Project Description

1 Results from Prior NSF Support

1.1 High Elevation Antarctic Terahertz (HEAT) telescopes for Ridge A

1.1.1 Summary

In 2010, the PI initiated an NSF-funded (ANT-0944335, 10/2010-9/2014) program to build two 60 cm terahertz telescopes for robotic operation at the summit of the Antarctic high plateau with the dual purpose of site testing and performing leading edge terahertz astronomy. These High Elevation Antarctic Terahertz (HEAT) telescopes operate from 150 to 600 microns wavelength and observe the brightest and most diagnostic far-infrared lines in the Galaxy. An international collaboration with Australia's University of New South Wales provided the PLATeau Observatory for Ridge A (PLATO-R), a platform for power and satellite communication. In January 2012, PLATO-R and the first HEAT prototype were successfully deployed to Ridge A and have performed admirably. A servicing mission to Ridge A in which the second-generation HEAT telescope will be installed is scheduled for January 2014. HEAT is the world's first robotic THz telescope. It has the first cryogenic receiver system in the deep field that operates for a full year between servicing missions. HEAT is showing that the Ridge A site is the best site on the planet from which to perform terahertz observations, with 10× more observing days suitable for 200 μm observations than Chajnantor (e.g. ALMA). Already, a preliminary public data release of 809 GHz (370 μm) data of atomic carbon J=2-1 line emission returned via Iridium satellite has been made available at `http://soral.as.arizona.edu/heat/`. Incremental followup data releases are expected 2 times per year for the duration of the program.

1.1.2 Activities

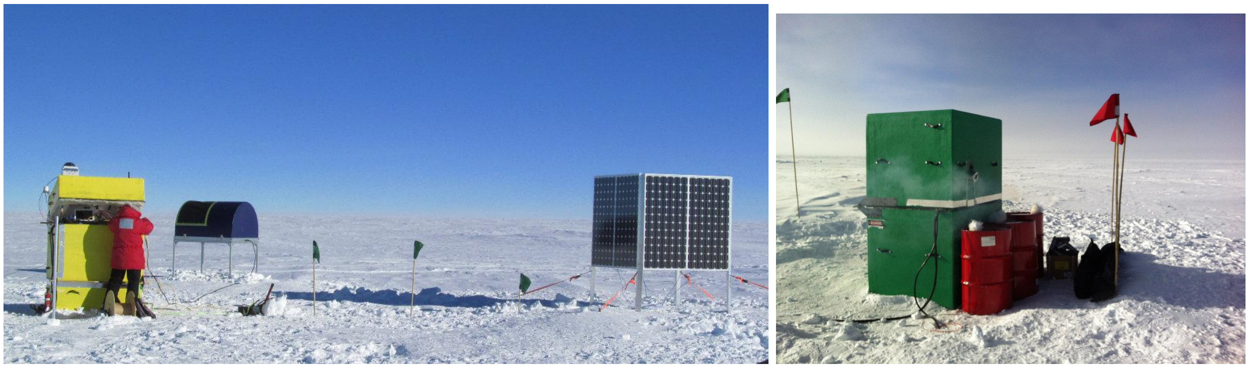

Figure 1: (left) A new far-infrared astronomical observatory was established on Ridge A, the inland summit of the polar plateau, as a joint collaboration between University of Arizona and the University of New South Wales in Australia in January 2012. Consisting of a (blue) High Elevation Antarctic Terahertz (HEAT) telescope and the (yellow and green) PLATeau Observatory (PLATO-R) instrument and engine modules, the observatory is designed to operate unattended for 12 months at a time.

The High Elevation Antarctic Terahertz (HEAT) telescope is forging new capabilities for ground-based infrared and submillimeter astronomy, by providing a window on the Universe which otherwise would be unavailable except via suborbital or space-based platforms. HEAT represents a true international pioneering effort between the US and Australia. The HEAT telescopes' key science project is a THz survey of the Galactic Plane observable from Antarctica in the CO J=7-6 and [CI] J=2-1 lines at 809 GHz, [NII] at 1461 GHz, and ultimately the [CII] line at 1900 GHz. Via spatially and spectrally-resolved line emission, HEAT uniquely probes the pivotal formative and disruptive stages in the **life cycles of interstellar clouds** and sheds crucial light on the **formation of stars** by providing new insight into the relationship between interstellar clouds and the stars that form in them; a central component of **galactic evolution**. A detailed study of the ISM of the Milky Way is needed to construct a template to **interpret global star formation in other spiral galaxies**. These science goals are discussed further in Section 2. The initial proposal supports the HEAT telescopes through the first 2 full years of science operations at Ridge A, which lies about 110 miles inland from the Chinese Kunlun station at Dome A but at essentially the same elevation.

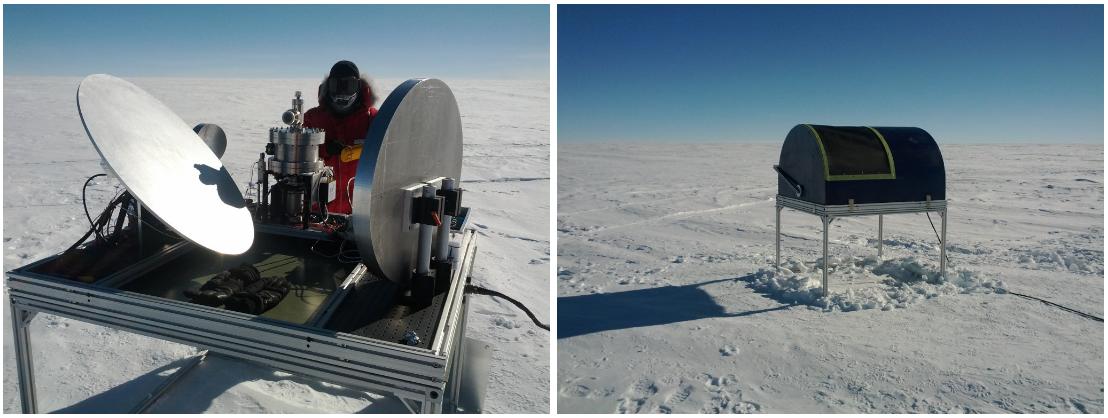

Figure 2: (left) The prototype 3-mirror off-axis Gregorian telescope, cryogenic receiver system and frozen PI are visible in this image. (right) Enclosed in a fiberglass shell and thin black HDPE "window" that is transparent to THz radiation, the HEAT telescope is ready for observations (January 2012).

