^{-3}, Zylka et al. 1992).

However, recent observations suggest that the conditions in GC clouds are not so clearly defined after all. 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^{-3} are claimed (Montero-Castaño et al. 2009). In order to identify the environmental factors which are responsible, the presence of these extreme gas properties must be constrained in a larger sample of GC clouds to determine if they are local anomalies or globally characteristic of the GC gas.

My research comprises a multiwavelength probe of the Galactic center environment and consists of four related studies which place new limits on the gas properties in a sample of clouds throughout the GC. Together, the studies I have led indicate the widespread presence of hot gas in GC clouds, determine the density of gas close to the black hole, and yield the first measurements of physical conditions in individual clumps interior to GC clouds.

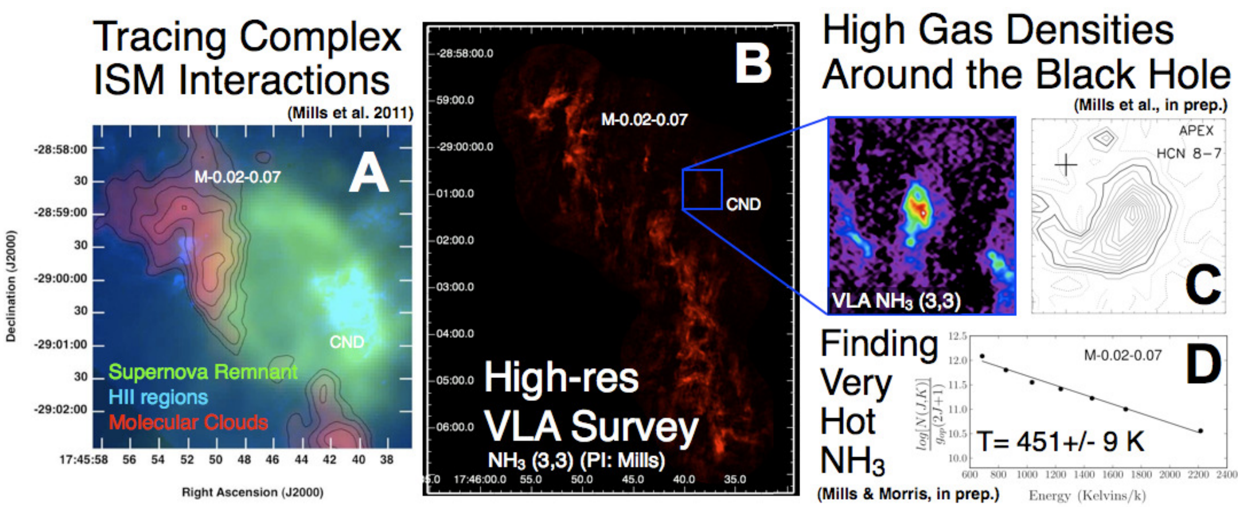

Fig. 1.— *From Left to Right:* **(A)** *Data from the HST and VLA trace the interaction between an unusual GC cloud and a group of H II regions.* **(B)** *A VLA survey yields the first high-resolution images of GC clouds.* **(C)** *NH_3 and highly-excited lines of HCN indicate very dense gas in the circumnuclear disk, a massive molecular ring in the central parsec.* **(D)** *GBT observations of highly-excited NH_3 find a very high-temperature gas component apparently common to GC clouds.*

1. Interactions between a Molecular Cloud and the GC Environment

The M-0.02-0.07 molecular cloud is a unique example of the variety of hostile environmental factors GC molecular gas is subject to. This cloud lies just 6 parsecs from the central supermassive black hole, is being compressed by the nearby Sgr A East supernova remnant (Serabyn et al. 1992), and has experienced recent star formation evidenced by a group of compact H II regions (Figure 1a).

