

What Regulates the Physical Conditions in the Galactic Center?

The dynamics and structure of present-day galaxies on kiloparsec scales are thought to result from physical processes which occurred in just a few tens or hundreds of parsecs, in their very centers. Here, processes such as winds or radiation from the central stars or black holes, broadly characterized as ‘feedback’ (Silk and Rees 1998; Hopkins and Elvis 2010) are suggested to have led to the observed tight relation between black hole mass and bulge properties in galaxies including our own Milky Way (Gebhardt et al. 2000; Ferrarese and Merritt 2000). Does this connection between the central and large-scale properties of our Galaxy continue today?

Currently, in the central 500 parsecs of our own Galaxy, we find gas conditions which are starkly different than those in the Galactic disk. The molecular gas is hotter, more turbulent, and signatures of ongoing star formation in this substantial reservoir of dense gas are lacking (Morris and Serabyn 1996). Are the unique central conditions the result of ongoing feedback?

New observations indicate that our central black hole plays a more active role than previously realized: gamma-ray lobes emanate from the center of the Galaxy (Su et al. 2010), an X-ray echo traces a recent outburst (Ponti et al. 2010; Capelli et al. 2012), and an infalling gas cloud (Gillessen et al. 2012) may soon increase the flux of the accretion disk by an order of magnitude (Bower et al. 2012). Could the black hole then be responsible for the gas conditions, or are cloud properties instead influenced by another factor: the high density of massive stars in the region (Figer and Morris 2002; Mauerhan et al. 2007, 2010)? Alternatively, the properties of the molecular clouds could be unrelated to either type of feedback, and instead controlled by the shocks, shearing, and release of gravitational energy as gas naturally migrates to the center of the galaxy.

The proximity of the Galactic center (hereafter, ‘GC’) offers the opportunity to test these scenarios by determining the central gas conditions in detail that cannot be achieved for any other galaxy. By investigating whether the black hole or a starburst controls the central gas conditions and acts as a feedback mechanism to suppress star formation, or whether the temperature, density, and turbulence of the gas are a consequence of its migration from large radii to the center, it is then possible to address an intriguing question: are the conditions in the center of our Galaxy evolving from the inside-out, or the outside-in?

As a postdoctoral researcher, I will use newly-available radio and millimeter facilities to constrain the physical conditions in GC gas on sub-parsec scales, identifying the physical processes responsible for these unique conditions. As an NSF fellow jointly at NRAO-Socorro and the New Mexico Institute of Mining and Technology, I will be in close proximity to both collaborators and support for the newly-available capabilities of these facilities. These institutions also provide ideal infrastructure for a program to enhance the science skills and toolkits of local educators.

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

All that we currently know about the properties of the molecular gas in the central 500 parsecs has been determined from studies of single GC molecular clouds, or low-resolution surveys of the entire GC, which yield an incomplete picture of conditions in this region. Surveys have determined average GC cloud densities to be $\sim 10^4 \text{ cm}^{-3}$ (Bally et al. 1987; Jackson et al. 1993), but studies of individual clouds indicate higher densities of 10^5 to 10^6 cm^{-3} exist in some clouds (Serabyn et al. 1992; Requena-Torres et al. 2012; Longmore et al. 2012, , Mills et al., in prep.). Surveys of GC clouds measure average temperatures of $< 200 \text{ K}$, but do not constrain the temperature structure in cloud interiors (Guesten et al. 1985; Huettemeister et al. 1993). Hotter gas in these clouds, with temperatures $> 200 \text{ K}$, has also not been uniformly searched for outside of a handful of the most massive GC clouds (Mauersberger et al. 1986; Wilson et al. 1982; Wilson et al. 2006, , Mills & Morris, in prep.). However, a recent survey of the highly-excited (9,9) line of ammonia indicates that this hot gas component may in fact be a common feature of GC clouds (Mills & Morris, in prep.). Finally, the reported average densities and temperatures from existing studies are generally an approximation of the multiple temperature and density components which exist in GC clouds.

