

Galactic-scale Therapy: What Makes the Center of our Galaxy so Hostile?

The Milky Way Galaxy in which we live is a relatively typical, quiet galaxy which stretches 100,000 light years from end to end. Our Sun is one of a hundred billion other stars, all of which orbit a supermassive black hole in the very center of the Galaxy with a mass of 3 million Suns. Much of the gas in our Galaxy which will form new stars is concentrated in the central 1500 light years around the black hole in giant clouds, each of which are tens of light-years across.

However, although our Galaxy is quiescent on larger scales, the conditions in this central gas are quite extreme, and starkly different than those in the surrounding Galaxy. On average, clouds of Galactic center (GC) molecular gas are significantly hotter, denser, and more turbulent than clouds in the rest of the Galaxy (Morris & Serabyn 1996). Are these unique central conditions the result of ongoing winds and irradiation from the nearby supermassive black hole or from the abundant massive stars in this region? If such ‘feedback’ processes are responsible, their effects could propagate outward and affect the evolution of the surrounding Galaxy. Or, do the properties of the GC molecular gas instead result from processes which remain confined to our Galaxy’s center: shocks, rotational shearing, and the release of gravitational energy as gas naturally migrates inward?

These extreme conditions may have additional implications for the stars that form in this gas. Observations indicate that the distribution of star masses forming in a cloud is the same throughout the galaxy (Bastian et al. 2010). However, based on the high temperatures and densities in GC gas, it is predicted that, on average, stars forming here should be heavier (Morris 1993). The effects of this should be apparent throughout the GC, but an excess of high-mass stars has only been measured in the central lightyear (Maness et al. 2007). Does this apparent lack of an excess indicate that the gas conditions do not have an effect on the star formation? Determining whether or not the stars which form in the GC are unusual is important: if stars forming in extreme gas conditions are themselves more extreme, the ultimate end of these massive stars as powerful supernovae will have a significant effect on how more active galaxies, and galaxies in the early universe, evolve.

As a President’s Postdoctoral Fellow at the University of Michigan, I will place the first constraints on the physical conditions in Galactic Center gas on the small scales interior to individual clouds 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 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 of GC gas (tens of lightyears, e.g., Bally et al. 1987; Hüttemeister et al. 1993), and the limited spatial coverage of recent studies which further probe the conditions in just a few clouds (e.g, Longmore et al. 2012) are not sufficient to constrain the full range of conditions that exist in this gas. To distinguish between different scenarios for the heating, turbulence, and densities of GC clouds requires a homogenous study of the gas conditions on both global scales and the small scales of cloud interiors which are most relevant to star formation.