To better depict the physical relationship between these sources, I used archival VLA observations and Paschen α images from the Hubble Space telescope to determine the extinction toward the H II regions (Mills et al. 2011). From the measured extinctions and source morphologies, I determined that three of the H II regions lie on the front side of the cloud and formed in the eastern part of the cloud which is unaffected by the supernova remnant's expansion. The higher extinction of the fourth H II region indicates it is embedded in the supernova-compressed ridge, and though younger than the other H II regions, is still older than the supernova. This work is an important determination of the their line-of-sight placement of these sources which helps to define their interaction and strengthens the case that the supernova did not trigger the formation of the H II regions.

2. A Very Hot Gas Component in the Galactic Center

In Sgr B2, a GC cloud with even more active embedded star formation, a very hot gas component has been detected using absorption lines of highly excited NH_3 ($\sim$ 700 K, Ceccarelli et al. 2002; Wilson et al. 2006). However, existing surveys are not sufficiently broad to indicate 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, in prep.). I observed multiple highly-excited lines of NH_3 , and detected emission from the (9,9) line of NH_3 (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 (Figure 1d), substantially higher than previous temperatures of 200-300 K measured for these clouds (Mauersberger et al. 1986). My widespread detections of gas hotter than 400 K indicates for the first time that his hot gas must be heated by global processes in the GC. Because these NH_3 lines are observed in emission, I further constrain the hot gas to have densities $> 10^3 - 10^4$ cm^{-3} , suggesting that the heating mechanism may be internal shocks.

3. Determining Gas Densities Near the Black Hole

Gas in GC clouds can achieve average densities of $10^5 - 10^6$ cm^{-3} (Longmore et al. 2012), but just how dense these quiescent clouds can ultimately become is uncertain. 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, indicate densities that exceed 10^8 cm^{-3} (e.g., Montero-Castaño et al. 2009). However, these densities are determined by assuming virial equilibrium, which may not apply. Other recent studies using low-density tracers such as CO, or dust properties, find lower densities of $10^4 - 10^5$ cm^{-3} (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^{-3} .

To determine the density of the CND, I observed multiple transitions of HCN and HCO^+ with the APEX telescope, a 12m ALMA propotype dish (Figure 1c). These molecules have critical densities $> 10^7$ cm^{-3} and directly constrain the existence of high-density gas. An excitation analysis of HCN and HCO^+ yields significantly tighter limits on the density ($n =$

$10^{5.7} - 10^{7.6}$ cm^{-3}), but I cannot rule out the possibility that the gas is tidally stable or in virial equilibrium (Mills et al., in prep.). To reduce the uncertainty due to averaging gas with different properties in the large 30″ APEX beam, I have proposed for complementary high-resolution Cycle 1 ALMA observations that will conclusively determine whether tidally stable clumps exist in the CND.

4. A High-resolution Study of Cloud Structure

In addition to constraining the global extremes of GC gas properties, I also want 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 (Figure 1b). The data were observed in early 2012 as part of the Resident Shared Risk Observing program (RSRO), and I spent summer 2012 in residence at NRAO-Socorro beginning the calibrations and analysis.

As part of this work, I observed the CND in multiple lines of NH_3. The temperature measurements I derive in this study can be used to refine the densities I derived from my excitation analyses of HCN and HCO^+ . I find preliminary CND gas temperatures of 100-200 K, which further limits the gas density in the CND to between $10^6 - 10^{6.8}$ cm^{-3} , indicating that the majority of the CND gas is likely not virialized or tidally stable (Mills et al., in prep.)

I also detect weak emission in several of these clouds from the highly-excited NH_3 (9,9) line I previously observed with the GBT. By comparing the line fluxes measured by these two telescopes I will be able to determine the fraction of the emission which is resolved out by the VLA, indicating the scales on which this emission arises. I will also compare the morphology of the (9,9) emission observed with the VLA to that from lower NH_3 lines to measure the temperature structure of this very hot gas in GC clouds.

An unanticipated discovery of this study has been hundreds of weak, collisionally-excited CH_3OH masers which are detected in all of the clouds we survey. We also find several rare NH_3 (3,3) masers coincident with the CH_3OH masers, which require local densities to be $< 10^6$ cm^{-3} (Walmsley & Ungerechts 1983). The masers are distributed non-uniformly in the clouds, with concentrations indicating regions of shock activity which may be driving the evolution of physical conditions in these clouds.