The low resolution and heterogeneous nature of prior studies are not sufficient to constrain the true variation in physical parameters in the dense gas across the GC and interior to individual GC clouds. To distinguish between different scenarios for the the heating, injection of turbulence, and lack of star formation in GC clouds requires a homogenous study of the dense gas conditions which is sensitive to the presence of multiple temperature and density components and allows for the physical conditions to be analyzed on both global scales and the small scales most relevant to star formation.

Using New Facilities for a Comprehensive Large-area, High-resolution Survey

With the new capabilities now available with both the Atacama Large Millimeter Array (ALMA) and the upgraded Karl G. Jansky Very Large Array (VLA), now is the ideal time to conduct a large-area, high-resolution study of the physical conditions in Galactic center gas. These facilities offer unprecedented sensitivity and wide instantaneous bandwidths that allow for fast mapping of large areas in multiple molecular lines. The combination of multiple molecular lines observed at radio and millimeter frequencies will probe a wide range of energies, facilitating excitation analyses to constrain the multiple temperatures and densities present in the molecular gas in an energetic region like the GC. My experience will allow me to rapidly capitalize on the capabilities of ALMA and the VLA to make the first surveys of physical conditions in GC clouds on scales as small as hundreds of AU, across the central 500 parsecs of our Galaxy (Figure 1).

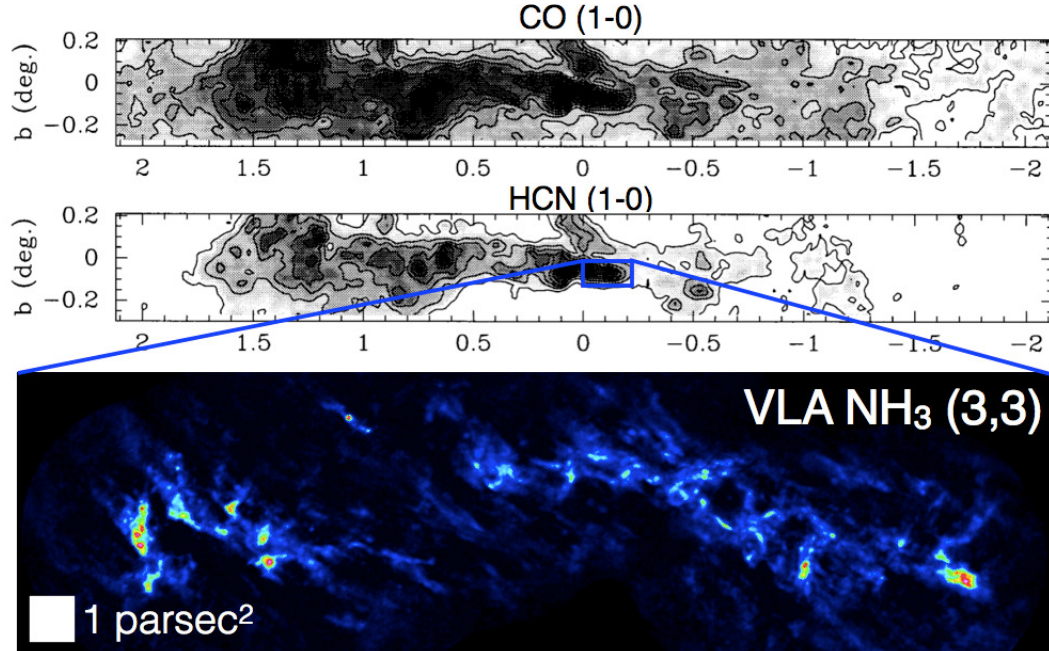


Fig. 1.— **Above**, Low-resolution maps of emission in $J = (1-0)$ lines of CO and HCN (Jackson *et al.* 1996), showing the central concentration of molecular gas which I propose to map at resolutions comparable to those shown **Below**, from a 2012 VLA survey (PI: Mills) of NH₃ and other molecules in four GC cloud complexes.