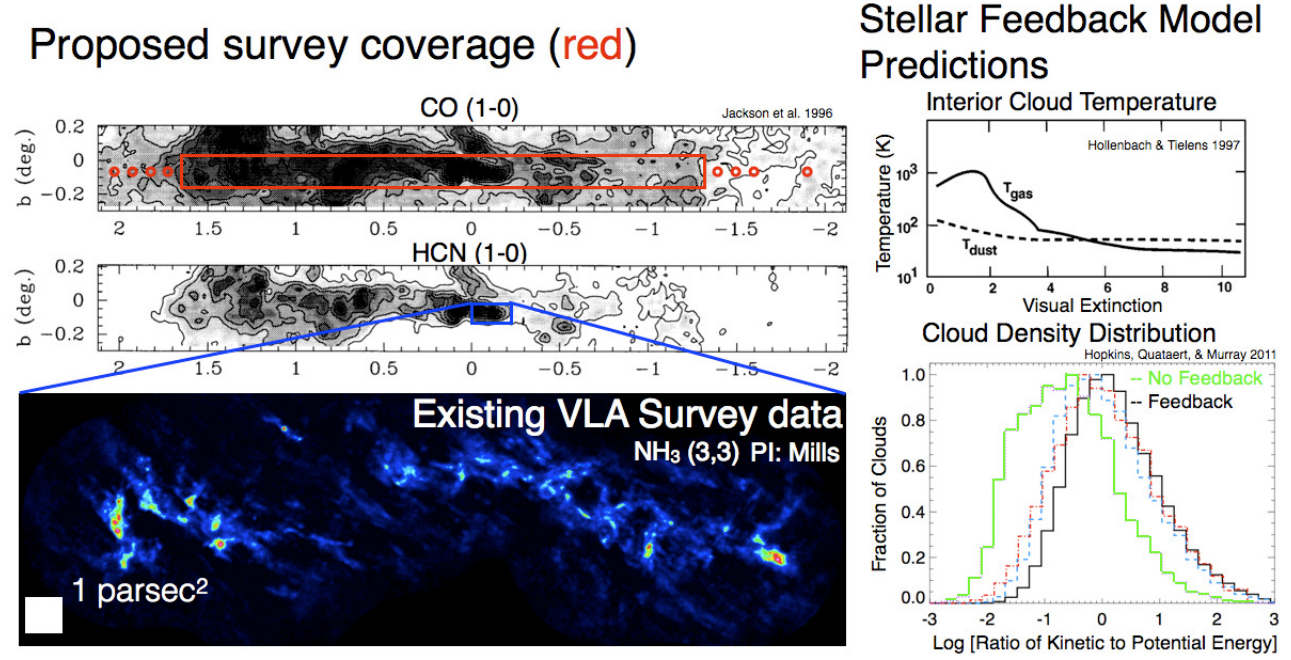


Fig. 1.— **Top Left:** The distribution of molecular gas in the Galactic center, showing the region I propose to survey in red. **Bottom Left:** A completed study of a sample of clouds, illustrating the higher resolution and sensitivity attainable with the VLA. **Right:** Global and local predictions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

I will improve on existing surveys by undertaking the first high-resolution survey of molecular line emission on scales as small as a tenth of a lightyear, across the central 1500 lightyears 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

Black Hole Feedback: Feedback from an actively accreting black hole can take the form of gas outflows or radiation that expel or heat the central gas (Silk & Rees 1998; Hopkins & 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 molecules such as carbon monoxide 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 & Ostriker 1977; Murray et al. 2010). 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 black hole heating in two important ways: (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 to the east of the black hole).

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 due to the barred structure of our Galaxy and proximity to the central supermassive black hole will both heat and disrupt GC clouds. 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 the large-scale shocks at the edge of the GC (where the gas becomes molecular, Binney et al. 1991) are primarily responsible for heating the gas, both temperature and shocks should decrease toward the center.

With measurements of the detailed density, temperature, and shock structure of GC as, I will determine whether its extreme 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 the clumps of gas which will form stars. These measurements will determine both how extreme these conditions are compared to the cloud as a whole, and the effect these conditions will have on the resulting star formation. 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 mass required for gravitational collapse, whether individual gas clumps are in gravitational equilibrium, or if they are turbulent structures.

Gravity vs. Turbulence: GC clouds are known to be extremely turbulent, but the contributions to this turbulence from the random motions of gas clumps within a cloud and smaller-scale turbulence within these clumps is not well constrained. By measuring the detailed structure of the velocity field and its dispersion in these clouds, I will determine the turbulent pressure within individual clumps. By comparing this pressure to the measured density, I will be able to test whether these clumps are gravitationally bound, or merely transient features like eddies in a turbulent flow, which will quickly dissipate.

Clump Mass Distribution: Using spatially-resolved measurements of the density structure within GC clouds, I will also make the first measurement of the distribution of gas clump masses inside of GC clouds. Recent observations elsewhere in the Galaxy suggest that the distribution of gas clump masses translates directly to the distribution of stellar masses which form from these clumps (e.g., Lada et al. 2008). By comparing the slope and characteristic mass of the clump mass distribution in a sample of GC clouds to those derived in other Galactic environments, I will perform a unique test of existing hypotheses that the GC environment causes the stellar mass distribution to differ from that in the rest of the Galaxy.