For orientation, the facility is shown in Figures 1 and 2. It is comprised of:

- PLATO-R's yellow instrument module, which houses 20 kW hr of LiFePO4 batteries, power distribution electronics, supervisor computers, and Iridium modems and antennas. The roof of the instrument module has an all-sky camera and a 7-camera webcam system which streams hourly mosaics to the HEAT web page. The all-sky camera will be replaced in January 2014 with a thermal infrared sky monitor, designed and built by University of Arizona *undergraduate student* Casey Honniball for her independent study project.
- A 4-panel Solar Cube, which provides up to 800 W of solar power to the instrument module during the summer months.
- PLATO-R's green engine module, which houses 800 liters of AN8 fuel in an internal bladder and another 800 liters in external fuel barrels. Two diesel engines are housed inside the temperature-controlled module. One operates at a time to provide up to 1500 W of power to the instrument module during winter.
- The HEAT telescope is connected to the yellow instrument module by a 10-meter umbilical which supplies ethernet and power. HEAT is a 62 cm aperture off-axis Gregorian telescope.

Optically, it is comprised of 1) a 45-degree flat mirror which steers in elevation and represents the only moving part of the telescope, 2) an off-axis parabolic primary mirror, and 3) an elliptical camera mirror, which re-images the Gregorian focus to a small cryostat cooled to 50K by a Sunpower Cryotel CT Stirling cycle cryocooler. The initial deployment featured 809 and 492 GHz receivers for the fine structure lines of atomic carbon and will be swapped for 809 GHz and 1461 GHz receivers starting in January 2014.

- A 15-meter weather tower, instrumented with temperature and wind sensors.

Indeed, the design and philosophy behind HEAT and PLATO-R more closely resembles a space observatory than a typical ground based telescope. The program has been a remarkable success; since the beginning of the effort in October 2010, the team has:

1. Designed, constructed, and deployed an autonomous, robotic observatory for the most remote site on Earth, and among the most hostile and challenging environments, using a blend of solar and diesel power, to operate without physical human intervention for a year at a time.
2. Deployed cryocooled heterodyne receiver systems and telescopes at THz frequencies that operate for a year at a time between servicings, with an all-up power budget of less than 200 watts.
3. Developed and deployed an advanced telescope scheduling system that can autonomously execute an observing plan with little human involvement, with a 3 watt computing power budget using mobile phone ARM processors.
4. Developed and deployed a data processing system that can return fully-reduced spectroscopic maps of the 4th Galactic quadrant over the ’soda straw’ bandwidth of an Iridium modem (2400 baud)... using the same mobile phone CPU.
5. Generated the deepest large-scale maps of the ISM in neutral carbon at 370 μm, with 205 μm ionized nitrogen arriving in 2014, and ultimately ionized carbon at 158 μm. By exploring molecular clouds and their environments in tracer species *other* than CO, HEAT will probe the entire carbon trail – and the full life cycle of interstellar clouds.
6. Provided the data products freely to the astronomical community after collection and calibration, with no proprietary period.

1.1.3 Site testing results

HEAT’s sensitivity is owed to the superlative atmospheric conditions above the summit of the Antarctic plateau. The extreme cold and exceptional dryness allow ground-based observations into the otherwise forbidden THz windows. Figure 3 demonstrates the exceptionally **transparent** and **stable** conditions that are routinely available at Ridge A. To illustrate, HEAT measured 86 days in 2012 in which the daily mean opacity at 200 μm (1.5 THz) was below 1.5. In comparison, the APEX radiometer for 2012 indicated only 4 days for the Chajnantor Plain, and the best estimates for Cerro Chajnantor (CCAT) indicate 12 days. Ridge A is especially remarkable in that $>10\%$ of the year yields usable atmospheric transmission in the 150 micron window, containing the pivotal 158 μm ionized carbon line.

A tabular comparison of Ridge A to other well-known submillimeter sites is shown in Table 1. To the proposers’ knowledge, the Ridge A results are the best measured anywhere from the ground. That such conditions are frequently realizable makes them even more remarkable.

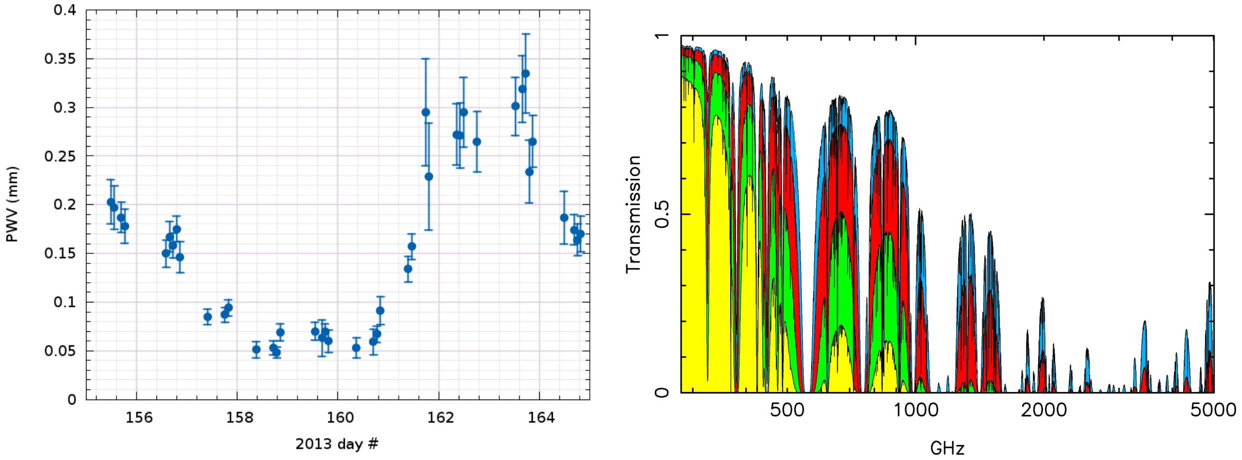

Figure 3: (left) A sample week of precipitable water vapor measurements from HEAT during winter 2013 shows an incredibly stable, transparent atmosphere, with a median winter PWV of 124 microns, and a best quartile of 87 microns! Such dry air leads to the upper-two (blue and red) transmission plots shown at right. The bottom two (green and yellow) curves represent the ALMA site and Mauna Kea, respectively. Ridge A opens entirely new atmospheric windows to routine observations from the ground.