Using Physical Conditions to Test Predictions of Feedback Models

AGN feedback: Feedback from an active galactic nucleus (AGN) is believed to take the form of outflows or radiation which expel or heat the gas in a Galaxy’s nucleus (Silk and Rees 1998; Hopkins and Elvis 2010). Recent simulations (Zubovas and Nayakshin 2012) suggest our Galaxy may have experienced a black hole outflow within the last 5 Myrs which formed the observed Fermi Bubbles (Su *et al.* 2010) and compressed the observed 120-parsec radius central ‘ring’ of molecular clouds (Molinari *et al.* 2011). This fossil outflow should result in higher densities and a higher abundance of shock-excited molecules in GC clouds at or interior to this radius.

Heating from more recent black hole activity, such as that traced by a 150-year old X-ray light echo (Capelli *et al.* 2012) leaves additional signatures in the GC gas. The efficiency of heating from the resulting X-rays and cosmic rays is predicted to increase strongly with density (Glassgold *et al.* 2012), yielding GC clouds that should be systematically hotter than the lower-density molecular GC gas traced by studies of CO and H₃⁺ (Oka *et al.* 2012; Goto *et al.* 2008). Another effect of these penetrating heating sources is that the gas temperatures should be higher than the dust temperatures throughout the entire cloud (Galli *et al.* 2002). **AGN feedback models then predict a shock and density-enhanced fossil outflow, a positive correlation between GC cloud temperatures and densities, and gas temperatures which are universally higher than the dust temperatures.**

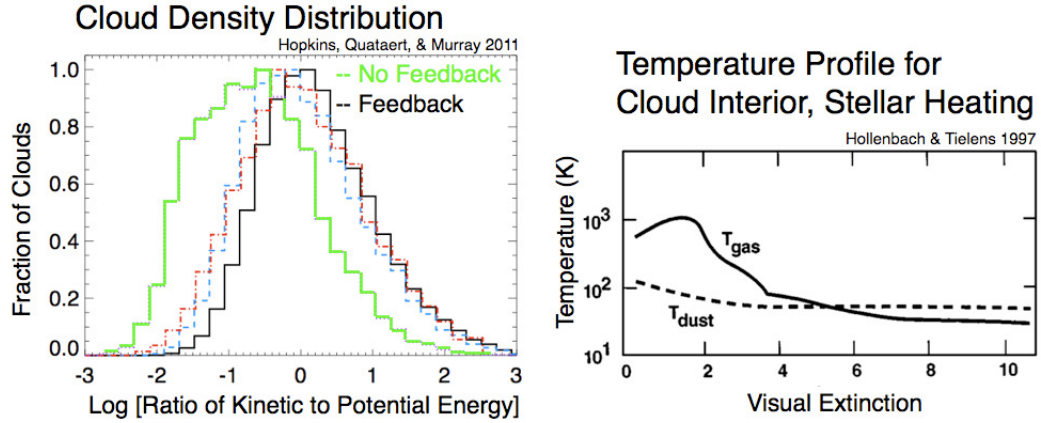


Fig. 2.— *Models from Hopkins et al. (2011) and Hollenbach and Tielens (1997), illustrating predictions of stellar feedback which are only testable with a uniform, large-area survey of cloud conditions on scales which probe their interior structure*

Stellar feedback: Stellar feedback – the injection of energy from evolved stars into the surrounding gas which turns off its star formation– can be caused by radiative heating, as well as winds from massive stars and supernovae (McKee and Ostriker 1977; Matzner 2002; Murray et al. 2010). Simulations of both types of Galactic-scale stellar feedback (Hopkins et al. 2011, 2012a,b) predict that not only are molecular cloud cores less gravitationally bound in the presence of stellar feedback (Hopkins et al. 2012b), but the fraction of gas at high densities decreases with increasing feedback strength (Hopkins et al. 2011). These predicted distributions of cloud densities (Figure 2) can be directly compared to the observed density distribution of gas in GC cloud interiors.

