Project Description

1 Results from Prior NSF Support

Over the past few years, the PI's group at the University of Arizona has built two spectroscopic heterodyne array receivers; *PoleSTAR*, a 4 pixel 810 GHz receiver now in operation on the 1.7 m AST/RO telescope at the South Pole and *DesertSTAR*, a 7 pixel 345 GHz array receiver for the 10-meter Heinrich Hertz Telescope (HHT) on Mt. Graham, Arizona. Both instruments are the very first of their kind. PoleSTAR has been fully integrated with the AST/RO telescope and offers excellent ($T_{\rm rec} < 700$K) receiver performance on all 4 pixels (Figure 1). DesertSTAR went into routine operation on the HHT with an initial complement of 3 pixels in October 2003 and will be expanded to the final hexagonal array of 7 pixels during summer 2004. Both instruments were funded by NSF programs; work on PoleSTAR was funded by the NSF Office of Polar Programs (A. Stark–PI: OPP-0126090), and DesertSTAR development has been a joint effort between the University of Arizona, the University of Massachusetts, and the University of Virginia with partial funding through the NSF ATI program (AST-9622569).

The experience and heritage gained through these past efforts will be invaluable in making HEAT a reality.

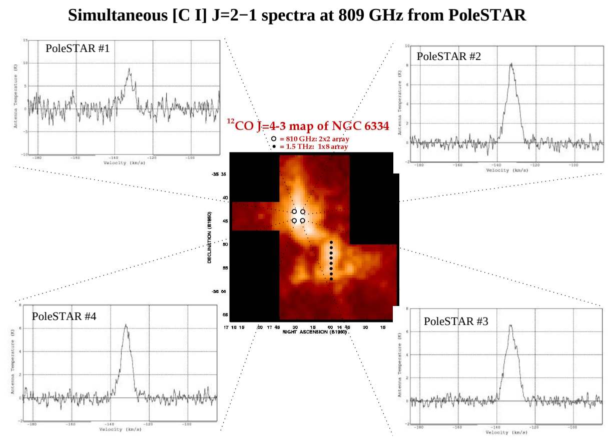

Figure 1: Simultaneous 4-channel spectra from PoleSTAR, the PI's 810 GHz array receiver, now in operation at the AST/RO telescope at the South Pole. Every imaged point in a heterodyne map of a molecular cloud also represents a high-resolution ($\lambda/\Delta\lambda \approx 10^6$) spectrum.

2 Research Activities

The proposed High Elevation Antarctic Terahertz Telescope (HEAT) will forge entirely new capabilities for ground based infrared and submillimeter astronomy, providing a window on the Universe which otherwise would be unavailable except via airborne or space-based platforms. The pioneering surveys to be performed by HEAT will be made available to the entire astronomical community. HEAT represents a true international pioneering effort in keeping with the spirit of the International Polar Year 2007-2008. Here, we outline HEAT's "key project", a THz survey of the Galactic Plane observable from Dome A, Antarctica.

2.1 *Introduction*

From the Milky Way to the highest-redshift protogalaxies at the onset of galaxy formation, the internal evolution of galaxies is defined by three processes closely related to their interstellar contents:

1. the transformation of neutral, molecular gas clouds into stars & clusters (star formation).
2. the interaction of the interstellar medium (ISM) with the young stars that are born from it, a regulator of further star formation.
3. the return of enriched stellar material to the ISM by stellar death, eventually to form future generations of stars.

The evolution of (the stellar population of) galaxies is therefore determined to a large extent by the life cycles of interstellar clouds: their creation, star-forming properties, and subsequent destruction by young (hot) stars.

The life cycle of interstellar clouds is summarized pictorially in Figure 2. These clouds are largely comprised of neutral hydrogen in both atomic and molecular form and atomic helium. These species are notoriously difficult to detect under normal interstellar conditions. Atomic hydrogen is detectable in cold clouds via the 21 cm spin-flip transition, but because its emissivity is insensitive to gas density, cold (T∼70K) atomic clouds are not distinguishable from 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 prevail-

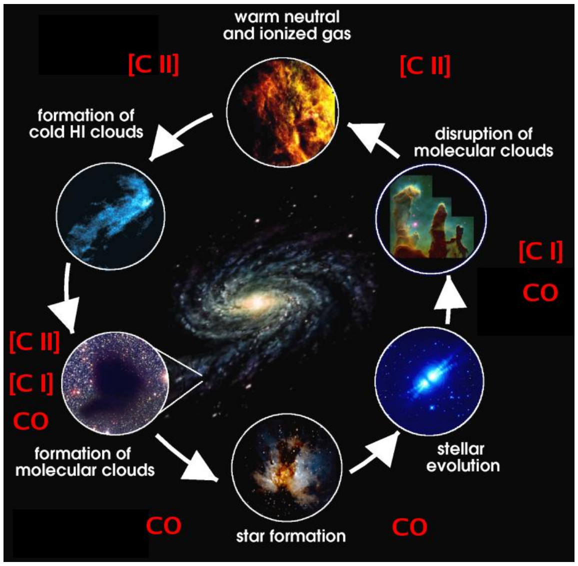

Figure 2: Life Cycles of the ISM

ing physical conditions in cold interstellar clouds. Thus, it is generally necessary to probe the nature of the ISM via rarer trace elements. Carbon, for example, is found in ionized form (C^+) in neutral HI 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 acute. The National Research Council's most recent *Decadal Survey* has identified the study of star formation as one of the key recommendations for new initiatives in this decade. Similarly, understanding the processes that give rise to star and planet formation represent the central theme of NASA's ongoing Origins program.

A new, comprehensive survey of the Galaxy must address the following questions to make significant progress toward a complete and comprehensive view of Galactic star formation:

- How do molecular clouds form, evolve, and become disrupted? How do typical atoms and grains cycle through the ISM?
- How and under what conditions do molecular clouds form stars?
- How do the energetic byproducts of stellar birth, UV radiation fields and (bipolar) mass outflows regulate further star formation in molecular clouds?
- How does the Galactic environment impact the formation of clouds and stars? What are the specific roles of spiral arms, central bars, infall and other influences from outside the Galaxy?

2.2 *HEAT Science Goals*

Via resolved C^+, C, CO, and N^+ 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 used to construct a template to **interpret global star formation in other spiral galaxies**.