4. Determining Physical Conditions from Molecular Line Observations

In order to determine the physical conditions in Galactic center gas, I will observe a variety of molecules within these gas clouds whose observable properties are sensitive to the physical conditions in the cloud. The temperature and density within the gas clouds control the frequency with which individual molecules collide with each other and are excited into more energetic configurations. By observing the intensity of spectral lines from molecules in different excitation states, one can derive the rate of collisions, and directly infer the gas properties. Depending on the structure of a molecule, and the way in which it is formed, different molecules are especially good at tracing temperature, density, and the presence of shocks in the gas.

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 (short on astronomical timescales), it should be tightly correlated with the location of the sources responsible for heating the gas. Ammonia (NH_3) is an ideal temperature tracer for this work as it is excited only in relatively dense gas ($n > 10^3 \text{ cm}^{-3}$) found in cloud interiors. However, even though ammonia is one of the most widely used temperature probes of molecular gas, collisional data necessary to model the excitation of lines which trace gas temperatures above 300 K do not exist. As part of this work I will extrapolate the existing data to develop an analysis code for modeling the high-excitation lines. This will let me conclusively determine its temperature, and the fraction of hot gas in each cloud.

Shocks: Along with highly-excited ammonia, methanol (CH_3OH) also traces the locations and velocities of shocks related to feedback or fueling. There are two types of methanol masers: collisionally-excited methanol masers (arising in shocks), and radiatively-excited methanol masers, which are seen near young stars, but also appear in absorption at the same location as the collisionally-excited masers (Menten 1991). I will observe both types, with the presence or absence of masering in these transitions serving as a probe of the 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 & Menten 1997).

Densities: Excitation analyses of optically-thin species such as formaldehyde (H_2CO) and cyanoacetylene (HC_3N) will tightly constrain the density of the gas (e.g., Mangum et al. 2008), especially when combined with temperatures determined using ammonia. 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. Facilities I Will Use in This Study

Most molecules have spectral lines in the microwave (millimeter wavelengths) and radio (centimeter wavelengths) bands. To study emission from these molecules, I will take advantage of the greatly expanded resolution, breadth, and sensitivity now available from a suite of world-class radio and millimeter telescopes, including the Karl G. Jansky Very Large Array (VLA) in New Mexico, the Green Bank Telescope (GBT) in West Virginia, and the Atacama Large Millimeter Array (ALMA) in Chile. Access to all of these telescopes is publicly available to astronomers at any institution, and I have a demonstrated history of leading successful observing

proposals for these facilities. As a graduate student, I have been the principal investigator for four successful proposals to use these telescopes, with several more currently pending.

Karl G. Jansky Very Large Array: Using the new capabilities of the VLA, I will conduct a large-area, high-resolution survey of dense gas in the GC (Figure 1, left) at two frequencies. I will observe the 4.8 and 14 GHz lines of the density-tracer formaldehyde which can be observed simultaneously with the shock-tracing 6.6 and 12.2 GHz methanol lines. With the large field of view of the VLA at these frequencies, mapping the proposed area is a medium-sized project (~ 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 0.3 lightyear-resolution VLA study of ammonia in five of the most massive GC clouds, for which I am principal investigator. These data will be combined with an existing single-dish survey of ammonia to increase sensitivity to emission on large scales, yielding accurate measurements of the temperature structure in GC cloud interiors.

The 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 several clumps in one cloud very close to the black hole using a variety of molecular tracers. I will propose to conduct similarly high-resolution (0.1 lightyears) 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).

Green Bank Telescope: I will also propose sensitive GBT observations of a large sample of clouds across the GC in two faint, high-excitation lines of ammonia, 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, for which I am also principal investigator, which indicates that the highly-excited ammonia is widespread (Mills & Morris, in prep.). This new study will cover a much larger fraction of the gas and will not only determine the actual temperature of the gas instead of a lower limit, but will also determine the fraction of gas in GC clouds which is at these high temperatures.

As a President's Postdoctoral fellow, I will build a picture of the physical conditions in the Galactic center from the largest to the smallest 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.