Purely radiative stellar feedback, which heats the gas at its interface with the photodissociation region, predicts gas temperatures in the most shielded regions to be cooler than dust temperatures (Tielens and Hollenbach 1985). However, shock-heating from stellar winds can elevate the gas temperature above the dust temperature, as is also expected for X-ray and cosmic-ray heating from the black hole. In this case, the global heating pattern should distinguish between the two processes, as the the global temperature pattern for stellar feedback should follow the asymmetry of young stars in the GC which are predominately located at positive Galactic longitudes. **Stellar feedback models then predict a specific density distribution of GC clouds, as well asymmetric global heating and regions where the dust temperature exceeds the gas temperature.**

Feedback or Fueling: is Galactic Center Evolution Inside-Out or Outside-In?

Although feedback processes may be one explanation for the temperature, density, and turbulent structure of GC gas, processes which fuel gas to the center of the Galaxy are another possible culprit. Tidal shearing due to differential Galactic rotation provides a mechanism to inject the observed turbulence into GC clouds as well as heat them (Fleck 1980; Wilson et al. 1982; Güsten 1989). As the strength of the shearing scales inversely with

distance to the center, GC cloud temperatures should increase with proximity to the center (Wilson et al. 1982). While this is a similar global pattern to that predicted by X-ray or cosmic-ray heating from black hole feedback, the two can be distinguished as shearing gives rise to turbulent shocks, and so the incidence of shocks should also increase with temperature.

Because the GC molecular gas is believed to originate in large-scale shocks along the bar at radii of 200 pc (Binney et al. 1991), similar to those observed in other galaxies (Meier and Turner 2005; Jogee et al. 2005), it is possible that these shocks alone are the primary origin of the high temperatures, densities, and turbulence in GC clouds. In this scenario, the shocks are strongest at these large radii, and tracers of shocked gas, such as methanol masers, should decrease with proximity to the center. The hot ($T > 400\text{K}$), dense gas component of GC clouds, which is also suspected to originate in shocks (Ceccarelli et al. 2002, Mills & Morris in prep) is an especially sensitive tracer of this hypothesis as its cooling time is only $\sim 10^3$ years (Wilson et al. 1982). If clouds are dominantly heated by shocks at larger Galactocentric radii, their maximum temperature, as well as the fraction of hot gas in each cloud, should decrease with decreasing radius. **Thus, fueling processes predict temperatures and the incidence of shocks to be correlated, both either increasing or decreasing with proximity to the center.**

Constraining the Processes that Suppress the Star Formation

In addition to distinguishing between the effects of feedback and fueling processes, measurements of the physical conditions in the clumps interior to GC clouds will also be used to identify the current barrier to star formation in this region: is it high temperatures, turbulence, or low densities?

High temperatures and turbulence: Models of supersonic flows in giant molecular clouds predict that stars will only form in cores where thermal pressure dominates over turbulent (Gong and Ostriker 2009, 2011). By observing a sample of dense cores, I will determine the relative contributions of thermal and turbulent pressure—calculating an expected thermal line width from the measured temperatures, and comparing this to the observed line width to determine the remaining contribution from turbulent pressure. I can further search for evidence in the sample that this ratio evolves, and determine whether thermal cores currently exist in this environment.

Low densities: Using spatially-resolved measurements of the density and velocity structure within GC clouds, I will test whether the observed dense clumps are virialized (and likely pre-stellar) or whether the clumps are in pressure equilibrium, or simply transient features. I will also make the first clump mass function for the GC. Recent observations suggest that the clump mass function maps directly to the stellar initial mass function, with an approximately constant star formation efficiency (Lada et al. 2008; Enoch et al. 2008). By comparing my derived GC clump mass function to those derived in disk environments, I will perform a unique test of existing hypotheses that the GC environment causes the initial stellar mass function to differ from that in the disk (Morris 1993; Morris and Serabyn 1996).