Joined with other surveys, HEAT will:

1. Map as a function of Galactic position the size and mass distribution and internal velocity dispersion of interstellar clouds in the Galaxy.
2. Construct the first barometric map in the Galactic Plane, the first map of the gas heating rate, and a detailed map of the star formation rate.
3. Probe the relation between the mass surface density (on kpc scales) and the star formation rate, so that we may be able to understand the empirical Schmidt Law used to estimate the star formation rate in galaxies.
4. Reveal clouds clustering and forming in spiral arms and supershells, and follow the growth of clouds to eventually shield molecules and become gravitationally bound.
5. Observe the formation and destruction of clouds throughout the Galaxy, and directly observe the feedback caused by supernovae and the ultraviolet radiation from massive stars.
6. Ultimately construct a Milky Way template connecting the line emission from C^+, N^+, C, CO, and dust continuum to star formation properties and state of the ISM. This template will be applied to nearby star-forming galaxies.

2.2.1 *Goal 1: The Life Cycle of Interstellar Clouds*

The formation of interstellar clouds is a prerequisite for star formation, yet the process has not yet been observed! HEAT is designed with the unique combination of sensitivity and resolution needed

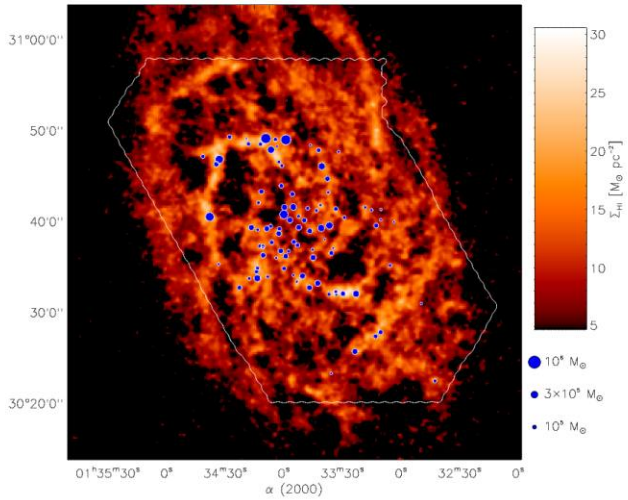

Figure 3: The location of GMCs in the nearby spiral galaxy M33 are overlaid upon an integrated intensity map of the HI 21 cm line (8). These observations show that GMCs are formed from large structure of atomic gas, foreshadowing the detailed study of GMC formation that HEAT will provide in the Milky Way.

to observe atomic clouds in the process of becoming giant molecular clouds (GMCs).

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 3). HEAT can distinguish these processes by:

1. Accounting for all the molecular hydrogen mass (the $H_2/C^+/C^0$ clouds as well as the H_2/CO clouds) when computing global measures of the interstellar medium.
2. Making a more complete, better characterized catalogue of interstellar clouds than CO or HI surveys alone.
3. Constructing spatial and kinematic comparisons of sufficient resolution, spatial coverage and dynamic range to probe a wide range of interstellar phases and environments.

Since the C^+ (and to a lesser degree, C^0) line emissivity barometrically 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 superlative 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, 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 from small H_2 clouds. These clouds will be seen in C^+ and C line emission by HEAT. Similarly, the N^+ observations of diffuse HII clouds provide an unprecedented spectroscopic survey of the location and rate of star formation in the Galaxy. The rate of star formation is determined by using the N^+ luminosity to determine the ionizing luminosity of OB stars, a standard metric for the star formation rate.

The high spectral resolution of HEAT enables crucial kinematic studies of the Galaxy to be made. HEAT will determine the kinematics and thermal pressures of most supershells, fossil superrings, and molecular clouds just condensing via gravitational instability of old superrings and supershells. HEAT can detect the H_2 clouds which 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^+ measures the flux of ionizing photons, and C^+ 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 catalogued 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 the nearby (within 0.1-30 pc) natal GMC. Such measurements are crucial for models of star formation feedback and global galactic evolution.

2.2.2 *Goal 2: The Galactic Star Formation Rate*

Star formation within galaxies is commonly described by two empirical relationships: the variation of the star formation rate per unit area with the (atomic + molecular) gas surface density (32; 19) and a surface density threshold below which star formation is suppressed (27). The Schmidt Law has been evaluated from the radial profiles of H and HI, CO emissions for tens of galaxies. The mean value of the Schmidt index, n, is 1.4 ± 0.15 (19), valid for kpc scales. This empirical relationship is used in most models of galaxy evolution with surprising success given its simplicity. 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, C^+ and N^+ emission provides the optimum set of data to calculate the Schmidt Law in the Galaxy. The N^+ 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^0 and C^+ 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. The Schmidt Law is constructed from the radial profiles of the star formation rate derived from N^+ 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 (19). The velocity-resolved star formation rate indicators provided by HEAT will be invaluable in interpreting more traditional indicators, like the far-infrared continuum. With its resolution and ability to gauge thermal ISM pressure, HEAT evaluates this critical, regulatory process in the Milky Way.

2.2.3 Goal 3: Constructing a Milky Way Template

C^+ and N^+ will be the premier diagnostic tools for studying external galaxies in the submillimeter for galaxies with large redshifts (Atacama Large Millimeter Array). 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 crucial diagnostic template or "Rosetta Stone" that can be used to translate the global properties of 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^+, C, CO, N^+, HI, FIR emission, and star formation.

2.3 Properties of the Proposed Survey

HEAT's science drivers represent a definitive survey that would not only provide the clearest view of interstellar clouds and their evolution in the Galaxy, but would also serve as the reference map for contemporary focused studies with Herschel, APEX, and the ALMA interferometer. The following properties define the science needs for HEAT.

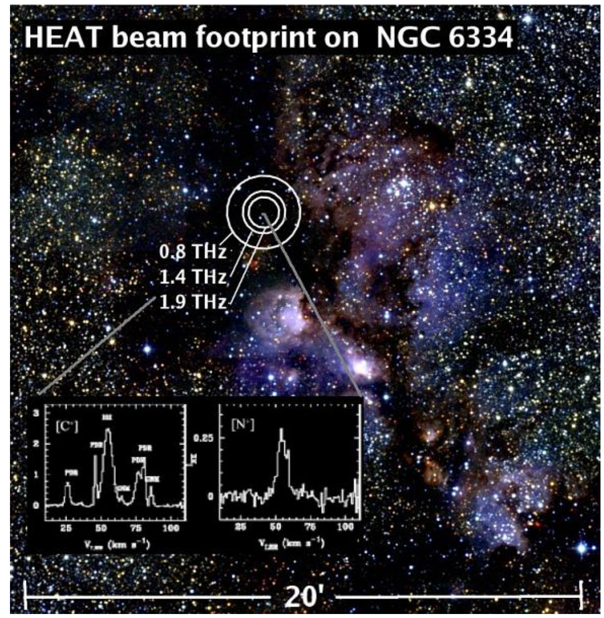

Figure 4: The power of HEAT: Each of the 3 heterodyne beams of HEAT are overlaid upon a 2MASS infrared image of NGC 6334. The beams will measure high-resolution spectra in the 0.81, 1.46, and 1.90 THz bands respectively, a small portion (25%) of each is shown as synthetic spectra of NGC 6334.