Site	**25%ile 50%ile winter PWV (mm)**		**Median winter transmission @660 GHz**	**Best 25% winter transmission @1500 GHz**	**Best 10% winter transmission @2000 GHz**
Ridge A, 4040m	0.09	0.12	77%	41%	28%
South Pole, 2850m	0.23	0.32	52%	9%	1%
Plano Chajnantor, 5050m	0.35	0.60	47%	10%	2%
Mauna Kea, 4100m	1.0	1.5	15%	0%	0%

Table 1: *Comparison of Ridge A with other established submillimeter observing sites, based on 2012 HEAT data for Ridge A, 2012 radiosonde data for South Pole, and Chajnantor from 2012 APEX radiometer data, Mauna Kea from literature values (Delgado et al., 1999; Hogg, 1992).*

The high elevation, cold stable atmosphere and benign wind conditions at Ridge A **open the Terahertz windows to ground-based observatories and are unlikely to be matched anywhere else on Earth**. Thus, even with an initial deployment of cooled Schottky mixer receivers, HEAT's sensitivity to each spectral line is already scientifically competitive.

1.1.4 Astronomical Results

In the light of 370 μm (809 GHz) atomic carbon J=2-1 emission, HEAT has obtained high-fidelity strip maps of the Galactic Plane (Figure 4) as well as a high priority $1^o \times 0.6^o$ map at Galactic longitude 328^o (Figure 1) that are now publically available. With a 3-sigma rms noise level of 100 mK, these are the largest, most sensitive maps in the atomic carbon line to date.

Preliminary results of these data indicate that atomic carbon, while of lower surface brightness than CO, is more widespread and is only slightly less abundant on large scales. Since all [CI] emission stems from regions where hydrogen is molecular, this implies that a substantial fraction (at least 30%) of the molecular mass is not probed by CO emission, the so-called "CO-

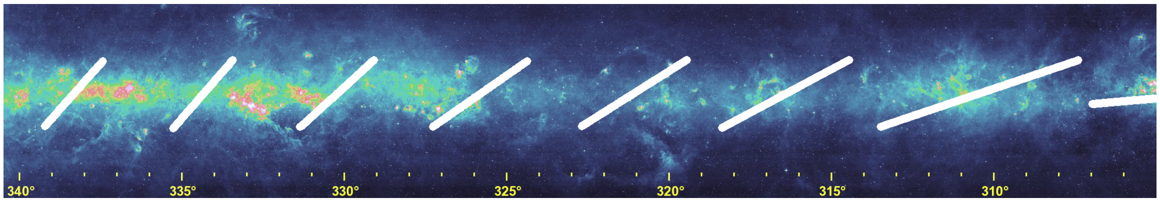

Figure 4: Eight of the fifteen Galactic strip maps observed by HEAT in 2012, atop a color-scale image of the MSX 8 micron infrared emission. To minimize telescope motion and maximize pointing accuracy, the maps are performed in drift scanning mode at constant azimuth and elevation, yielding strips of differing inclination when plotted atop the Galactic Plane.

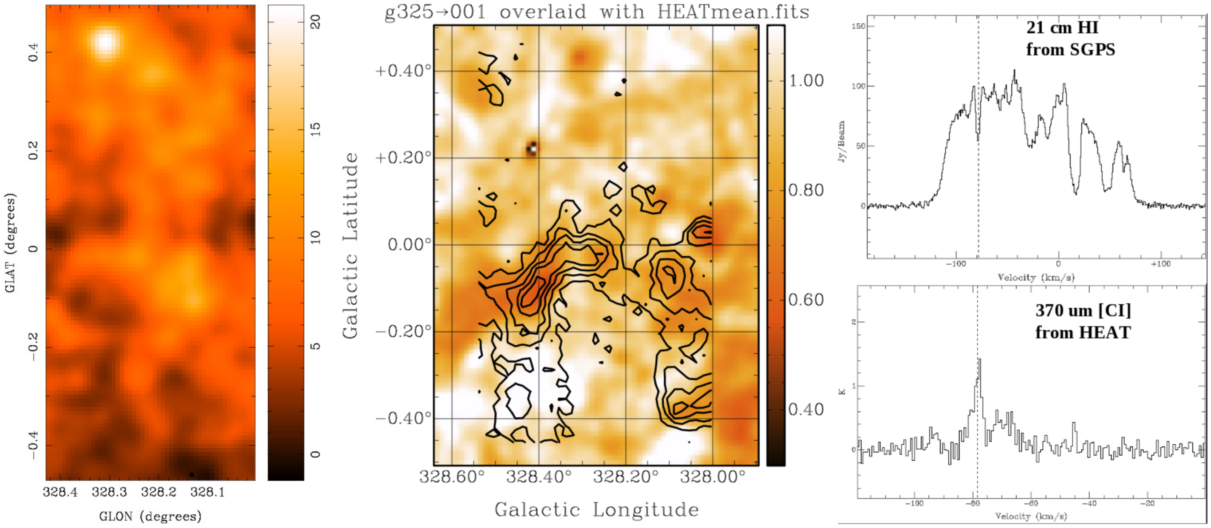

Figure 5: (left) Integrated intensity map of [CI] line emission toward l=328^o shows that diffuse atomic carbon emission fills the Galaxy and is nearly as abundant as CO. (center) The molecular gas shown by HEAT's detected line emission at -78 km/s V_{lsr} (contours) appears to be associated with self-absorption in the 21 cm HI line (color scale) at the same velocity. The high abundance of [CI] suggests that this molecular gas is chemically-young; it has not yet converted much of its elemental carbon to CO. Such a signature is indicative of a natal cloud. Establishing where these clouds are forming in a Galactic context is one of the primary goals of the HEAT telescope and one of the main motivations to extend its initial mission.

dark gas" (Grenier et al., 2005; Wolfire et al., 2010). (Kulesa et al. 2014, in preparation, see `soral.as.arizona.edu/heat` for latest publication updates).

Specific regions in the first square degree to be mapped by HEAT (at l=328^o) are already providing evidence of molecular cloud formation. [CI] appears to be well correlated with cold HI gas observed in absorption. A quiescent filament spanning 0.5 degrees on the sky is observed at -78 km/s V_{lsr} with high [CI] abundance relative to CO, suggestive of recent cloud formation. This work has been submitted to ApJ (Burton et al. 2014) and is currently being reviewed.