Determining Physical Conditions from Molecular Line Observations

Temperatures: As described above, measuring the global and internal temperature structure of GC clouds is one of the best diagnostics of the physical processes which affect GC clouds, discriminating between AGN feedback, stellar feedback, and tidal heating. To measure the internal temperature structure of GC clouds, I will observe multiple transitions of ammonia (NH_3), which are sufficient to constrain kinetic temperatures in excess of 300 K (Mauersberger et al. 1986; Flower et al. 1995), and map the distribution of the hottest gas in each cloud across the GC (Wilson et al. 2006). 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 ($n > 10^3 \text{ cm}^{-3}$).

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. As part of this study, I will contribute both extrapolations of the existing collisional coefficients as well as analysis software to model the high-excitation lines I observe. I will collaborate on this project with Juergen Ott at NRAO-Socorro, who has developed analysis code for lower NH_3 lines (Ott et al. 2005).

Shocks: Tracing the distribution and strength of shocks in GC clouds, as previously described, is the primary diagnostic of the effects of feedback vs. fueling. In addition to using highly-excited lines of NH_3 to trace hot, shocked gas, methanol (CH_3OH) will also serve as an ideal tracer of the locations and kinematics of shocks. 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 1991a). The presence or absence of masing in multiple transitions will be used as a probe of the excitation conditions in the shocked gas (Cragg et al. 1992; Menten 1991b). In addition, non-masering emission and absorption from these lines that is also present in GC clouds will be used as a secondary probe of temperature and the density in non-shock regions (Mehringer and Menten 1997).

Densities: As shown previously, measuring the distribution of GC gas densities and the density structure interior to GC clouds is critical for constraining the strength of potential stellar feedback, as well as identifying the processes hindering current star formation in cloud interiors. To effectively constrain GC cloud densities, I will use optically thin tracers of dense gas such as formaldehyde (H_2CO) and cyanoacetylene (HC_3N).

Excitation analyses of these species yield good constraints on the physical conditions, the temperature and especially the density of the gas (e.g., Güsten and Henkel 1983; Zylka et al. 1992; Mangum et al. 2008; Ginsburg et al. 2011), which can be significantly improved by restricting the allowed temperatures to those determined using NH_3 (Mills et al. in prep, Figure 3). By using multiple lines of multiple density tracers, including CH_3OH , HC_3N , and H_2CO , it will be possible to approximate the conditions in GC clouds as at least two temperature/density components, a significant improvement on previous studies which determined a single bulk temperature and density for each cloud.

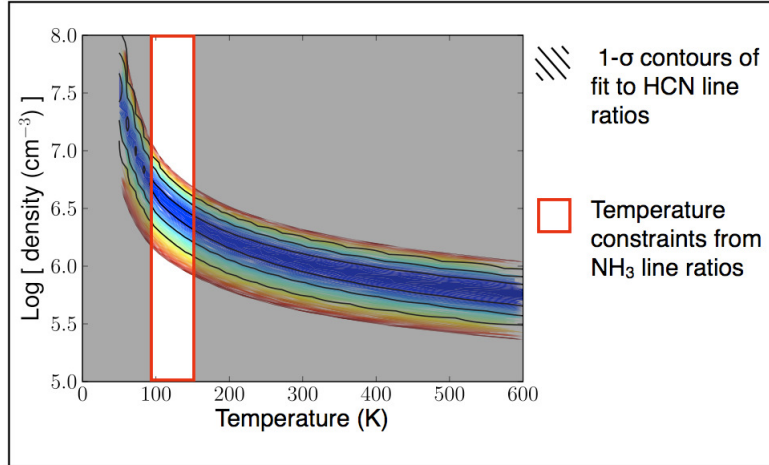


Fig. 3.— Combining dense gas tracers with temperatures from NH_3 yields a powerful density constraint. Here, an analysis using multiple lines of the dense gas tracer HCN constrains the gas density to within two orders of magnitude. However, by adding temperature constraints derived from NH_3 , the density is constrained to within a factor of 2.