2.3.1 High Resolution Spectroscopic Imaging

Techniques commonly used to diagnose the molecular ISM include submillimeter continuum mapping of dust emission (17) and dust extinction mapping at optical and near-infrared wavelengths (25). Large format detector arrays in the infrared are now commonplace, and with the advent of bolometer arrays like SCUBA 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 large-scale evolution of molecular clouds 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 per-channel resolution of 0.4 km s^{-1} over 370 km s^{-1} of spectrometer bandwidth, in excess of the Galactic rotational velocity.**

2.3.2 *A Terahertz Galactic Plane Survey*

Molecular line surveys have been performed over the entire sky in the light of the 2.6 millimeter $J = 1-0$ 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. The CO J=7-6 line measured by HEAT is a better probe of the energetic gas that plays a role in stellar/interstellar feedback machanisms. It probes gas that 1) participates in molecular outflows, 2) senses radiation fields at the photodissociated surfaces of clouds, and 3) is warmed by star-formation in cloud cores. It will help interpret even basic properties of clouds derived from existing mm-wave observations by constraining excitation conditions.

As already described in Section 2.2, the dominant spectral lines of the Galaxy are the fine structure far-infrared and submillimeter lines of C, CO, C^+ and N^+. They probe and regulate all aspects of the formation and destruction of star forming clouds. They 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 regulator of further star formation and a critical component of galactic evolution.

2.3.3 *Angular Resolution and Full Sampled Maps*

Good angular resolution is a critical aspect of improvement for a new Galactic survey. Previous surveys of [N II] and [C II] were limited to very small regions (KAO, ISO) or had low angular resolution (COBE, BICE) (2; 28). HEAT will fully sample both species over large regions of sky to their diffraction limited resolution of 1.7′ and 1.3′, respectively. Arcminute resolution with proper sampling is crucial to disentangling different clouds and cloud components over large distances in the Galaxy. For example, the Jeans length for star formation in a GMC is approximately 0.5 pc. This length scale is resolved by HEAT to a distance of 500 pc at CO J=7-6 & [C I], and 1200 pc at [C II]. Warm and cold HI clouds and GMC's can be resolved well past 10 kpc.

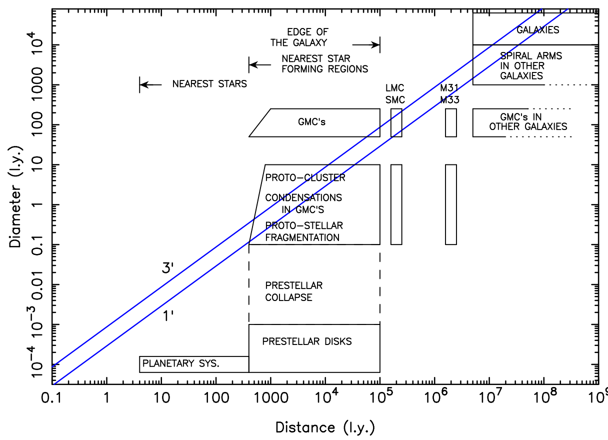

Figure 5: **The need for high angular resolution:** HEAT has the unique blend of wide field-of-view and good angular resolution to easily resolve GMC's throughout the Galaxy, even to the LMC and SMC. HEAT will study all star forming regions in detail within a distance of 1 kpc, and all interstellar components to a distance of >10 kpc.

2.3.4 *High Sensitivity*

HEAT's high sensitivity, even in the far-infrared, is owed mostly to the superlative atmospheric conditions above Dome A, Antarctica. The bitter cold and exceptional dryness allow ground-based observations into the otherwise forbidden THz windows. A plot of the expected atmospheric transmission for the full range of winter observing conditions is plotted in Figure 6. The implications for the sensitivity to each spectral line is discussed below.

CO $J = 7 \rightarrow 6$

We aim to detect all CO to A_V=1, where essentially all hydrogen has formed H_2 and CO is just forming. This extinction limit, corresponds to N(^{12}CO)$\sim$ 2×10^{15} cm^{-2}, or an integrated intensity (T_k $\sim$ 70K) of 1.5 K km s^{-1} in the J=7-6 transition at $n_H = 10^5$ cm^{-3}. This sensitivity limit is achievable (3σ) within 2 seconds of integration time at 806 GHz in *median* winter atmospheric conditions (T_{sys} $\sim$1000K) on Dome A. Limits on J=7-6 in that time would constrain the gas density, based upon the line brightness of millimeter wave transitions.

Atomic carbon $J = 2 \rightarrow 1$

The same extinction limit ($A_V = 1$ mag) set for CO will also be applied to the $J = 2 \rightarrow 1$ fine structure line of atomic carbon at 809 GHz. The corresponding column density of atomic carbon is $N(C) = 1 \times 10^{16}$ cm^{-2}, yielding a line intensity of 0.7 K km s^{-1} at $T_k = 50$K and $n_{\rm H} = 10^4$ cm^{-3}, achiev-

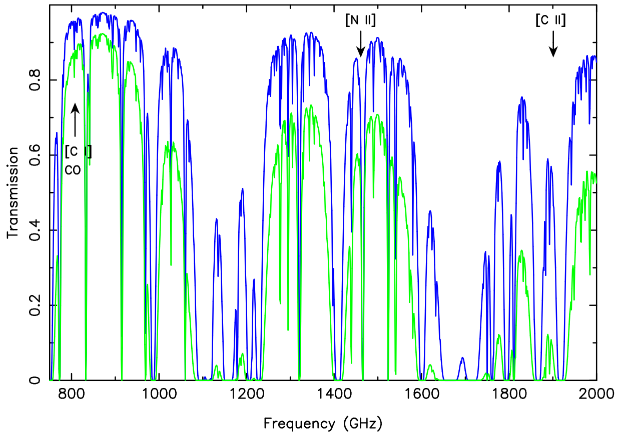

Figure 6: Atmospheric transmission in the far infrared/submillimeter, derived from the PWV estimates for Dome A of Lawrence (2004). The pwv content for each model atmosphere is 120 and 30 microns respectively, corresponding to ∼75 percentile and ∼10 percentile winter weather at Dome A. Arrows indicate the wavelengths of the [N II], [C II], and CO/[C I] lines.

able (3σ) in 8 seconds of integration time with HEAT during winter on Dome A.