While excellent progress has been made, much of the effort to date has focused on the technological development of this pathfinding observatory, and only recently has shifted full-time to data product generation and scientific publication. **The goal of this proposal is to complete this transition: to maximize HEAT's scientific productivity by extending normal, stable operations for one year with no major instrument development, and providing for a follow-up year funded expressly for analysis and publication.**

2 Science Goals

2.1 Introduction

From the Milky Way to high redshift protogalaxies, the internal evolution of galaxies is determined to a large extent by the life cycles of interstellar clouds, as shown in Figure 6.

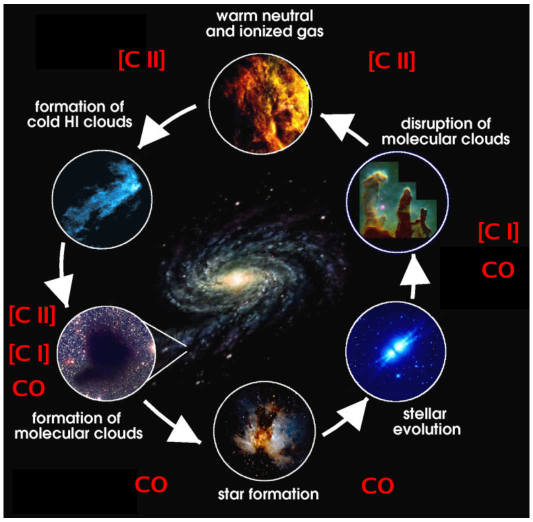

Figure 6: *The HEAT telescopes will ultimately observe the fine structure lines of [N II], [C II], [C I], and CO that probe the entire life cycle of interstellar clouds. In particular, HEAT will witness the transformation of neutral atomic clouds into star-forming clouds, the interaction of the interstellar medium (ISM) with the young stars that are born from it, and the return of enriched stellar material to the ISM by stellar death.*

These clouds are largely comprised of atomic & molecular hydrogen and atomic helium, which are notoriously difficult to detect under normal interstellar conditions. Atomic hydrogen is detectable via the 21 cm spin-flip transition and provides the observational basis for current models of a multiphase Galactic ISM. Its emission is insensitive to gas density and does not always discriminate between cold (T$\sim$70K) atomic clouds and the warm (T$\sim$8000K) neutral medium that is thought to pervade the Galaxy. Furthermore, neither atomic helium nor molecular hydrogen (H_2) have accessible emission line spectra in the prevailing physical conditions in cold interstellar clouds. Thus, it is important to probe the nature of the ISM via rarer trace elements. Carbon, for example, is found in ionized form (C^+) in neutral clouds, eventually becoming atomic (C), then molecular as carbon monoxide (CO) in dark molecular clouds.

Although we are now beginning to understand star formation, the formation, evolution and destruction of molecular clouds remains shrouded in uncertainty. The need to understand the evolution of interstellar clouds in the context of star formation has become a central theme of contemporary astrophysics. The most recent decadal survey, "Astro2010: New Worlds, New Horizons", specifically identifies the questions "*What controls the mass-energy-chemical cycles within galaxies*", "*how do stars form*", "*what determines the star formation rates and efficiencies in molecular clouds*", and "*what determines the properties of pre-stellar cloud cores and what is the origin of* *the stellar mass function*" as among the key questions for radio and (sub)millimeter facilities in this decade. Further, the specific recommendation is made: **"A large-field mapper operating at millimeter and submillimeter wavelengths is required to pave the way for follow-up observations with ALMA"**. HEAT is a direct answer to this recommendation!

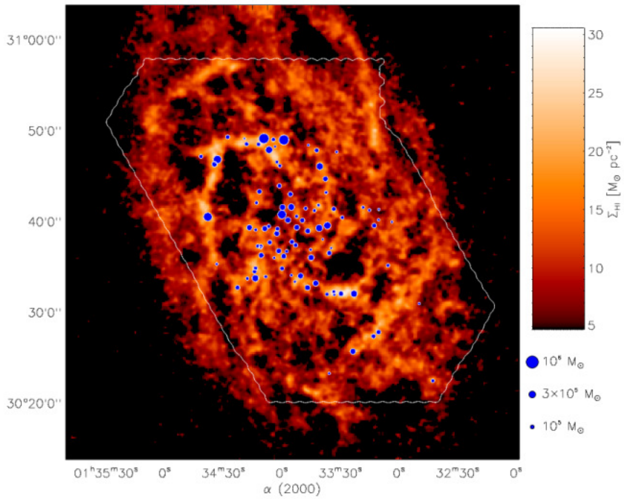

Figure 7: *The location of GMCs in the nearby spiral galaxy M33 are overlaid upon an integrated intensity map of the HI 21 cm line (Engargiola, Plambeck, Rosolowsky, & Blitz, 2003). These observations show that GMCs are formed from large structure of atomic gas, highlighting the detailed study of GMC formation that HEAT is providing in the Milky Way.*

2.2 Goal 1: Observing the Life Cycle of Interstellar Clouds

The formation of interstellar clouds is a prerequisite for star formation, yet the process has not yet been identified observationally! HEAT is designed with the unique combination of mapping speed, sensitivity and resolution needed to observe atomic clouds in the process of becoming giant molecular clouds (GMCs) and their subsequent dissolution into diffuse gas via stellar feedback.

Theories of cloud formation are guided and constrained by observations of the atomic and molecular gas components. Based primarily on HI and CO observations, several mechanisms have been proposed to consolidate gas into GMC complexes (Figure 7). HEAT can distinguish these processes by 1) accounting for the entire H_2 mass (including H_2 clouds with little CO) when computing global measures of the interstellar medium, and 2) constructing spatial and kinematic comparisons of sufficient resolution, spatial coverage and dynamic range to probe a wide range of interstellar phases and environments. Within its survey region, HEAT will generate a better characterized catalog of interstellar clouds than CO or HI surveys alone.