Facilities I Will Use in This Study

Very Large Array: Using the new capabilities of the VLA, I will conduct a large-area ($\sim 3 \times 0.3^\circ$), high-resolution ($8''=0.5$ pc) survey of dense gas in the GC, spanning the entire central 3° (440 pc), with additional pointings out to central 4° (600 pc) to examine the transitions of gas properties at the edge of the GC. 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. The large VLA field of view ($\text{FWHM} = 4\text{--}7'$) makes mapping all of these lines 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, thereby limiting the susceptibility to resolving out large-scale emission that is a frequent complication of interferometric studies. Further, to facilitate comparison of the conditions in our own Galactic center with other, more extreme environments, I will also collaborate with David Meier at New Mexico Tech to conduct matching studies of nearby galaxies.

I already have data from an existing high-resolution (0.1 pc) VLA study of NH_3 , CH_3OH , and HC_3N in five of the most massive GC clouds (PI Mills, Figure 1) which can be used as a preliminary study of shock and densities in GC clouds. The NH_3 data can be combined with an existing lower-resolution Australian Telescope Compact Array (ATCA) survey of NH_3 in the entire GC to preserve the large scale emission structure (PI: Juergen Ott), yielding detailed maps of the temperature structure in GC cloud interiors.

Green Bank Telescope: I will also conduct 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 which indicates that the highly-excited (9,9) line is

widespread (Mills & Morris, in prep.), and determine the distribution of high-temperature gas across the GC. Combining these data with lower-excitation lines from ATCA will allow modeling of the fraction of GC cloud gas which exists at each temperature.

ALMA: ALMA's high resolution and relatively small field of view ($1'$) is ideal for follow-up of individual dense cores to study their density structure and kinematics. For a sample of 20-30 especially dense and/or compact clumps identified by the VLA survey, I will conduct targeted ALMA observations with higher spatial resolution (100-1000 AU) in higher-excitation lines of the same species observed with the VLA: HC_3N , H_2CO and CH_3OH . measure the physical conditions interior to these clumps. With the sensitivity of ALMA, observing a sample of this size will be a medium-sized project ($\sim 40 - 50$ hours)

Together, the proposed surveys combined with existing data will support each other to build a picture of unprecedented completeness of the physical conditions in the Galactic center from the largest (600 pc) to the smallest (100-1000 AU) scales which will identify the mechanisms behind the unique gas properties of the GC and the suppression of star formation, and complete our picture of the environment of this volatile region.

The physical conditions which this work will derive may be used as more accurate inputs and constraints for modeling e.g. feedback in central regions (Hopkins and Elvis 2010), as well as star formation in turbulent environments (Gong and Ostriker 2009, 2011). They will also enable more direct comparison of physical conditions in the pre-starforming gas of the GC with nearby observations of regions of more normal modes of star formation. These surveys will further deliver large data sets, made available to public, containing unstudied molecular lines, radio and millimeter continuum emission, which will be used for many future studies of this region, and the comparison of our own Galactic center to those in other galaxies.

Choosing NRAO and New Mexico Tech as Host Institutions

By taking the NSF fellowship simultaneously to both the National Radio Astronomy Observatory (NRAO) and the New Mexico Institute of Mining and Technology (NMT), both located in Socorro, NM, I will be able to collaborate with researchers at both institutions. At NRAO, I will be able to work closely with Juergen Ott on the NH_3 data, combining my existing VLA data with his ATCA data, and developing new analysis code for the highly-excited lines which I will observe. At NRAO, I will further have access to support for planning, executing, and reducing my observation using the newly upgraded VLA. At NMT, I will collaborate with David Meier on modeling the physical conditions as well as eventually comparing the conditions I derive on large scales in the center of our Galaxy to those observed in more extreme extragalactic environments. At NMT, I will also have the opportunity to mentor graduate students on summer projects or masters theses using these data. These opportunities will help me to develop as a scientist and prepare for a career at a research-based institution.

Teaching Them to Fish: Organizing and Supporting Outreach for Educators

As an NSF GK-12 fellow, I collaborated with a partner teacher in a local middle school classroom for a year, and experienced firsthand the challenging climate teachers experience. Teachers are overworked, often depend on activities from the internet, and are eager to bring in new activities and demonstrations to enhance their lessons and excite their students— as long as they understand them. Having an outside expert like myself help by visiting the classroom for each unit, or even for a single lesson, is often not feasible.