N^+ and C^+

The fine structure lines of ionized carbon and nitrogen represent the dominant coolants of the interstellar medium of the Galaxy and starforming galaxies. Indeed, the integrated intensity of the 158 μm C^+ line alone represents 1% of the bolometric luminosity of the Galaxy! As such, these lines are relatively easy to detect in the ISM. Our most demanding requirements for detection of C^+ and N^+ lie in the search for the formation of giant molecular clouds (via C^+) and the measurement of the diffuse warm ionized medium in the Galaxy (via N^+). A flux limit of 1 K km s^{-1}will detect N^+ in warm HI as far away as the Molecular Ring, achievable in median winter weather in 30 seconds with velocity smoothing to 2 km s^{-1}, appropriate for hot ionized gas. Similarly, the accumulation of GMC's from many cold neutral clouds of atomic hydrogen occurs at low relative column densities of $\sim 5 \times 10^{20}$ cm^{-2}. Since essentially all carbon in such clouds is ionized, $N(C^+) \sim 10^{17}$ cm^{-2}. At the $T = 70$K common in cold atomic clouds and $n_{\rm H} = 10^3$ cm^{-3}, the expected C^+ line emission would be 2.4 K km s^{-1}, detectable in 30 seconds in excellent winter weather on Dome A. The 3σ limit achievable with deep integrations (15 minutes) with HEAT would reach densities of $n_{\rm H} = 10^2$ cm^{-3}. This limit would readily determine whether interstellar material causing significant infrared extinction but without CO is gravitationally bound and likely to be a forming molecular cloud, or is simply a line of sight with numerous overlapping diffuse HI clouds.

2.3.5 *Mapping Coverage of the Galactic Plane*

Figure 7 demonstrates the needed sky coverage of a far-infrared/THz Galactic plane survey. From previous CO surveys it is known that the scale height of CO emission toward the inner Galaxy is less than one degree (6; 7). 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 the inner Galaxy, the outer Galaxy, and the $l = \pm 100^o$ tangent arms to obtain a statistically meaningful survey that encompasses the broad dynamic range of physical conditions in the Galaxy. We propose therefore to probe the entire Galactic plane as seen from Dome A ($0 > l > -120^o$). A *completely unbiased survey* will be undertaken, covering up to 240 square degrees ($-1^o < b < 1^o$). The "inner" Galaxy survey will coincide with GLIMPSE, a Spitzer Space Telescope (SST) Legacy Program (3). Above $l = 90^o$, most of the CO emission is located at higher Galactic latitude, so l and b strip mapping will locate the best regions to map, generally following the CO $J = 1 \rightarrow 0$ distribution(6; 7) and the best characterized star forming regions in the Galaxy – while maximizing synergies with the "Cores to Disks" SST Legacy program (9), and other SST GTO programs.

As discussed in Section 3, HEAT exceeds all of these needs and constitutes an exceptional Galactic survey instrument.

2.4 *Survey Activities*

2.4.1 *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 back and forth across a field while the backends are read-out at a sufficient rate to eliminate aliasing and beam smearing.

The broad coverage of the Galactic Plane Survey and the circumpolar nature of the sky rotation over Antarctica lends itself naturally to efficient, 24-hour/day mapping. HEAT can reach the requisite

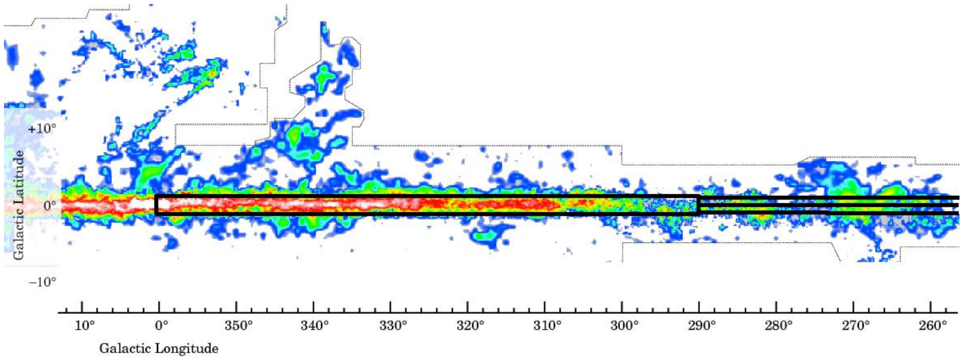

Figure 7: The power of HEAT, part II: a definitive chemical and kinematic survey of star forming clouds in C^0 J=2-1, ^{12}CO J=7-6, and [N II] over 120 square degrees (^{12}CO) of the sky can be performed in a single season. Full coverage of the Galactic Plane seen from Antarctica will be added in the second season of operations. ∼30 square degrees will be mapped in the crucial 158 μm [C II] line per season. No other site on Earth allows routine access to both far-infrared lines.

sensitivity of 1σ=0.1 K km s^{-1} per beam at 810 GHz (1σ=0.5 K km s^{-1} at 1.4 THz) over a fully sampled (at 1.4 THz) square degree in 20 hours, assuming median winter conditions of $\tau \sim 1$. 120 square degrees from $0 > l > -70^o$ will be mapped, accounting for low elevation near the Galactic Center, in about 140 days. The Outer Galaxy will be mapped in Season 2. When the atmospheric opacity at 1.9 THz drops below ∼1.5, focused surveys including C^+ will begin. Of the best 35 days of August/September weather, 3-4 weeks will be devoted to a medium-sensitivity C^+ survey (1σ ∼ 1 K km s^{-1}), with each square degree of mapping requiring about 20 hours each, for a total of up to 24-32 square degrees of coverage per season. 7-10 days will be devoted to deep C^+ surveys of selected regions guided by 2MASS and GLIMPSE for the formation of molecular clouds – a total of 0.5 square degrees will be mapped to 1$\sigma \sim 0.2$ K km s^{-1} each season.

HEAT's IF bandwidth, coupled with chopping OTF techniques, allows detection of the 158, 205, and 370 μm dust continuum emission. Thusly, we will also simultaneously record total power scans and construct dust continuum maps.

2.4.2 Initial Deployment at South Pole

As discussed in Section 3.4, HEAT will spend its first year on a Univ. of New South Wales AASTINO at South Pole. This time will be spent characterizing and testing the instrument and telescope in all phases of operation while at a continuously-manned site with excellent logistical support. During this time, HEAT will execute 4-5 months of observations (approx. June to October 2007) observing the CO J=7-6 and [C I] lines at 810 GHz toward the Lupus and Chameleon II clouds in direct support of the "From Cores to Disks" Spitzer Legacy program (9). The AST/RO telescope is proposing to observe CO $J = 4 \rightarrow 3$ and [C I] $J = 1 \rightarrow 0$ lines (460-492 GHz) for these sources, with similar beam size to HEAT at 810 GHz. Thus, even in its first "shake-out" year at South Pole, HEAT will provide an outstanding set of maps with immediate astrophysical application – a small prelude to what will be possble from Dome A.