Since the [C II] and [C I] line emissivity selects *clouds* of atomic gas and H_2 clouds with little CO, regions of GMC formation may therefore be tracked by a large density of clouds per beam, or regions with individual clouds with higher than average columns or pressures. With HEAT's high spectral resolution, these regions can be identified with superrings or spiral arms or convergent parts of a turbulent medium. With guidance from 2MASS extinction mapping and existing CO and 21 cm HI surveys, HEAT will follow cold HI clouds and H_2 clouds as they transit the spiral potential, and will witness the process of cloud formation directly from the atomic substrate or small H_2 clouds. Similarly, the [N II] luminosity determines the ionizing luminosity of OB stars, a standard metric for the star formation rate. Therefore, [N II] observations of ionized gas provide an extinction-free, low-density measurement of the location and rate of star formation in the Galaxy.

HEAT's high spectral resolution enables crucial kinematic studies of the Galaxy to be made. HEAT will determine the kinematics and thermal pressures of supershells, fossil superrings, and new molecular clouds condensing out of old superrings and supershells via gravitational instability. HEAT can determine the role of OB association-driven supershells and superrings in the production of molecular clouds and the cycling of gas between the various phases of the ISM. Since [N II] measures the flux of ionizing photons, and [C II] measures their impact upon neighboring cloud surfaces, HEAT will measure the resolved photoevaporating atomic or ionized gas driven from clouds with UV-illuminated surfaces, thereby determining the rate of mass loss from all cataloged clouds, and their destruction timescales. HEAT's survey will correlate the star formation rate in a given OB association with the rate of destruction of any nearby (within 30 pc) natal GMC. Such measurements are crucial for models of star formation feedback and galactic evolution.

2.3 Goal 2: Constructing a Milky Way Template for Star Formation

HEAT will probe the relation between the gas surface density on kpc scales and the N^+-derived star formation rate, so that we might be able to better understand the empirical Schmidt Law used to estimate the star forming properties of external galaxies.

[C II] and [N II] will be the premier diagnostic tools for far-infrared studies of external galaxies with large redshifts (e.g. with Herschel & ALMA). In such spatially unresolved galaxies, however, only global properties can be measured. Detailed interstellar studies of the widely varying conditions in our own Milky Way Galaxy serve as a diagnostic template or "Rosetta Stone" that can be used to translate the global properties of more distant galaxies into reliable estimators of star formation rate and state of the ISM. The HEAT mission covers a broad range of density and UV intensity, establishing the relationship between physical properties, [C II], [C I], CO, [N II], HI, FIR emission, and star formation. This relationship can be tested by application to nearby galaxies in the SINGS Spitzer Legacy Survey (Kennicutt et al., 2003), for which a large amount of ancillary optical, infrared and submm data exist.

For example: star formation within galaxies is commonly described by two empirical relationships: the variation of the star formation rate per unit area with the gas surface density (Schmidt, 1959; Kennicutt, 1998) and a surface density threshold below which star formation is suppressed (Martin & Kennicutt, 2001). The Schmidt Law has been evaluated from the radial profiles of HI & CO emission for tens of galaxies. The mean value of the Schmidt index, n, is 1.4 ± 0.15 (Kennicutt, 1998), valid for kpc scales. This empirical relationship is used in most models of galaxy evolution with surprising success given its simplicity. Furthermore the SFR-dense gas relation established in nearby galaxies is a linear one (Gao & Solomon 2004) and this has been extended to the Milky Way dense cores (Wu, Evans, Gao et al. 2005), and possibly high-z galaxies and QSOs as well (Gao et al. 2007), implying that the same physics drives the active massive star formation in both GMC dense cores and galaxies near and far.

Oddly, there has been little effort to evaluate the Schmidt Law in the Milky Way owing to the difficulty in deriving the star formation rate as a function of radius within the plane. The HEAT survey of CO, [C I], [C II] and [N II] emission provides an initial set of data to calculate the Schmidt Law in the Galaxy. The [N II] line is an excellent tracer of the star formation rate as it measures ionizing luminosity with unmatched sensitivity, angular and spectral resolution, and is unaffected by extinction. The [C I] and [C II] lines, in conjunction with HI 21cm and CO line emission, provide the first coherent map of the neutral interstellar gas surface density and its variation with radius. HEAT's high spectral resolution allows one to assign a radial location of any emission feature assuming a rotation curve. A preliminary Schmidt Law will be constructed from the radial profiles of the star formation rate derived from [N II] emission and the gas surface density. The column density threshold is inferred from the absence of star formation activity in the outer radii of galaxies where there is still a significant reservoir of gas (Kennicutt, 1998).

2.4 Implementation of Science Objectives

HEAT's science drivers highlight a survey that would not only provide the first comprehensive view of interstellar clouds and their evolution in the Galaxy, but would also serve as a reference for contemporary focused studies with Herschel, SOFIA, APEX, and the ALMA and SMA interferometers. How will the HEAT telescope address the scientific goals that have been illustrated?

2.4.1 Velocity-Resolved Imaging Spectroscopy

Techniques commonly used to diagnose the molecular ISM include submillimeter continuum mapping of dust emission (Hildebrand, 1983) and dust extinction mapping at optical and near-infrared wavelengths (Lada, Lada, Clemens, & Bally, 1994). Large format detector arrays in the infrared are now commonplace, and with the advent of bolometer arrays like SCUBA2 at the JCMT and SHARC at the CSO, both techniques have performed degree-scale maps of molecular material. However, these techniques have limited applicability to the study of the structure of the Galactic ISM due to the complete lack of kinematic information.

The confluence of many clouds along most Galactic lines of sight can only be disentangled with spectral line techniques. Fitting to a model of Galactic rotation is often the only way to determine each cloud's distance and location within the Galaxy. With resolution finer than 1 km s^{-1}, a cloud's kinematic location can be even distinguished from other phenomena that alter the lineshape, such as turbulence, rotation, and local effects such as protostellar outflows. These kinematic components play a vital role in the sculpting of interstellar clouds, and a survey that has the goal of understanding their evolution **must** be able to measure them. **HEAT will easily resolve the intrinsic profiles of Galactic interstellar lines, with a resolution of $<$0.4 km s^{-1} up to 370 km s^{-1} of spectrometer bandwidth, comparable to the Galactic rotational velocity.**

2.4.2 Uniqueness of a [CI], [CII], [NII] and CO Survey

Molecular line surveys have been performed over the entire sky in the light of the 2.6 mm J=1-0 line of ^{12}CO, and have been used to synthesize our best understanding of the molecular content of the Galaxy. Still, our understanding of the evolution of Galactic molecular clouds is woefully incomplete! Figure 8 depicts a plane-parallel cross-sectional representation of an interstellar cloud which highlights several ways that HEAT's THz surveys can shed new light on our understanding of the life cycles of clouds:

1. A significant column of "hidden" gas exists between where the atomic to molecular transition of H to H_2 takes place, and where CO finally becomes the dominant form of gas-phase carbon. A significant volume of the cold neutral gas in the Galactic ISM is likely in this state (Wolfire et al., 2010), and all molecular clouds should be dominated by this material at certain points in their evolution. CO is, at best, a faithful tracer of well-established, shielded molecular material.
2. This translucent material is best probed by [CII] and [CI]. Both lines are therefore more revealing than CO of the formative and destructive states in the evolution of a molecular cloud. They will reveal natal molecular (H_2) regions that are weak or absent in CO emission.