I have used a diverse set of observations to set new constraints on the extreme gas conditions which exist in the GC. This work demonstrates my experience analyzing a variety of millimeter and radio data, and paves the way toward the work I will undertake as Jansky fellow to understand the processes which control the evolution of molecular gas in this volatile region.

References

Bally, J., et al. 1987, ApJS, 65, 13 • **Ceccarelli**, C., et al. 2002, A&A, 383, 603 • **Etxaluze**, M., et al. 2011, ApJ, 142, 134 • **Figer**, D. & Morris, M. 2002, ASPCS, 285, 381 • **Hüttemeister**, S. et al. 1993, A&A, 280, 255 • **Longmore**, S. N., et al. 2012, ApJ, 746, 117 *bullet* **Mauerhan**, J., et al. 2007, ApJ, 662, 574 • **Mauersberger**, R., et al. 1986, A&A, 162, 199 • **Mills**, E., et al. 2011, ApJ, 735, 84 • **Montero-Castaño**, M., et al. 2009, ApJ, 695,1477 • **Ponti**, G., et al. 2010, ApJ, 714, 732 • **Serabyn**, E., et al. 1992, ApJ, 395, 166 • **Sjouwerman**, L., et al. 2010, ApJL, 710, 111 • **Walmsley**, C. & Ungerechts, H. 1983 A&A 122 164 • **Wilson**, T., et al. 2006, A&A, 460, 533 • **Zylka**, R., et al. 1992, A&AS, 96, 525

What Regulates the Physical Conditions in the Galactic Center?

The gas conditions in the center of our Galaxy are starkly different than those in the surrounding Galactic disk. On average, Galactic center (GC) molecular clouds are significantly hotter, denser, and more turbulent than disk clouds. Are these unique central conditions the result of ongoing feedback (e.g., winds and radiation from the central stars or supermassive black hole), the effects of which will propagate outward to the surrounding Galaxy? Or, are the properties of the GC molecular 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 gas conditions in the GC are so extreme, it has also 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 measured bulk gas properties throughout the GC then actually characteristic of conditions in the unresolved individual star-forming cores?

As a Jansky fellow at NRAO-Socorro, I will use NRAO facilities to study the 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.

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

The low resolution of prior surveys ($1' - 2'$, 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 improve on existing surveys by undertaking the first high-resolution survey of molecular line emission on scales as small as thousands of AU, across the central 500 parsecs of our Galaxy, using multiple molecular tracers which are sensitive to both high temperatures and densities. This work will constrain the full range and spatial distribution of density, temperature, and turbulence in GC gas, with which I will directly probe the initial conditions of GC star formation and test the predictions of models for the processes that control gas conditions in the GC.

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 (Silk and Rees 1998; Hopkins and Elvis 2010). Although the Milky Way's central black hole is currently quiescent, its recent activity is traced by gamma-ray lobes which emanate from the center of the Galaxy (Su et al. 2010) and an X-ray echo from an outburst in the last hundred years (Ponti et al. 2010). Frequent black hole activity can result in a higher flux of X-ray and cosmic rays in the GC. These heating sources 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 which are everywhere 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 (McKee and Ostriker 1977; Murray et al. 2010).

