1 Results from Prior NSF Support

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

In 2010, the PI initiated an NSF-funded (ANT-0944335, 10/2010-9/2014, $1.486M) 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.

1.1.1 Broader Impacts: Activities

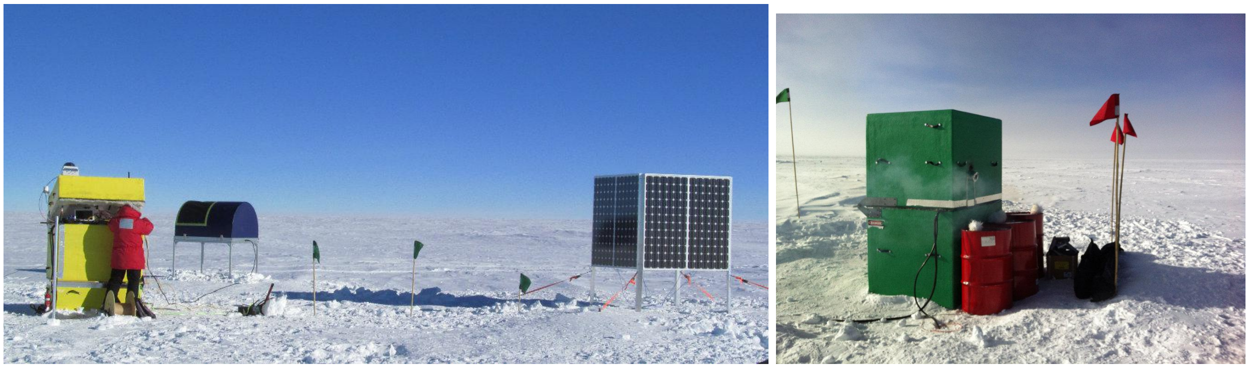

Figure 1: (left) A new far-infrared astronomical observatory was established on Ridge A, the inland summit of the polar plateau, as a joint collaboration between the University of Arizona and the University of New South Wales in Australia in January 2012. Consisting of a (blue) High Elevation Antarctic 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. 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.

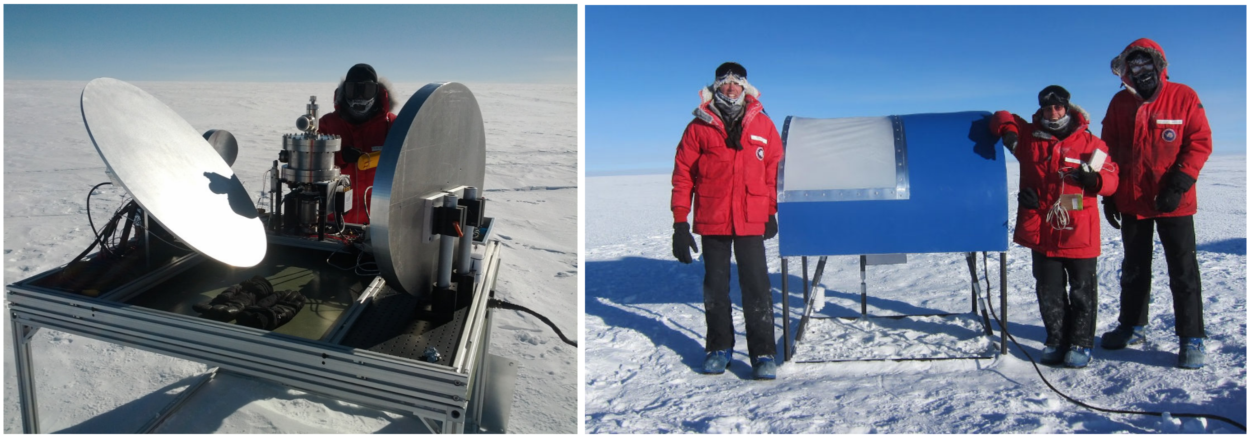

Figure 2: (left) The prototype 3-mirror off-axis Gregorian telescope (2012) , cryogenic receiver system and frozen PI are visible in this image. (right) Enclosed in a fiberglass shell and teflon film “window” that is transparent to THz radiation, the HEAT telescope is ready for observations (January 2014).