3. In regions of significant UV radiation, [NII] can be used to disentangle the fraction of [CII] emission that stems from ionized gas, versus neutral clouds.

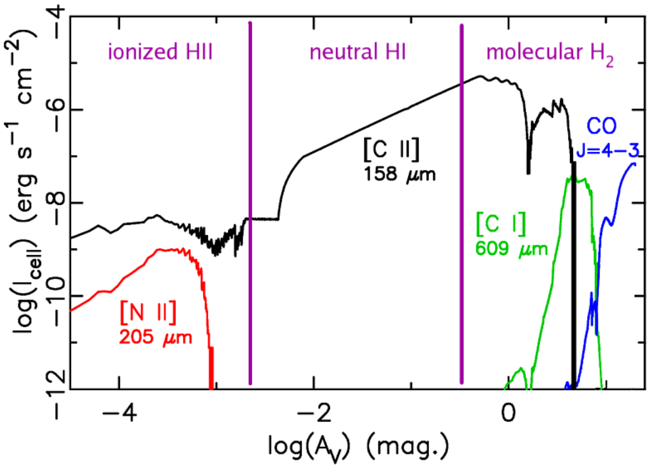

Figure 8: **The uniqueness of HEAT's [CI], [CII] and [NII] surveys.** *A model depiction of the intensity of diagnostic lines of carbon and nitrogen species as viewed through a UV-illuminated cloud from depths of A_V=0 to 20 mag. Vertical purple lines overlay the HII-to-HI-to-H_2 boundaries found at the edges of dense interstellar clouds. This figure demonstrates that [CII] and [CI] probe H_2 clouds with little CO, and depicts the need to use [NII] to disentangle the portion of [CII] emission stemming from ionized gas.*

HEAT will ultimately provide a velocity-resolved large-scale mapping survey in all these species. For this proposal effort, the existing receiver systems at [CI], CO, and [NII] will be the main focus, with a 4K [CII] system arriving in the next instrumental development phase, beyond the proposed effort. HEAT will ultimately measure all three principal forms of carbon in the gas phase: ionized, neutral, and molecular. In combination with existing infrared, HI and CO surveys, the potential to identify the formation and destruction of molecular clouds and GMCs observationally may finally be realized! This survey will provide the first barometric maps of the Galaxy, and illuminate the properties of clouds and their life cycles in relation to their location in the Galaxy. They will highlight the delicate interplay between (massive) stars and the clouds which form them, a critical component of galactic evolution.

2.4.3 Diverse Mapping Coverage of the Galactic Plane

From previous CO surveys it is known that the scale height of CO emission toward the inner Galaxy is less than one degree (Dame et al., 1987; Dame, Hartmann, & Thaddeus, 2001). The BICE experiment demonstrated that the C^+ distribution is more extended, but still is confined to $|b| < 1$. Interstellar pressure, abundances, and physical conditions vary strongly as a function of Galactocentric radius, so it is necessary to probe both the inner and outer Galaxy, and both spiral arms and interarm regions, to obtain a statistically meaningful survey that encompasses the broad dynamic range of physical conditions in the Galaxy.

Ultimately, we propose to probe the entire Galactic plane as seen from Ridge A ($0 > l > -100^o$); see Figure 9. However, for the initial implementation, using Schottky mixer receivers, an initial total of 40 square degrees is targeted. It will probe three crucial components of the Galaxy; the Scutum-Crux spiral arm, an inter-arm region, and portions of the Carina, Lupus, and Chamaeleon II cloud complexes, and high luminosity portions of the LMC. The Galaxy survey will coincide with GLIMPSE, a Spitzer Space Telescope (SST) Legacy Program (Benjamin et al., 2003) and will be designed to maximize coverage with the "Cores to Disks" Spitzer Legacy program (Evans et al., 2003) and Herschel GOTC+ open time key program (Langer et al., 2010).

The remaining sky coverage in the Galactic Plane survey will be provided in the future by HEB mixers from SRON, using a cryocooled 4K system. This next-generation instrument development is beyond the scope of this proposal but planned for the 2016-19 timeline.

2.4.4 Synergies with Other Observatories

HEAT is timely. The Spitzer Space Telescope Legacy program GLIMPSE, and Herschel program Hi-Gal, provide a thermal infrared survey of the Galactic plane that provides a complete census of OB stars, the stellar structure of the molecular ring, maps the warm and cold interstellar dust, and constrains extinction laws as a function of galactocentric radius. HEAT will provide the best corresponding interstellar cloud survey that will provide the kinematic information that can associate star formation with specific clouds of molecular gas. HEAT can measure the dense cloud material that forms stars, cloud interactions with formed stars, and kinematic disruptions by mass ejection, outflow, and supernova remnants.

HEAT naturally complements the capabilities of heterodyne receivers on SOFIA and Herschel. The higher angular resolution afforded by larger telescopes necessarily reduces their field of view and mapping speed. **The HEAT survey would require many months of dedicated observing time on either Herschel or SOFIA, inconsistent with their use as general purpose observatories.** For example, the most intensive [CII]-related key project for Herschel is "GOTC^{+}" (PI: W. Langer), which observed the [CII] line toward over 900 selected points in the Galactic Plane with the HIFI instrument. HEAT, by virtue of being a dedicated mapping instrument with a focused mission and a long mission lifetime, will map almost 400 times the areal coverage of "GOTC^{+}" during this proposal period, and could exceed the Herschel coverage in [CII] by a factor of 2-5 in a single season. HEAT will provide ideal reference maps of THz line emission for more detailed followup with SOFIA and Herschel, and the HEAT data distribution and databasing system will be aligned as much as possible with the `HIPE` software to be used with Herschel data products.