6. Incorporating Diverse Backgrounds into the Research Process

Each stage of the research process described above – proposal writing, data analysis, publication, and presentation of results – offers opportunities for student involvement and professional development. Traditionally, students are involved in the most basic stages: for example, taking the raw data observed from the telescope, and correcting it for artifacts, or reading papers to get background on the work. Although technical reading and repetitive computer tasks are

necessary parts of research, they can also be both daunting and off-putting to beginning students. Having students focus only on these tasks can discourage them from pursuing careers in astronomy or other sciences because these tasks do not emphasize students' diverse abilities.

We do not want to unnecessarily limit the field of people pursuing astronomy to those who feel confident in skills such as reading and computer-assisted analysis. We also do not want students to come out of their research experience having optimized only these skills, without the necessary preparation they will need for other aspects of research. The research projects which I propose to undertake will require many different types of skills: from visualization and pattern finding to look for unexpected features in our data, to interpreting and writing these results, to networking to disseminate these results, and creativity to devise follow-up studies. I plan to use these opportunities to get students involved in research in very different stages to engage a broad range of students, with different backgrounds, experiences, interests, and talents.

There are many ways to involve even beginning students in advanced stages of my research efforts. To introduce students to the data, I can have students look through images of molecules in different clouds, and pose questions, hypothesize about what they are seeing, and draw models of what they think is occurring. I can then discuss with them how their hypotheses and models relate to the goals of this research. As students get more involved with data calibration, I will use fellowship support and grant funds to bring them with me to conferences to give a 1-2 minute description of the data or the calibration as part of a talk I give. To get students involved with more technical reading, I will have them draft the abstract for a group paper, and then help them edit it to its final form. I will also involve all of the students I work with in helping to brainstorming follow-up ideas. For example, which clouds should we examine further? What other observations could we make to observe hot gas? Even if a student does not yet have the technical expertise to determine how to investigate an idea they may have, I will assist with that aspect, and show them how to turn their idea into a telescope proposal. Through my mentoring, my goal is to scaffold students – transitioning from supporting students in learning a wide range of research skills to giving students the tools to succeed on their own – and in doing so to make sure that students feel like collaborators, and not subordinates.

One of my personal goals is also to help students feel like insiders in the community. I plan to do this both by involving them in all stages of the research process, and by helping them discuss their work, network to start new collaborations, and understand where their work fits into the big issues in the field– all of which is part of life as a scientist. To help students understand how their research contributions tie in to larger issues, I will refer students not just to technical papers I have written, but to more general, popular articles, such as Wikipedia, press releases, and blog posts. To facilitate students making professional connections, I will take students to local and conference dinners to introduce students to colleagues, and send students to learn about data analysis techniques from my collaborators at nearby universities such as Iowa and Indiana. Most critically, I will ensure that my students periodically summarize, contextualize, and interpret the work they are doing, so that they can explain its importance to their friends and family.

By exposing students to a wider variety of research activities I hope to help students find aspects of research which appeal to them, and in which they excel, to increase their confidence and motivation. Perhaps more importantly, it will also expose them to research activities they may not be comfortable doing initially (such as giving a talk), giving them experience with the

variety of skills necessary to succeed throughout their careers. By introducing students to how research is done, from inception to completion, it is my goal to make the future steps in their career path appear less mysterious, and more attainable and relatable.

7. Researching Diversity

As an undergraduate, I participated in two NSF-sponsored Research Experience for Undergraduates or REU programs. One of the goals of these programs is to increase diversity by offering women and minority undergraduates considering pursuing a career in astronomy a real research experience. However, many students who go through astronomy REU programs ultimately do not choose to pursue an astronomy career. I am interested in the factors that contribute to students making this choice, especially those factors related to their experience doing REU research.