For orientation, the facility is shown in Figures 1 and 2. It is comprised of several components: PLATO-R’s yellow **instrument module** houses 20 kW hr of LiFePO4 batteries, power distribution electronics, supervisor computers, and Iridium modems and antennas. A 4-panel **Solar Cube** provides up to 800 W of solar power to the instrument module during the summer months. PLATO-R’s green **engine module** 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, providing up to 1500W of power to the instrument module during winter. Finally, 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, like SPT. 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 810 and 492 GHz receivers for atomic carbon and was swapped for 810 GHz and 1460-1500 GHz receivers starting in January 2014.

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 an extreme environment, 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 a total power budget of less than 200W.
3. Developed and deployed an advanced telescope scheduling system that can autonomously execute an observing plan with little human involvement, with a 2 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 CO J=13-12 and [NII] at 200 μm installed in 2014, and ultimately ionized carbon at 158 μm (this proposal). By exploring molecular clouds and their environments in tracer species *other* than CO, HEAT will probe the entire carbon trail & 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.

1.1.2 Intellectual Merit: 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 such 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.

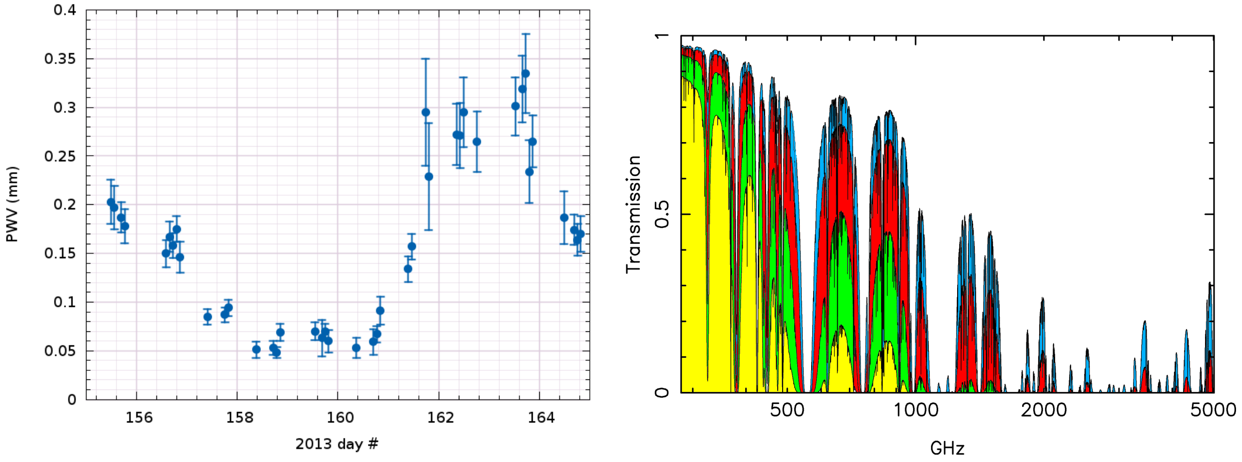

Figure 3: (left) A sample week of precipitable water vapor measurements from HEAT during winter 2013 shows an incredibly stable, transparent atmosphere, with a median winter PWV of 124 microns, and a best quartile of 87 microns! Such dry air leads to the upper-two (blue and red) transmission plots shown 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.

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.

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 diode mixer receivers, HEAT's sensitivity to each spectral line is already extremely competitive.

Site	25%ile	50%ile	Median winter transmission @660 GHz	Best 25% winter transmission @1500 GHz	Best 10% winter transmission @2000 GHz
	winter PWV (mm)				
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).*