Similarly, the small field of view of the **ALMA interferometer** (7-30$''$) means that many tens of thousands of pointings will be needed to map a single square degree. Multi-square-degree large-scale imaging with ALMA will be prohibitively time consuming but is a task effectively performed by single-dish telescopes like HEAT. Indeed, HEAT's Southern survey in atomic carbon, [NII] and high-J CO emission will be an ideal survey for active star forming clouds and cores and represents an exceptional reference map for detailed follow-up with ALMA.

HEAT distinguishes itself from other small ground-based observatories such as NANTEN and the RLT in that (1) HEAT is a dedicated observatory with an autonomous and efficient year-round observing schedule, and (2) it is at the only ground based site that can stably and reliably observe the terahertz lines warranted by these scientific goals (Section 2.4.2). In combination with the surveys produced by these other telescopes, HEAT will be able to address questions which other surveys alone could not. It should be noted that both AST/RO and the RLT have made pioneering, targeted observations of [N II] (Oberst et al. 2006, Marrone et al. 2005). These observations have been helpful in optimizing the larger scale survey with HEAT from Ridge A.

Finally, the reflight of the Stratospheric Terahertz Observatory (STO-2: PI-Walker, DPI-Kulesa) is a funded long duration balloon (LDB) project which complements the Galactic plane survey capabilities of HEAT. It has a 0.8m aperture and is designed to observe high lying THz lines including [C II], [N II], and [O I]. The STO-2 science flight will occur in late 2016 and will last for $\sim$2-4 weeks. Such flights can be repeated on 2-3 year timescales. HEAT plays an important role with respect to STO-2, which has a restricted view of the Galactic Plane (from l=-20 to l=-50) owing to Solar angle restrictions and the occulting of the sky by the helium balloon itself. Unlike STO-2, which due to its trajectory has limitations in its sky coverage, HEAT is mapping the important southern Lupus, Carina, and Chamaeleon molecular cloud complexes, in addition to deeper, smaller scale maps of the Large Magellanic Cloud. HEAT and STO observations will therefore be coordinated to provide maximum science return (Figure 9).

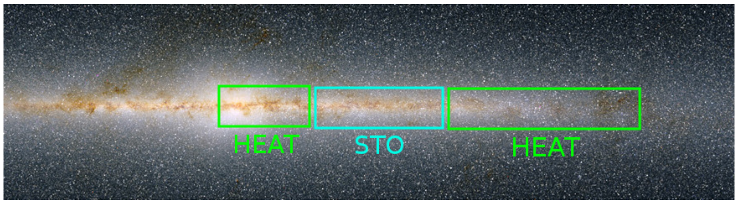

Figure 9: *Regions of the Galactic Plane from l=0 to l=-100, mappable by STO-2 and HEAT. The large scale HEAT survey will initially focus on [CI] and CO, with smaller maps performed in [NII] and eventually [CII].*

2.5 Survey Activities

2.5.1 Mapping Strategy

The most efficient mode of data collection which produces the highest fidelity images is On-the-Fly (OTF) mapping. In this mode, the telescope continuously scans across a field while the backends are read-out at a sufficient rate to eliminate aliasing and beam smearing. This is the mode in which HEAT currently operates and no changes are planned.

The broad coverage of the HEAT survey and the circumpolar nature of the sky rotation over Antarctica lends itself naturally to efficient, 24 hr/day mapping. HEAT can reach the requisite sensitivity of 1σ=0.15 K km s^{-1} per beam at 810 GHz (1σ=0.9 K km s^{-1} at 1.4 THz) over a fully sampled square degree in 10 days, assuming median winter conditions of τ_{810} ~0.5. 25 square degrees distributed from $0 > l > -20^o$ and $-45 > l > -100^o$ will be mapped in ≈300 days.

2.5.2 Science Products and Dissemination

A challenge of OTF mapping is data management. We therefore plan to adopt a scheme akin to that developed at FCRAO, whereby coadded and regridded data is written as FITS & CLASS files, and headers for each scan are written into a MySQL relational database, which facilitates efficient logging and retrieval of the data. The most demanding storage requirements for the final 40 square degree maps, regridded to 45$''$ spacing, with 1024 spectral points per grid position, is less than 4 GB. This volume is handled by embedded computers with disks of nonvolatile flash memory.

Access to these data products to the greater scientific community will be provided through a web browser interface that will interface with MySQL and the FITS data cubes. Standard Virtual Observatory (VO) services will be enabled in this interface. Preprocessed data cubes will be transferred from HEAT over Iridium satellite, while raw data will be collected from the telescope annually during maintenance. Thus, there will be biannual data products – a preliminary Austral summer release in November, and a final release of the previous season's data in March. The final release will be fully calibrated and will include all science products.

All science tools, packaged reduction software, data products and science products will be made freely available from the HEAT web page: `http://soral.as.arizona.edu/heat/`

2.5.3 Roles of the Collaboration Participants

Participant	Affiliation	Participation Activity
Michael Ashley	UNSW	Advisor: PLATO-R operations and site testing
Michael Burton	UNSW	Advisor: Companion CO 1-0 Survey from the Mopra 22m
David Hollenbach	SETI	Advisor: ISM physics
Craig Kulesa	Univ. Arizona	PI, HEAT development and testing, ISM physics
Mark McCaughrean	ESA	Advisor: synergy with Planck and JWST
Christopher Walker	Univ. Arizona	Co-PI, leads student advising
Mark Wolfire	U. Maryland	Advisor: PDR modeling
Abram Young	Univ. Arizona	Lead: annual HEAT servicing mission

Table 2: Activities of the HEAT Science Team

Personnel initially using HEAT comprise the Science Team tabulated in Table 2. *Both graduate and undergraduate students are participating in both the instrument development and science study.*

3 Project Management

3.1 Organization

HEAT is an exciting, challenging project that requires the coordinated participation of scientists and engineers from several academic institutions and leading-edge companies. Collectively the HEAT team members represent many years of successful telescope and instrument development in Antarctica. Table 2 provides a listing of the roles of each member in the organization.

A schedule of key project milestones and tasks is provided in Figure 10. In January 2015, the [CI] and [NII] receiver will be swapped in the field and HEAT will begin a second year of operations at these two frequencies. 2015 will feature publication and distribution of the 2014 data, and in turn, the 2015 data will be released and published in 2016.