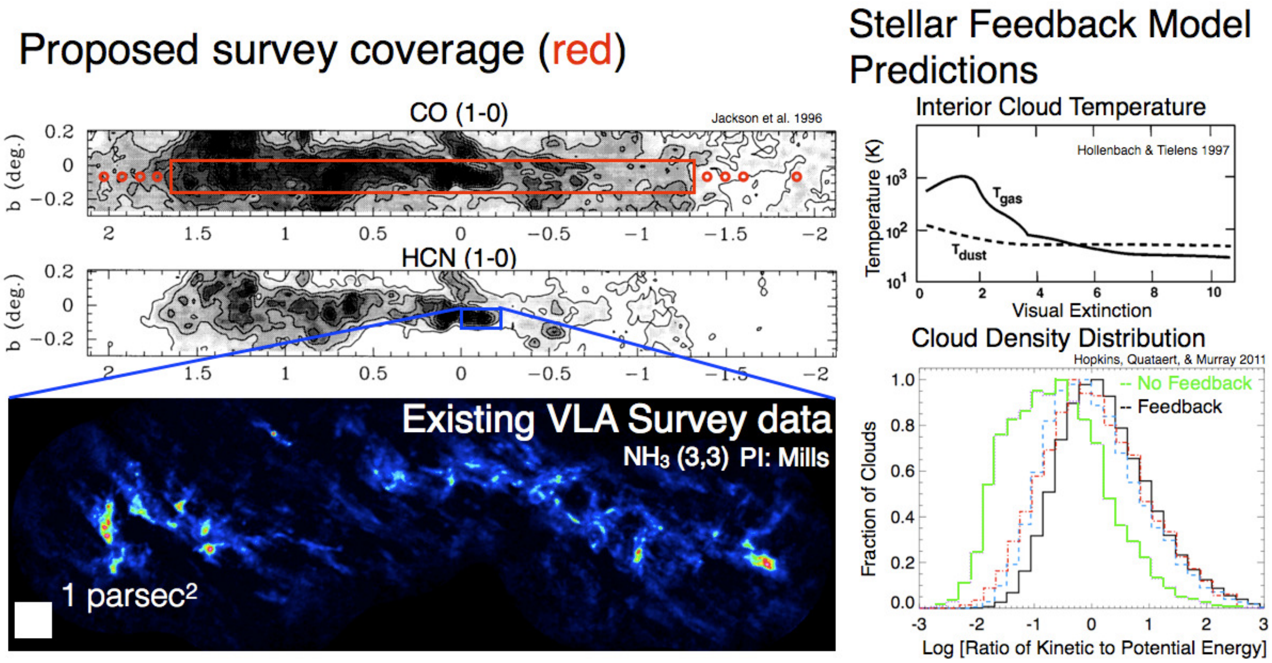

Fig. 1.— **Top Left:** *The distribution of molecular gas in the Galactic center, showing the region I propose to survey in red.* **Bottom Left:** *A completed study of a sample of clouds, illustrating the resolution and sensitivity attainable with the VLA.* **Right:** *Global and local predictions of feedback models which can only be tested with large-area, high-resolution survey of the Galactic center gas like that which I propose.*

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 and 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.

3. Constraining the Initial Physical Conditions for GC Star Formation

I will also use measurements of the physical conditions within GC clouds to investigate the conditions in pre-stellar clumps. By characterizing the temperatures, turbulence, and densities on the smallest spatial scales I will constrain the initial conditions of future star formation in this gas, including the characteristic Jeans mass for collapse, whether the cores are virialized, and the extent to which turbulent pressure supports these cores.

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 determine the turbulent pressure in individual clumps. By comparing this pressure to the measured density, I will further test 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. Recent 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 measure the internal temperature structure of GC clouds and map the distribution of the hottest gas (T > 400 K) in each cloud across the GC. As this 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. NH_3 is an ideal temperature tracer for this work as it has multiple transitions covering a wide range of energies which are closely spaced in frequency, and it is excited only in relatively dense gas ($n > 10^3$ cm^{-3}). Even though NH_3 is one of the most widely used temperature probes of molecular gas, the collisional coefficients necessary to model the excitation of lines which trace gas temperatures above 300 K do not exist. I will collaborate on both extrapolating collisional coefficients and modeling the high-excitation lines with Juergen Ott at NRAO-Socorro, who has developed a code to analyze lower-excitation NH_3 lines.

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). In addition, non-masering emission and absorption from these lines will also help determine the temperature and density in non-shocked regions (Mehringer and Menten 1997).