2.4.3 Science Products and Dissemination

A primary 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 a FITS cube or CLASS file, and headers for each scan are written into a MySQL relational database, which facilitates efficient logging and retrieval of the data. Our most demanding storage requirements for 240 square degree maps, regridded to 50″ spacing, with 1024 spectral points per grid position, is 7 GB. Even today, this volume can be readily handled by a single embedded computer with a either a disk array and/or flash RAM.

Access to these data products to the greater scientific community will be provided through a Java-based web browser interface that will interface with MySQL and the FITS data cubes.

All science tools, packaged reduction software, data products and science products will be made available from the HEAT web page.

Important science tools include the following:

Clumpfinder and *Outflowfinder*: All Galactic cloud cores and star forming regions will be separated, identified and analyzed from the master dataset as a function of position in the Galaxy. An unbiased survey of Galactic outflows, and their energy inputs to the ISM will be tabulated.

Analysis Package and Cloud Models: Tools used to extract physical properties of clouds will be released. These tools will include statistical equilibrium calculations, radiative transfer codes Monte Carlo techniques, a basic chemical network capable of following H and C chemistries, and foundational models of molecular clouds and PDR's.

2MASS Extinction Maps and the Formation of Molecular Clouds: The release of the 2 μm All Sky Survey will be used to make extinction maps over the surveyed regions to be compared with the measured CO emission and used to guide our selection of regions to map in C^+ emission.

Systematic calibration of the dataset: DP-I Kulesa is executing a unique survey of Galactic molecular clouds, using high resolution infrared absorption line spectroscopy of H_2 and ^{12}CO, using ARIES (Arizona Infrared Image and Echelle Spectrometer) at the 6.5-meter MMT. These observations directly measure ^{12}CO abundances relative to a precisely measured column density of H_2 (24). These pointed measurements will be used to comprehensively calibrate the observations provided by HEAT and the generated infrared extinction maps from the 2MASS survey.

2.4.4 *Roles of the Collaboration Participants*

Personnel who will initially develop and use HEAT comprise the Science (S) and Instrument (I) Teams tabulated in Table 1. They are also represented in an organization chart, Figure 16 in Section 3.4. *In addition to the two teams, numerous students will participate in the instrument and science development; at least 4 graduate students and 2 undergraduates at the University of Arizona.*

3 Research Instrumentation and Needs

3.1 *Overview*

HEAT will be a fully automated, state-of-the-art THz observatory designed to operate autonomously from Dome A in Antarctica. The combination of high altitude (4,200 m), low precipitation, and extreme cold make the far-IR atmospheric transmission exceptionally good from this site. In Figure 6 we present a plot of the expected atmospheric transmission above Dome A as a function of wavelength (Lawrence 2004), indicating that winter weather at Dome A approaches (to order of magnitude) the quality of that achieved by SOFIA. The wavelengths of several important astrophysical lines are indicated with arrows. HEAT is designed to take advantage of these unique atmospheric conditions and observe simultaneously in [C II](158 μm), [N II](205 μm), and CO J=7-6/[C I] (370 μm).

A conceptual drawing of HEAT is shown in Figure 8. For robustness and efficiency, the telescope and instrument are integrated into a common optical support structure (OSS). HEAT will be mounted on top of a University of New South Wales AASTINO (Automated Astrophysical Site-Testing InterNational Observatory). The AASTINO provides power and communications for the HEAT telescope and instrument. The total power budget for HEAT (including cryogenics, telescope drive system, and instrument control system is ~ 550 W, which can be readily provided by Stirling engines within the AASTINO. Data transfer and command and control of HEAT will be done via satellite and is described in more detail in Section 3.3.8. The University of New South Wales will provide an AASTINO specifically for HEAT and participate in all aspects of design, integration, deployment, and operation (see Support Letter from J. Storey). The HEAT/AASTINO facility is functionally equivalent to a space-based observatory. Indeed, many of the key components used in the instrument were originally developed for space applications. A 3D rendering of HEAT mounted atop an AASTINO is shown in Figure 9.

3.2 *Telescope*

The telescope is designed to have maximum efficiency and the minimum number of optical components. Its design is similar to that of Kraus (1966). Incoming light is reflected horizontally off a 45°, 0.5×0.7 m flat reflector to an f/5 off-axis parabolic

Participant	Team	Affiliation	Partipation Activity
Christopher Walker	I, S	U. Arizona	Project PI
Craig Kulesa	I, S	U. Arizona	Deputy PI
Thomas McMahon	I	U. Arizona	Project Manager
Ed Churchwell	S	Wisconsin	Provides synergistic access to GLIMPSE SST survey
Michael Ashley	I, S	UNSW	AASTINO Systems and site testing
J. R. Gao	I	SRON	THz HEB mixers
David Glaister	I	Ball Aerospace	Cryogenic Systems
Willy Gully	I	Ball Aerospace	Cryogenic Systems
Chris Groppi	I, S	NRAO	Receiver systems, Submm star formation studies
Frank Helmich	S	SRON	Physics and Chemistry of Cloud Cores
Karl Jacobs	I	U. Köln	Receiver Systems, SIS mixers
Jacob Kooi	I	Caltech	Receiver Systems and Telescope Integration
Robert Loewenstein	I	U. Chicago	Telecommunications
Imran Mehdi	I	JPL	THz LO sources
Robert Pernic	I	U. Chicago	Telescope Implementation & Polar Operations
Gordon Stacey	I, S	Cornell University	FIR Instrumentation & spectroscopy
Anthony Stark	I, S	SAO	Telescope Optics & Systems; Synergy w/ AST/RO surveys
John Storey	I, S	UNSW	AASTINO Systems, Site testing, Polar Operations
Jürgen Stutzki	S	U. Köln	Physics & Chemistry of the ISM
Mark Swain	I, S	U. of Arizona/JPL	Telescope Systems and Optics; FIR Spectroscopy
Sander Weinreb	I	JPL	IF amplifiers & chains; correlator system
Harold Yorke	S	JPL	Synergy with Herschel surveys