Transitioning HEAT from an instrument development effort to a scientific workhorse is an exciting prospect that our team has been working towards for years. Collectively the HEAT team members represent many years of instrument building, observing experience, and theoretical expertise. As related by Table 2, the main components of the organization are the PI, who has overall responsibility for the project and coordinates the activities of the participants; Co-PI Walker who shares in these responsibilities and lead the student advising efforts; and the distributed members of the science team who act as an advisory council to the PI and Co-PIs to ensure that the project stays on course. A schedule of key project milestones and tasks is provided in Figure 10. Routine communications between project participants is essential. There will be monthly science team telecons to monitor progress and provide insight into solutions to emerging problems, and redefine priorities as needed. A HEAT wiki at Arizona will provide a resource for team communications and documentation.

The HEAT team will continue to work closely with the NSF, USAP, ASC, and the International Community to implement an optimal plan for deployments to Ridge A.

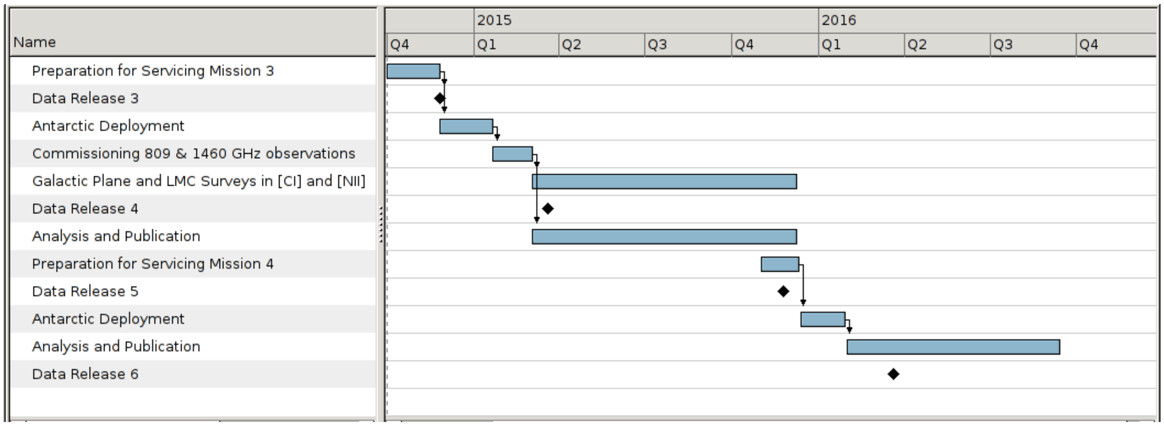

Figure 10: High level project timeline

Note that without an active NSF program, e.g. this proposed project, we cannot continue to operate HEAT and will have to disassemble and retrograde the experiment. We cannot service it without NSF and USAP logistical backing, nor are we allowed to "pause" and leave it on the plateau, by the Antarctic Treaty.

4 Educational Impact

The visage of the dusty lanes of the Milky Way has inspired artistic and scientific imaginations for generations. This inherent fascination is a powerful tool to attract "students" of all ages and callings to a better, more literate appreciation of the sciences. Thus, spreading enthusiasm for science and training the next generation of scientists is a significant component of this research program. Three examples of these efforts to be performed during the proposal performance period are outlined below.

4.1 Instrument Development Experience

The training of students in the development of state-of-the-art instrumentation is essential to the future of science. This is particularly true in mm/submm astronomy where technological advances are happening so rapidly. Ironically, there are only a handful of laboratories in the world where students gain hands-on experience in the design, fabrication, and fielding of radio astronomy instrumentation. In Co-PI Walker's lab we have had a number of students (both graduate and undergraduate) participate in the development of submm-wave instrumentation for Antarctica (i.e. AST/RO) and the Heinrich Hertz Telescope (HHT) on Mt. Graham, Arizona. This work, and the astronomy that has come from it, has been a major component of 9 Ph.D. dissertations. Numerous undergraduate research projects have also resulted; the most recent and relevant to this effort is an infrared sky brightness monitor (for site testing) designed and built by Casey Honniball as part of her independent study research. HEAT is a natural extension of these research efforts. In the proposed budget for HEAT, partial funding for one graduate student is requested. However, as is customary in the lab, many other students will also participate in making the program a success. Indeed, one of the most important aspects of training students in instrument development is experience in working in teams. Astronomical instrumentation is becoming ever more complex, and requires the talents of many individuals. Providing students with both technical training and team-work experience increases their probability of success. This is especially true for the HEAT project, where direct collaborations between students and faculty at universities in Australia and the US will be ongoing.

4.2 HEAT: A Portable, Accessible THz Telescope for Education

Two HEAT telescopes and receivers were constructed, so that one would be swapped with the other in the field, allowing one to be in operation at Ridge A while the other is refurbished at Arizona. The 'off duty' HEAT telescope remains a complete facility: with heterodyne receiver, IF processor, FFT spectrometer, and data system. However its portability and accessibility makes it particularly ideal for education: it is "ALMA in a box". We propose to use the 'off duty' telescope in support of education and public outreach activities. Roof-top astronomical observations in CO J=1-0 from campus, and 492 GHz [CI] observations during the best spring and fall weather on Mt. Lemmon (9157' elevation) would be undertaken by undergraduate and graduate students to gain expertise in terahertz astronomy and astronomical spectroscopy. Unlike optical telescopes, HEAT can be used day and night, on-site or remote, making it ideal for classroom instruction. During the course of developing and operating HEAT we will develop instructional modules for various age groups that focus on the science and technology of HEAT. We will exploit the 'off duty' telescope as a hands-on demonstrative laboratory with the goal of providing students with an intuitive understanding of underlying physical concepts.

4.3 Development of a NOVA ScienceNow video

Reception of public blogs during HEAT's annual deployments is positive and popular. Indeed, the overall experiment and particularly the human story of deployment to Ridge A captures the kind of 'high adventure' spirit that drives many young individuals to science in the first place – but which many scientific programs do not advance. Many of us gained our scientific awareness and creative excitement through programs like PBS's NOVA, and it would seem only appropriate for us to work to collect the videographic and photographic materials needed to produce a short science video highlight for the program. Initial interest in this development at PBS was highly favorable and would be explored for the 2014-15 deployment to Ridge A.

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