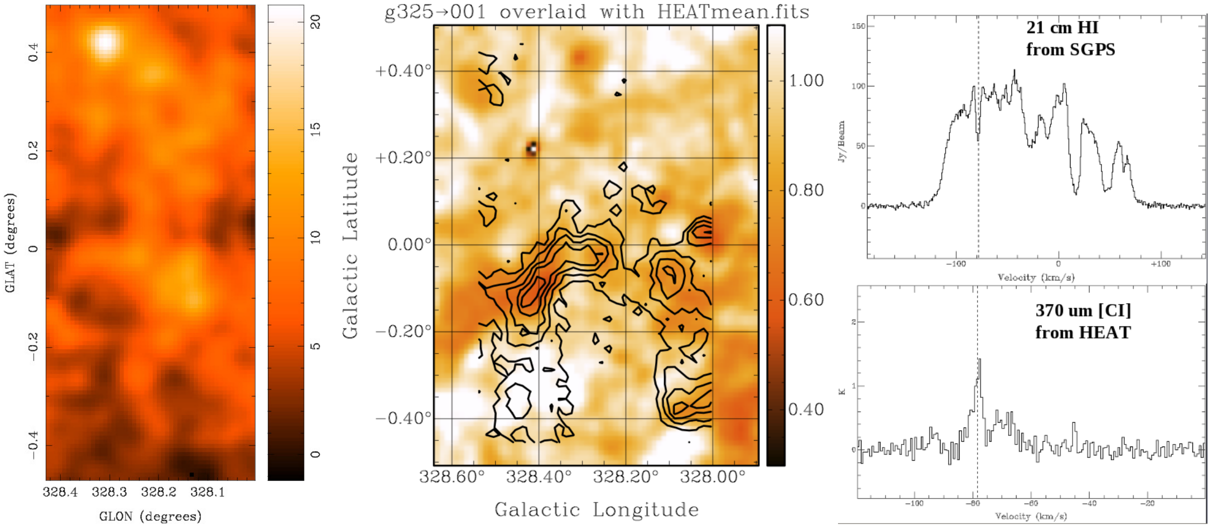

Figure 4: (left) Integrated intensity map of [CI] line emission toward l=328^o shows that diffuse atomic carbon emission fills the Galaxy and is nearly as abundant as CO. (center) The molecular gas shown by HEAT's detected line emission at -78 km/s V$_{lsr}$ (contours) appears to be associated with self-absorption 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.

1.1.3 Intellectual Merit: 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 as well as a high priority $1^o \times 1^o$ maps that are now publically available. With a 3-sigma rms noise level of 100 mK and almost 10 square degrees released, these are the largest, most sensitive maps in the atomic carbon line to date.

Early 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-dark gas" (Grenier et al., 2005; Wolfire et al., 2010). HEAT has already produced in its 2014 season maps of CO

J=13-12 data at 1497 GHz and to-be-downlinked results at [NII] 1461 GHz (Figure 5).

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 (Burton et al. 2014).

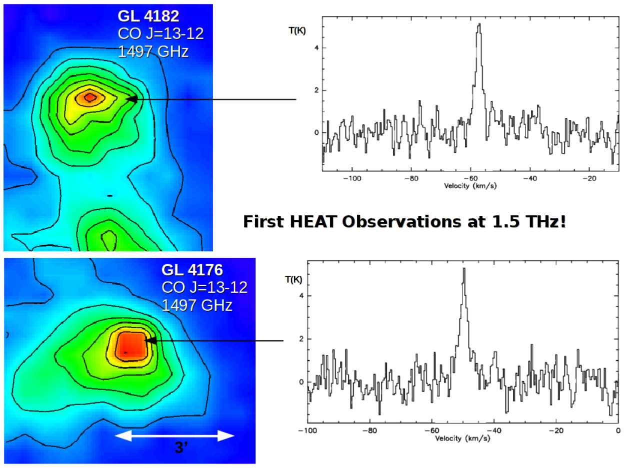

Figure 5: Commissioning observations of CO J=13-12 toward two high mass star forming regions performed by HEAT in 2014. In total, HEAT's 2014 observations at 200 microns nearly quadruple the amount of THz measurements made from the ground!

1.1.4 Publications and Research Products

The first major data releases (DR1 and DR2) from the HEAT telescope are online and comprise data acquired during the 2012 and 2013 seasons at Ridge A. Preliminary 2014 data are now available in DR2. The following papers have been published or are currently in press at the time of review. **Please visit soral.as.arizona.edu/heat/ for data and updates on publications and results!**