Many of the NSF-sponsored astronomy REU sites have operated for more than a decade. These programs have online databases of students, some of which already track the career choices of their students. With more than 20 NSF-sponsored REU programs, each of which accept 5-10 students, REU programs comprise a significant sample of undergraduate students with interest in astronomy. I propose to survey REU students from within the past 5 years about their research experiences. For example: How would they characterize the research they did (observing, data analysis, writing?). What sort of ownership did they feel over the process: did they help at all to determine the direction of their research, or was the entire project already laid out for them? Was their relationship with their advisor closer to a peer or boss? How did they feel about this research: challenged, bored, curious, confused? I will then survey these students again after they graduate from college (if they have not already done so). I will then compare the demographics of all students in REUs, and those who ultimately chose to pursue astronomy graduate school and search for correlations between retention, research experience, and the diversity and backgrounds of students.

The results of this research can be used to inform not just the design of REU programs and the choices and training that go into selecting mentors, but also mentor and research practices in general. Ultimately, I want to be able to provide advice on how we as astronomers and scientists can diversify our advising styles and make the way we involve students in research more conducive to building a profession which is itself diverse.

REFERENCES

- Bally, J., Stark, A. A., Wilson, R. W., & Henkel, C. 1987, *ApJS*, 65, 13
- Bastian, N., Covey, K. R., & Meyer, M. R. 2010, *ARA&A*, 48, 339, 1001.2965
- Binney, J., Gerhard, O. E., Stark, A. A., Bally, J., & Uchida, K. I. 1991, *MNRAS*, 252, 210
- Cragg, D. M., Johns, K. P., Godfrey, P. D., & Brown, R. D. 1992, *MNRAS*, 259, 203
- Galli, D., Walmsley, M., & Gonçalves, J. 2002, *A&A*, 394, 275, arXiv:astro-ph/0208416
- Glassgold, A. E., Galli, D., & Padovani, M. 2012, *ApJ*, 756, 157, 1208.0523

- Goto, M. et al. 2008, ApJ, 688, 306, 0807.4522
- Hopkins, P. F., & Elvis, M. 2010, MNRAS, 401, 7, 0904.0649
- Hopkins, P. F., Quataert, E., & Murray, N. 2012, MNRAS, 421, 3488, 1110.4636
- Hüttemeister, S., Wilson, T. L., Bania, T. M., & Martin-Pintado, J. 1993, Astronomy and Astrophysics (ISSN 0004-6361), 280, 255
- Lada, C. J., Muench, A. A., Rathborne, J., Alves, J. F., & Lombardi, M. 2008, ApJ, 672, 410, 0709.1164
- Longmore, S. N. et al. 2012, The Astrophysical Journal, 746, 117
- Maness, H. et al. 2007, The Astrophysical Journal, 669, 1024
- Mangum, J. G., Darling, J., Menten, K. M., & Henkel, C. 2008, ApJ, 673, 832, 0710.2115
- McKee, C. F., & Ostriker, J. P. 1977, ApJ, 218, 148
- Mehringer, D. M., & Menten, K. M. 1997, ApJ, 474, 346
- Menten, K. 1991, in Astronomical Society of the Pacific Conference Series, Vol. 16, Atoms, Ions and Molecules: New Results in Spectral Line Astrophysics, ed. A. D. Haschick & P. T. P. Ho, 119
- Morris, M. 1993, ApJ, 408, 496
- Morris, M., & Serabyn, E. 1996, ARA&A, 34, 645
- Murray, N., Quataert, E., & Thompson, T. A. 2010, ApJ, 709, 191, 0906.5358
- Ponti, G., Terrier, R., Goldwurm, A., Belanger, G., & Trap, G. 2010, ApJ, 714, 732, 1003.2001
- Silk, J., & Rees, M. J. 1998, A&A, 331, L1, arXiv:astro-ph/9801013
- Su, M., Slatyer, T. R., & Finkbeiner, D. P. 2010, ApJ, 724, 1044, 1005.5480
- Tielens, A. G. G. M., & Hollenbach, D. 1985, ApJ, 291, 722
- Wilson, T. L., Ruf, K., Walmsley, C. M., Martin, R. N., Batrla, W., & Pauls, T. A. 1982, A&A, 115, 185