Table 1: Activities of the Science (**S**) and Instrumentation (**I**) Teams

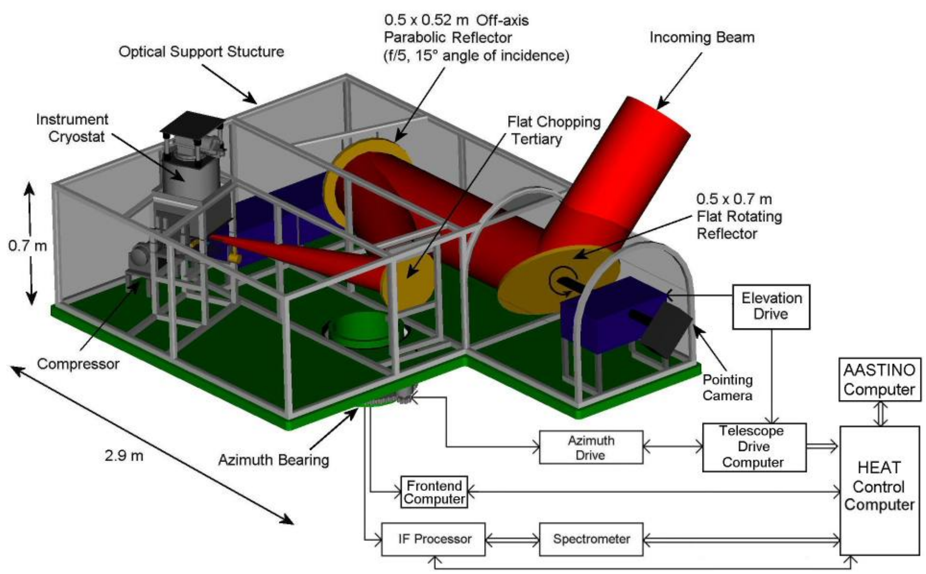

Figure 8: HEAT concept: The telescope has an effective collecting area of 0.5m. Elevation tracking is accomplished by rotating the 45° flat reflector. The entire telescope structure rotates for azimuth tracking and is warmed well above ambient by waste heat from the AASTINO module below. The HEB and SIS mixers used in the instrument package are cooled to ~ 4 K using closed-cycled cryo-cooler technology developed for space-based applications.

mirror. The converging beam is intercepted by a flat tertiary mirror that directs it into the receiver. The tertiary mirror can chop the incoming beam between source and reference positions ($\Delta\mathrm{az} \sim 10'$) at a rate of 0 to 4 Hz. All three mirrors are fabricated from aluminum on a numerical milling machine and have a surface roughness $\leq 3\,\mu$m rms. Elevation tracking is achieved by rotating the first flat reflector. Azimuth tracking is achieved by rotating the OSS on a bearing attached to the roof of the AASTINO. The absolute pointing accuracy will be 15″, 1/5 of the smallest diffraction-limited beam. The slew speed will be 1° per sec. Vertex-RSI has reviewed the proposed design and provided a cost estimate for the delivery of a telescope meeting these specifications. The cost estimate, which includes detailed design, fabrication, and testing of the telescope and drive system, is provided in the budget.

To prevent ice accumulation, the telescope is enclosed and warmed to $\sim$ 0° C by waste heat forced up through the azimuth bearing from the AASTINO. A small radome made of a low-loss dielectric (e.g. Goretex or polyethylene) encircles the first flat reflector. This optical configuration provides an unobstructed view of the sky. A CCD camera (provided by UNSW) and 1–5.3 μm IR camera are mounted just outside the radome on an extension of the elevation axis. The cameras provide optical pointing and crucial site testing data.

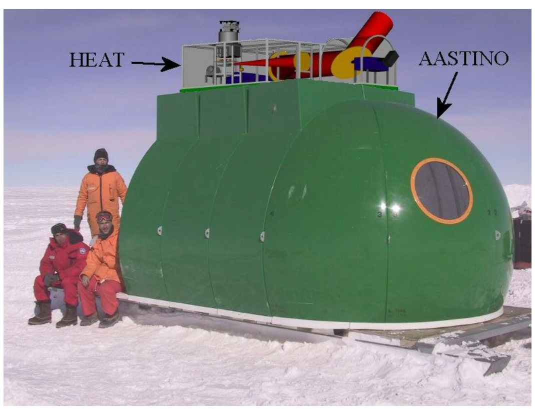

Figure 9: Rendering of HEAT atop a UNSW AASTINO

3.3 *Receiver*

3.3.1 *Design Approach*

Heterodyne receivers are needed to achieve the sensitive, high spectral resolution ($R = \lambda/\Delta\lambda > 10^6$) observations of [N II], [C II], and CO/[C I] required for the proposed Galactic plane survey. The key components of a submillimeter-wave heterodyne receiver are the mixer and local oscillator (LO). The mixers and LO's that will be used in HEAT were originally developed for use in the HIFI instrument for the *Hershel Space Observatory*. There are 3 types of mixers in common use; the Schottky diode mixer, the SIS mixer, and, more recently, the Hot Electron Bolometer (HEB) mixer. The Schottky diode mixer is less sensitive than either SIS or HEB mixers and requires orders of magnitude more LO power. Their principal advantages are robustness and ability to operate at room temperature. Below ∼1 THz SIS mixers provide the lowest receiver noise temperatures ($T_{rec} \leq 400$ K). Above 1 THz HEB mixers have the best performance ($T_{rec} \leq 900$ K). The $\sim$ 1 THz upper limit to SIS mixer performance is currently set by the availability of suitable superconducting materials. Therefore, HEAT will use an SIS mixer for the CO/[C I] channel and HEB mixers for the [N II] and [C II] channels.

3.3.2 *Receiver Optics*

A close-up of the receiver optics is shown in Figure 10. The incoming beam from the folding tertiary encounters two bandpass filters, the first centered on the [N II] (1.459 THz) line and the second on the [C II] (1.9 THz) line.

Outside of their nominal passband, the filters are highly reflective. Therefore, when the incoming beam encounters the first filter, all but a narrow range of frequencies around the [C II] line are reflected to the [N II] filter. The light reflected off the [N II] filter contains the CO J=7-6 and [^{12}C I] and [^{13}C I] J=2-1 lines. The three emerging beams are collimated and directed into the instrument cryostat. Before entering the cryostat, the corresponding LO signals are injected into the collimated beams using Mylar (for the 810 GHz mixer) and silicon (for the 1.45 and 1.9 THz mixers) beam splitters. The Mylar is used to inject the 810 GHz LO because it is both low-loss and wideband, permiting DSB operation at the low IF frequency (1.5 GHz) required for simultaneous observations of CO and [CI] lines. Silicon etalons can serve as efficient LO diplexers, passing >95% of the signal while reflecting >50% of the LO power (Mueller and Waldman 1994). These properties make silicon etalons attractive beam splitters for THz mixers where LO power is precious and the size and complexity of Martin-Puplett diplexers can be prohibitive. The IF frequency of the [C II] and [N II] mixers is 3 GHz. Upon entering the cryostat, the beams pass through infrared blocking filters. For the HEB mixers, the same type of bandpass filters used for frequency diplexing will be used at the entrance window of the 4 K radiation shield. Here the filters not only prevent infrared loading on the 4 K stage, they also help to prevent the HEB mixers from being saturated by the incoming radiation field.