1. Kulesa, C., "Terahertz Spectroscopy for Astronomy: From Comets to Cosmology", IEEE Transactions on Terahertz Science and Technology, 2011, 1, 232.
2. C. Kulesa, C. Walker, A. Young, J. Storey, and M. Ashley, "HEAT: The High Elevation Antarctic Terahertz Telescope", 22nd International Symposium on Space Terahertz Technology, (2011), 9.
3. Craig A. Kulesa, Michael C.B. Ashley, Yael Augarten, Colin S. Bonner, Michael G. Burton, Luke Bycroft, Jon Lawrence, David H. Lesser, John Loomis, Daniel M. Luong-Van, Christopher L. Martin, Campbell McLaren, Shawntel Stapleton, John W.V. Storey, Brandon J. Swift, Nicholas F.H. Tothill, Christopher K. Walker and Abram G. Young, "Opportunities for Terahertz Facilities on the High Plateau", IAU Symposium 288, 2012, 256.
4. Burton, M. G., Braiding, C., Glueck, C., Kulesa, C. et al. 2013, "The Mopra Southern Galactic Plane CO Survey", PASA, 30, 44.
5. Burton, M. G., Ashley, M. C. B., Braiding, C., Storey, J.W.V., Kulesa, C., Hollenbach, D., Wolfire, M., Glueck, C., Rowell, G., "The Carbon Inventory in a Quiescent, Filamentary Molecular Cloud in G328", 2014, ApJ, 782, 72.
6. Kulesa, C. A., Honniball, C., Lesser, D., Swift, B. J., Walker, C.K., Young, A.G., "The High Elevation Antarctic Terahertz (HEAT) telescopes on Ridge A, Antarctica", IEEE Transactions on Terahertz Science and Technology, 2015, in review.

7. Kulesa, C. A, Ashley, M., C. B., Braiding, C., Storey, J.W.V., Lesser, D., Hollenbach, D., Wolfire, M., "An Antarctic [CI] and CO Survey of the Milky Way", 2015, ApJ, in review.
8. Kulesa, C.A., Ashley, M. C. B., Storey, J.W.V., Honniball, C., Lesser, D., Walker, C.K., Young, A.G., "New Far-Infrared and Terahertz Astronomical Capabilities over the High Antarctic Plateau", 2015, ApJ, in review.

1.1.5 Relation to Current Proposal

Much of the effort to date has focused on the technological development of this pathfinding observatory and achieving its first results. While the choice of Schottky diode mixer receivers at an operating temperature of 50K was done for robustness, the state of the art in detector sensitivity is achieved using superconducting devices at temperatures of ∼4K. Now that basic operation of HEAT and PLATO-R has been proven, augmentation of a superconducting receiver system would improve the mapping speed and scientific capability of the system by an order of magnitude. **The goal of this proposal is to develop a superconducting receiver system using existing best-of-breed Hot Electron Bolometer (HEB) mixers from 1.4-1.9 THz to augment the existing cryogenic Schottky diode mixers from 0.8 to 1.5 THz. This augmentation will bring world-class instrument sensitivity to the very best site on the face of the Earth for astronomy at terahertz frequencies.** This is the next development phase for the observatory.

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. 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∼70K) atomic clouds and the warm (T∼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 and is available now!

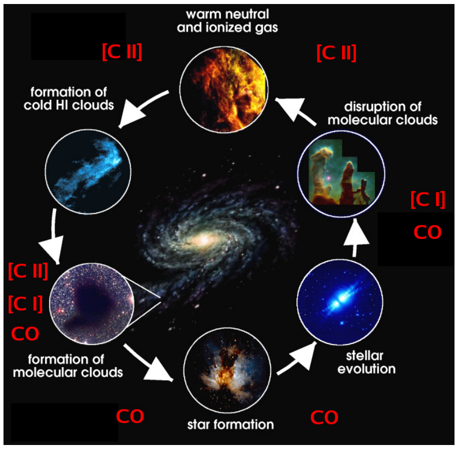

Figure 6: The HEAT telescopes will observe the fine structure lines of [N II], [C II], [C I], and CO that probe the entire life cycle of interstellar clouds. In particular, HEAT will witness the transformation of neutral atomic clouds into star-forming clouds, the interaction of the interstellar medium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

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. HEAT can distinguish between the mechanisms proposed to form clouds 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 probes 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] are 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. 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 APEX, and the ALMA and SMA interferometers (in addition to current studies using Herschel data). How will the HEAT telescope address the scientific goals that have been illustrated?