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

5. NRAO Facilities I Will Use in This Study

Karl G. Jansky Very Large Array: Using the new capabilities of the VLA, I propose to 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 which can be observed simultaneously with the shock-tracing 6.6 and 12.2 GHz CH_3OH lines. With a $4'$-$7'$ field of view, mapping the proposed area is a medium-sized project ($\sim$ 70 hours). By using the most compact array configuration, this study will be sensitive to emission on scales of entire clouds, limiting the susceptibility to resolving out large-scale emission that is a frequent complication of interferometric studies.

I already have data from a 0.1 pc resolution VLA study of NH_3 in five of the most massive GC clouds (RSRO Program 11B-210, PI: Mills). These data will be combined with an existing Australian Telescope Compact Array (ATCA) survey of NH_3 (PI: Juergen Ott) to increase sensitivity to emission on large scales, yielding accurate measurements of the temperature structure in GC cloud interiors.

Green Bank Telescope: I will also propose sensitive GBT 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 (Programs 10C64 & 11B74, 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: ALMA's high resolution is ideal for follow-up of individual dense cores to study their density structure and kinematics. I have already submitted a pilot project for ALMA Cycle 1 to study the conditions in group of clumps in the Circumnuclear disk using a variety of tracers including SO, HCN, and CS. I will propose to conduct similarly high-resolution (10^3-10^4 AU) ALMA observations for a larger sample of 20-30 especially dense clumps identified by the VLA survey to measure the physical conditions in their interiors. With the sensitivity of ALMA, observing a sample of this size will be a medium-sized project ($\sim 40 - 50$ hours).

6. NRAO-Socorro

By taking the Jansky fellowship to NRAO-Socorro, I will be able to collaborate with researchers at both NRAO and New Mexico Tech. I will work closely with both Juergen Ott and Dave Meier to model the physical conditions in the gas and develop new analysis code for the highly-excited NH_3 lines which I will observe. At NRAO, I will further have access to support for planning, executing, and calibrating observations using the newly upgraded VLA.

As a Jansky fellow, I will build a picture of the physical conditions in the Galactic center from the largest (600 pc) to the smallest (10^3 AU) scales. Together, the surveys I lead will identify the mechanisms behind the unique GC gas properties, quantify their effect on the initial conditions for star formation, and ultimately determine whether current conditions in the GC have implications for the future evolution of the entire galaxy.

References

Bally, J., et al. 1987, ApJS, 65, 13 • **Binney**, J. et al. 1991, MNRAS, 252, 210 • **Cragg**, D., et al. 1992, MNRAS, 259, 203 • **Galli**, D., et al. 2002, A&A, 394, 275 • **Glassgold**, A., et al. 2012, ApJ, 756, 157 • **Goto**, M., et al. 2008, ApJ, 688, 306 • **Hopkins**, P. & Elvis, M. 2010, MNRAS, 401, 7 • **Hopkins**, P., et al. 2012, MNRAS, 421, 3488 • **Hüttemeister**, S. et al. 1993, A&A, 280, 255 • **Lada**, C. J., et al. 2008, ApJ, 672, 410 • **Longmore**, S. N., et al. 2012, ApJ, 746, 117 • **Maness**, H., et al. 2007, ApJ, 669, 1024 • **Mangum**, J., et al. 2008, ApJ, 673, 832 • **McKee**, C. & Ostriker, J. 1977, ApJ, 218, 148 • **Mehringer**, D. & Menten, K. 1997, ApJ, 474, 346 • **Menten**, K. 1991, ASPCS, 16, 119 • **Morris**, M. 1993, ApJ, 408, 496 • **Murray**, N., et al. 2010, ApJ, 709, 191 • **Ponti**, G., et al. 2010, ApJ, 714, 732 • **Silk**, J. & Rees, M. 1998, A&A, 708, 1 • **Su**, M., et al. 2010, ApJ, 724, 1044 • **Tielens**, A. & Hollenbach, D. 1985, ApJ, 291, 722 • **Wilson**, T., et al. 1982, A&A, 115, 185