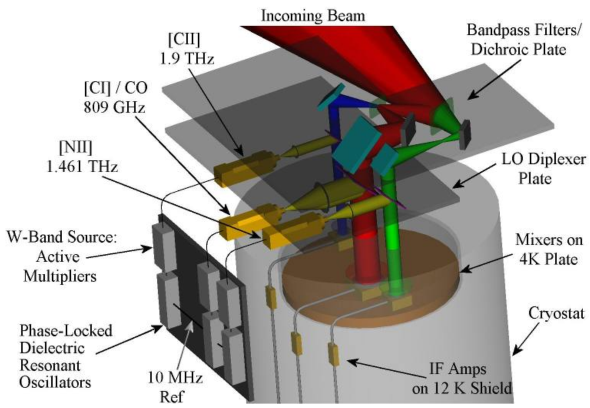

Figure 10: Optical subsystem and LO injection for HEAT's HEB and SIS mixers.

3.3.3 *Mixer Performance*

The HEB mixers for HEAT will be provided by SRON/Delft (see support letter from J. R. Gao) and follow the successful quasi-optically coupled, NbN phonon-cooled design of Gao *et. al.* (2004). *These mixers have the lowest noise temperatures and LO power requirements of any mixers measured to date (T_{rec} = 940 K and P_{LO} = 0.17 μW at 1.89 THz).* A plot summarizing the noise performance of HEB mixers world-wide is shown in Figure 11. Recent Allan variance measurements (Kooi 2004) of HEB stability (Figure 12) show excellent performance can be achieved if the incoming beam is chopped at ≥ 1 Hz. The HEAT telescope is designed to accommodate sky chopping at frequencies up to ~ 4 Hz.

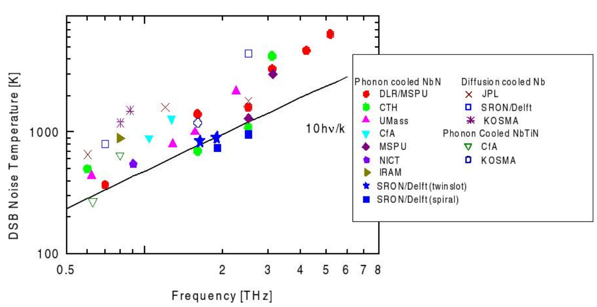

Figure 11: Comparison of measured HEB mixer noise temperatures worldwide (from Gao et al. 2004)

The SIS mixer will be provided by the University of Cologne (see Support Letter from J. Stutski). The design and fabrication of the SIS mixer is described by Puetz *et al.* (2004) and has been successfully used on the AST/RO telescope at the South Pole for several years. The noise temperature is expected to be ∼200K.

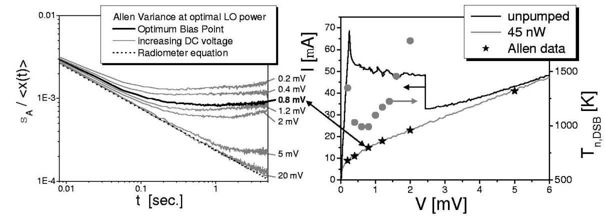

Figure 12: Allan variance stability tests for Delft HEB mixers are in accordance with the radiometer equation if a chopping secondary is used.

3.3.4 *Local Oscillators*

HEAT will employ 3 solid-state local oscillator chains built by the Jet Propulsion Laboratory (see Support Letter from I. Mehdi). The 809 GHz chain will consist of three doublers. The 1.45 Thz chain will have four doublers, and the 1.9 THz chain will be comprised of one doubler and two triplers. *These chains leverage heavily from the technology developed for Herschel and have had their performance validated in lab measurements.* All three chains easily meet our LO power requirements of > 100 μW at 809 GHz and > 1 μW at 1.46 and 1.9 THz. The JPL LO chains will be pumped by CTI/Millitech DRO (dielectric resonant oscillator)/active multiplier chains that can source $\sim$ 3 dBm of power between 90-106 GHz. Each of the phase-locked DRO's is fixed tuned to a single frequency, that when up-converted, corresponds to one of the three target astrophysical lines. A CAD drawing illustrating the integration of the LO's is provided in Figure 10. Since each of the three receivers acts independently, any increase in phase-noise that might occur by using an active multiplier chain has minimal, if any, impact on the quality of the collected data. The frequency stability of the LO chains will be better than ± 0.5 MHz at 809 GHz and ± 1.0 MHz at 1.46 and 1.9 THz.

3.3.5 *IF Processing & Spectrometers*

The IF output of the HEB mixers is centered at 5 GHz. In order to simultaneously detect the CO $J = 7 \rightarrow 6$ line in the lower sideband and the [C I] line in the upper sideband, the SIS mixer will have an IF center frequency of 1.5 GHz. The IF output of each mixer is amplified by a low-noise

MMIC amplifier and downconverted to baseband for processing by three, 1024 lag autocorrelators. The autocorrelators for the [N II] and [C II] channels will each have 2 GHz of instantaneous bandwidth and $\sim$ 2 MHz resolution. The autocorrelator for the lower frequency CO/[C I] channel will run at half the clockspeed of the other two channels, yielding an instantaneous bandwidth of 1 GHz and frequency resolution of ~ 1 MHz resolution. These correlators provide velocity coverage in access of 316 km/s at a resolution ≤ 0.4 km/s, enabling all three lines to be resolved and observed throughout the Milky Way without needing to retune. Spaceborne Inc. of La Canada, CA has demonstrated a 2 GHz wide, 1024 lag correlator that meets our design specifications (see Figure 13) and provided a quote for the complete HEAT correlator system.

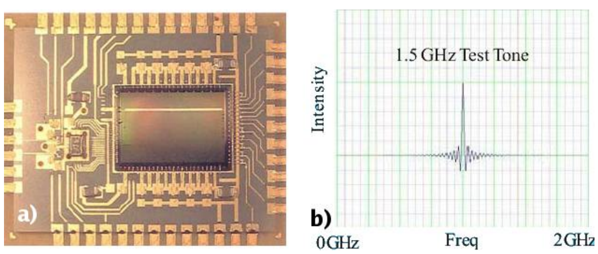

Figure 13: The Spaceborne digital autocorrelator provides an ideal "off-the-shelf" multichannel spectrometer for HEAT. a) 2 GHz Spaceborne correlator chip. b) Laboratory measurement of spectral response.