2.4.1 A Superconducting HEB Mixer Receiver at 4 Kelvin

The main technical advance of this proposal is to integrate a more sensitive receiver capability to the HEAT telescope. The current deployment of Schottky diode mixers are robust and operate at ambient temperatures and improve substantially when cooled. Nevertheless, they are a factor of ∼3 less sensitive than superconducting Hot Electron Bolometer (HEB) mixers. This sensitivity is most critical for the very highest frequencies, such as 1.9 THz, where the good weather opportunities are limited. In order to maximize the science return at the highest frequencies, state-of-the-art mixers must be deployed. J.R. Gao in the Division of Sensor Research and Technology at SRON in the Netherlands has published the most sensitive HEB mixer receiver results in the world (e.g. Kloosterman et al. 2013). Indeed, very recent lab results delivering a noise temperature of 500K DSB at 1.9 THz have been achieved (Gao, private communication). He will provide HEB mixers at 1.9 THz for use with HEAT. in turn, the University of Arizona will fabricate the coupling optics, electronics and packaging to integrate with the existing HEAT telescope optics. The University of Arizona team has extensive experience with HEB devices through the STO project (Section 2.4.5). To house the SRON mixers, we will develop a hybrid cryostat that leverages the very successful design currently used on HEAT (Figure 2). The proposed cryostat has a radiation shield cooled to 50K by the current Sunpower Cryotel CT stirling engine, which also cools the existing Schottky diode mixers and maintains an excellent vacuum year-round through cryopumping. When the weather is especially good, a second cold work surface is cooled even further to 4-6K using a Sumitomo RDK-101 cold head attached to a matching CNA-11 helium compressor in a specially-insulated vessel, modified to operate from PLATO-R's 120 VDC bus. Helium compressor lines are short, insulated, with seals replaced with fluorosilicone rings rated to -60C and temperature-regulated. The compressor will be integrated to the HEAT telescope and PLATO-R system using a cold-rated, simplified VFD (variable frequency drive). The system will be environmentally tested to -60C using a large dry ice chamber. This hybrid system provides year-round observations with Schottky diode mixers at 810 GHz or 1460 GHz at a low total power consumption of 150-200W, and superconducting operation at 4-6 Kelvin with a total power consumption of 1000W during the days of best weather, when precipitable water vapor drops to 100 microns (0.1 mm) or lower. PLATO-R can already provide this power capability. Table 2 shows the measured noise temperatures of the HEAT receivers at different operating temperatures, demonstrating the marked improvement possible with the 4K system.

2.4.2 Velocity-Resolved Imaging Spectroscopy

Large format detector arrays in the infrared are now commonplace, and such arrays on the ground and in space (e.g. Spitzer and Herschel) have performed large-scale maps of molecular material. However, such continuum surveys 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

HEAT Receiver	**T_{rec} at 290K**	**T_{rec} at 50K**	**T_{rec} at 4.2K**
0.8 THz Schottky	5000K	1500K	–
1.5 THz Schottky	10000K	3500K	–
1.5, 1.9 THz HEB	–	–	750K

Table 2: Double-sideband receiver noise temperatures for HEAT receivers at different temperatures. Mapping speed is inversely-proportional to receiver noise temperature squared; so a 2x reduction in noise temperature generally results in a 4-fold increase in mapping speed.

a model of Galactic rotation is often the only way to determine each cloud's distance and location within the Galaxy. With HEAT's fine spectral resolution, better 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.

2.4.3 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 7 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. In particular, 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. 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.

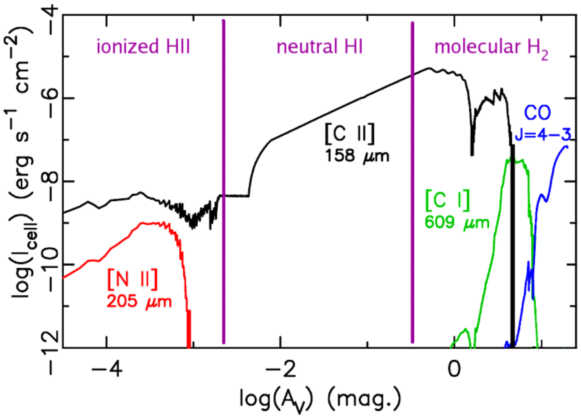

Figure 7: **The uniqueness of HEAT's [CI], [CII] and [NII] surveys.** A model depiction of the intensity of diagnostic lines of carbon and nitrogen species as viewed through a UV-illuminated cloud from depths of A_V=0 to 20 mag. Vertical purple lines overlay the HII-to-HI-to-H_2 boundaries found at the edges of dense interstellar clouds. This figure demonstrates that [CII] and [CI] probe H_2 clouds with little CO, and that adding [NII] disentangles the [CII] emission stemming from ionized gas.