At NRAO/NMT, I will work to organize and develop existing programs to teach and support educators both locally and using internet resources. Teaching K-12 educators about astronomy, and giving them tools and materials which they both understand and are comfortable utilizing will influence classrooms full of children, year after year. It is easier for an organization to sustain in the long term than annually visiting the same schools and classrooms, and allows for a larger impact. As a national research center, NRAO has high visibility, and is a common field trip destination for surrounding schools in the state. There are many innovative ideas already in place at NRAO and NMT to support and educate teachers, however, these ideas need more manpower, organization, and publicity so that educators can find and utilize them.

In my first two years, I will work with the NRAO Education Officer Judy Stanley to organize two programs in early stages of development. For the first, I will help run and publicize workshops for local teachers to learn to use astronomy materials which NRAO and NMT offer on loan. This collection includes telescopes, lessons, and activity packets, but they are not being utilized because their availability is not well advertised. To facilitate the use of these materials I will organize an annual workshop at the start of the school year for local teachers to learn how to use these materials and telescopes, which they will then be eligible to borrow in the future. To ensure future support for this program, I will further recruit NMT graduate students and the NMT undergraduate astronomy club to assist with running this workshop. My commitment to this program will be 1-2 weeks each year to organize and run the workshop, plus 2-3 days a month visiting the classrooms the first two years to assist with the first use of these materials in the classroom.

For the second program, I will work as a liaison to connect NRAO scientists by webconference to classrooms around the country. The goal of the program is to host web meetings where a scientist can discuss popular topics and answer questions from students in multiple classrooms. I plan to act as a facilitator for the first few sessions with each scientist, to help them effectively communicate and to moderate questions from the multiple audiences which will be participating. I estimate the time commitment for starting this program to be several days a month to recruit the scientists and develop continuing relationships with classrooms. An important part of organizing these two programs will be to enhance NRAO's educational web presence and improve its interface with educators, describing and publicizing these programs as part of a standardized set of outreach activities which will be available for both

local and national schools. By spending much of my time in the first few years developing the infrastructure for the continuation of these programs, I hope to leave behind a program whose maintenance requires a lower level of continuing support.

In my last year, I plan to use educator feedback from the previous two years – on which types of tools and activities teachers find most useful in their classrooms – to design an effective radio astronomy activity to complement those publicly available for other wavelengths (e.g., from NASA and NOAO). To test the development of these materials, I will also have the opportunity to teach sample lessons to educators in NMT’s Master of Science for Teachers program.

The ultimate goal of my efforts will be to increase the effectiveness and sustainability of the NRAO education and outreach. This will enhance the positive effect of proximity to a National Observatory for the surrounding New Mexico community, and improve public awareness and understanding of radio astronomy at a time of large national investment in cutting-edge radio and millimeter facilities such as the VLA and ALMA.

Three-year Timeline

Academic Year 2013-2014	Academic Year 2014-2015	Academic Year 2015-2016
Combine GBT data (proposed for in 2012) with existing VLA & ATCA NH ₃ data.	Analyze VLA data , conducting excitation analyses of multiple species	Publish study of physical conditions in GC clouds: densities and shocks
Publish study of internal temperature structure of GC clouds, & distribution of the hottest gas	Identify targets from VLA survey & propose for ALMA followup	If proposal is successful, receive ALMA data
Propose for compact-configuration VLA observations in Winter 2014 and if successful, begin receiving & calibrating data in summer 2014.	Redesign NRAO’s education webpage to publicize available outreach activities and educational materials	Begin analyzing ALMA data, prepare to publish study of gas conditions in pre-starforming clumps in GC clouds
Hold workshop to train local educators to use available teaching supplies	Recruit local scientists and begin hosting science talks on the on the web for K-12 classrooms	Develop and test radio astronomy activity for public distribution

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