This proposal brings the crucial [CII] mapping capability to HEAT, with the high sensitivity needed to perform a statistically meaningful survey of Galactic emission. This is a unique capability that cannot be done from the ground. There are no space observatories that can provide these data, and the only suborbital platforms (SOFIA & balloons) can only fly for limitied missions. HEAT will uniquely 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.

2.4.4 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 ($0 > l > -100^o$). The survey 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 the Herschel "GOTC+" open time key program (Langer et al., 2010). The target line sensitivity is set to identify all ionized, atomic, and molecular (CO) carbon to a column density corresponding to a visual extinction of 1 magnitude (1.8×10^{21} cm^{-2}).

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 using the On-The-Fly (OTF), or "drift scanning" technique. HEAT can reach the requisite sensitivity of 1σ=0.15 K km s^{-1} per beam at 810 GHz over a fully sampled square degree in 10 days, assuming median winter conditions of τ_{810} ~0.5. 20 square degrees distributed from $0 > l > -20^o$ and $-45 > l > -100^o$ will be mapped in ≈300 days. The superconducting [CII] channel will map a square degree in 15 days during the best weather, when the opacity at 1900 GHz drops to 2. It is expected that 2-3 square degrees can be mapped per season in [CII] to the required sensitivity (3σ rms noise of 1K or less) and an additional 2 square degrees to shallower sensitivity (3σ rms noise of 2K or less).

2.4.5 Broader Impact: Synergies with Other Observatories

HEAT is timely. The Spitzer 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 interstellar dust, and constrains extinction laws as a function of galactocentric radius. HEAT provides the best corresponding spectroscopic survey that will provide key 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 results provided by SOFIA and Herschel. The higher angular resolution afforded by larger telescopes necessarily reduces their field of view and mapping speed. 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 500 times the areal coverage of "GOTC$^+$" during this proposal period, and will exceed the Herschel coverage in [CII] by a factor of 200 in a single season. Given the expiration of Herschel and SOFIA's limited flying hours, the terahertz astronomy provided by the HEAT telescope has become even more critical!

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 very effectively performed by single-dish telescopes like HEAT. Indeed, HEAT's Southern survey in atomic carbon, [NII], [CII] 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 2.4.3). The addition of HEAT will be able to address questions which other surveys alone could not. Both AST/RO and the RLT have made pioneering, targeted observations of [N II] (Oberst et al. 2006, Marrone et al. 2005). These observations are used to optimize 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 2016 and will last for $\sim$2 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. HEAT will map 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 be carefully coordinated to provide maximum science return.

2.4.6 Broader Impact: Site testing of the coldest place on Earth

Analysis of 1 km land surface temperatures from the MODIS instruments on NASA's Aqua and Terra satellites shows surface skin temperatures that exceed the record low temperature of -89.2C measured at Vostok in 1983. One such site to have experienced temperatures as low as -92C twice in the last 3 seasons, is a mere 26 km from HEAT and PLATO-R, which lie at a comparatively "warm" location. One hypothesis suggests that the local topography drives the cold air drainage rate; when winds are calm, local minima act as "sinks" for cold air and represent places where record cold temperatures are achieved. In contrast, HEAT & PLATO-R lie along the ridge where the coldest air easily drains downhill and the turbulent boundary layer becomes vanishingly small. Indeed, during such periods of calm, HEAT typically witnesses a sharp rise in air temperatures (from -75C to -55C), not a drop as is common at downstream sites such as Vostok or South Pole

Station. In collaboration with lead NSIDC researcher Ted Scambos, remote weather monitoring systems will be installed both at Ridge A and at the neighboring "cold" site as a part of the fieldwork that services HEAT and PLATO-R. These weather monitoring systems, funded separately, will address critical questions for aeronomy and glaciology:

1. What is controlling the record minimum skin temperature level, which is consistently -91.5 to -93C in several widely-spaced locations?
2. Does air drainage rate, related to local topography, control the inversion layer temperature gradient? What weather patterns favor record low temperature events?
3. Can increasing CO_2, CH_4, etc. levels in the atmosphere, or changing H_2O or SO_2 in the stratosphere, affect the minimum temperature levels over time?

2.4.7 Science Products and Dissemination

Access to HEAT data products to the greater scientific community will be provided through a web browser interface that will interface with a SQL database that accesses and the FITS data cubes that HEAT generates. 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. Early access of data downlinked from the experiment in the current season will be released each Fall. A more formal annual data release will be made each Spring after the annual collection of raw data products from HEAT. This annual data 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/`

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 3 provides a listing of the roles of each member in the organization.

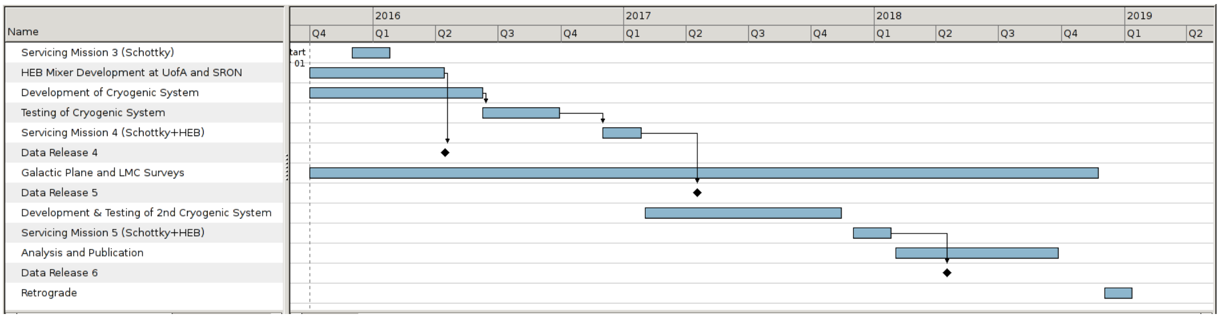

Figure 8: High level project timeline

Participant	Affiliation	Participation Activity
Michael Ashley	UNSW	PLATO-R lead; site testing
Michael Burton	UNSW	Lead: Companion CO Survey from the Mopra 22m
J.R. Gao	SRON	Provides HEB mixers for 1.5-1.9 THz channels
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
Ted Scambos	NSIDC	“Coldest Place on Earth” site testing campaign
Christopher Walker	Univ. Arizona	Co-PI, leads student advising
Mark Wolfire	U. Maryland	Advisor: PDR modeling
Abram Young	Univ. Arizona	Systems lead: leads cryostat design

Table 3: Activities of the HEAT Instrument and Science Team

Collectively the HEAT team members represent many years of instrument building, observing experience, and theoretical expertise. As related by Table 3, 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 leads 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 8. 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.

A schedule of key project milestones and tasks is provided in Figure 8. A maintenance servicing of the Ridge A robotic facility will be undertaken in 2015-16 to resupply the site with the 810 GHz and 1.5 THz Schottky mixers. In 2016, an aggressive receiver development effort will be coordinated between Arizona and SRON to develop a cold-rated HEB receiver system for deployment in the the 2016-17 field season. Each year, a readiness review will be performed prior to shipping to assess the following system requirements: 1) fully remote operation, 2) low power dissipation 3) receiver sensitivity, and 4) receiver stability. A second HEB receiver system will be constructed in 2017 to exchange with the first, minimizing time and risk in the deep field. 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 (see Supplementary Documents).

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

4 Broader Impact: Education

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 THz 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 THz 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 is an infrared sky brightness monitor for HEAT designed and built by Casey Honniball as part of her independent study research.** In the proposed budget for HEAT, partial funding for one undergraduate and 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 effectively "an ALMA dish 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

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. The overall HEAT 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 fail to 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 "pay it back" by collecting the videographic and photographic materials needed to produce a short science video highlight for the program. Initial interest in this development at NOVA was highly favorable and would be explored for the 2016-17 deployment to Ridge A.

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