3.3.6 *Cryogenics*

A reliable, efficient, low-vibration 4 K cryogenic system is essential to the success of HEAT. Experience has shown that care must be taken to insure the uninterrupted operation of cryogenic systems over extended periods. This philosophy is crucial for the proposed remote, automated facility at Dome A. Indeed, the system requirements for HEAT are more like those of a spacecraft than a ground-based observatory. It is for this reason that we have a teamed with Ball Aerospace (see Ball support letter) to adapt one of their successful space-based cryogenic systems to work for HEAT.

HEAT Cryogenic Subsystem Trades and Approach

The cryogenic subsystem for HEAT must maintain the detectors at 4 K. A number of approaches, including off-the-shelf commercial cryocoolers (or mechanical refrigerators), were evaluated against the system requirements. The need for unattended operation for at least 1 year eliminates the possibility of using liquid expendable cryogens. The remote and harsh Antarctic environment prevents the use of off-the-shelf commercial cryocoolers primarily due to limited power (<600 W) provided by the AASTINO. High cost prevents the use of fully space qualified cryocoolers for HEAT. The optimum cryogenic system that meets both technical and cost requirements is a combination of commercial and aerospace cryocooler hardware. The HEAT cryogenic system requirements are shown in Table 2.

Requirement	Specification
4K cooling capacity	4 mW
14 K cooling capacity	220 mW
70 K cooling capacity	3.6 W
4 K temperature stability	$\pm$0.01 K
Input power	<500 W
Lifetime	>2 years
Vibration	Low
Vacuum level	$< 10^{-5}$ Torr (at 1 yr)
Cost	Low to Moderate

Table 2: Cryogenic system requirements for HEAT

Table 3 shows a compilation of cryocooler approaches and their power consumption. Only the hybrid system can consume less than the 500 W requirement. The Pulse Tube G-M has a number of attractive features (*e.g.* low maintenance and vibration), however low efficiency makes its power consumption unsuitable for HEAT. The extra cost of the semi-custom cryosystem enables the great reduction in input power needed for operation from a remote site.

Cryo System Implementation

The proposed cooler has a high degree of technology maturity. *All of the cryocooler components and their integration have been proven in test.* Cooling capacities in excess of 25 mW were measured for temperatures down to 5 K. Tests with ^{3}He as the J-T working fluid extended the temperatures down to 3.5 K, and demonstrated 12 mW of cooling at 3.8 K, more than adequate for cooling HEAT's complement of mixers.

Leveraging off Ball Aerospace's system and instrument expertise, the cryogenic system has been designed to meet the HEAT's unique requirements. A block diagram of the HEAT cryogenic system is shown in Figure 14.

The 4 K temperature control as well as the cry-

Capacity at 4K	Manufacturer	Input power (W)	Meets Requirement?
0.1 W (G-M)	Sumitomo SRDK-101D	1300	No
0.5 W (G-M)	Sumitomo SRDK-205D	3500	No
0.5 W (Pulse Tube G-M)	Sumitomo SRP-052A	7500	No
20 mW (Hybrid G-M/J-T)	Ball Aero - HEAT	400	Yes

Table 3: Cryocooler approaches and applicability to HEAT

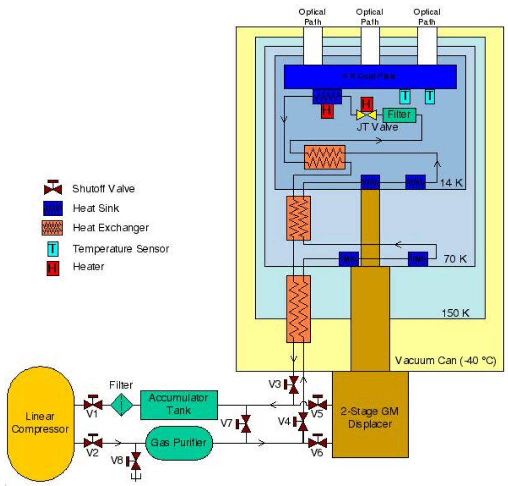

Figure 14: The cryocooler supporting the HEAT cryogenic system is a hybrid cooler consisting of a modified Gifford McMahon precooler and a Joule-Thomson cooler.

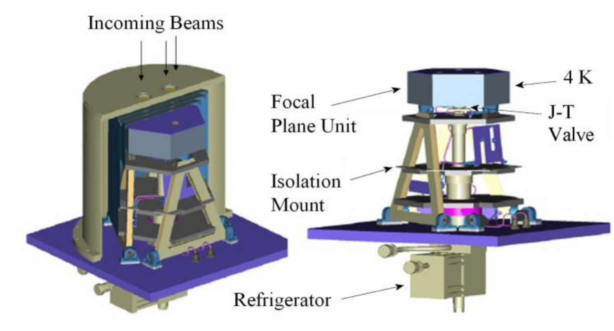

Figure 15: Cut-away views of low-vibration, long-life, 4 K closed-cycle cryostat designed by Ball.

ocooler on/off and a safety defrost heater will be handled by a commercial temperature controller from Lakeshore Cryotronics. A mW-level trim heater will maintain 4 K with changing environmental conditions. The analog output will provide remote operation and access to a safety defrost heater used in case the JT orifice plugs.

Extremely low vibration operation is essential on a spacecraft. Ball brings this expertise to HEAT. To comply with the tight vibration and thermal requirements, Ball will provide a separate structural mount for the detector package, and use the J-T to refrigerate the isolated system (see Figure 15). The temperature of the cold plate will be actively regulated to within 10 mK. To meet the tight power constraints, Ball has designed a special dewar that uses the cold Antarctic environment to minimize power consumption. This type of optimization and design strategy is common for space missions where power conservation and reliability are essential. To our knowledge this is the first time this philosophy is being employed to such a degree on a ground-based instrument.

3.3.7 Calibration

HEAT will be able to calibrate observations through several means. 1) A vane with an ambient temperature absorbing load will be located at the dewar entrance window, allowing standard chopper wheel calibration to be performed. 2) HEAT will routinely perform sky-dips to compute the atmospheric optical depth in each of it's three wavelength bands. 3) HEAT will regularly observe a standard list of calibration sources. 4) The AASTINO will also host a Fourier Transform Spectrometer (funded through the Australian program) that will measure atmospheric transmission throughout the FIR. These measurements will be coordinated with HEAT spectral line observations to provide cross calibration.

3.3.8 Control System and Communication

The HEAT control system will consist of a centralized control computer that communicates with the telescope drive system, receiver frontend (*e.g.* mixers, LO's, and cryostat) computer, backend (spectrometer) computer, and the AASTINO via Ethernet. HEAT will be designed to work autonomously for up to a week at a time, performing pre-programmed observational programs and storing astronomical and housekeeping data in non-volatile memory. Preprocessed sample data will be uploaded to control centers at the Universities of

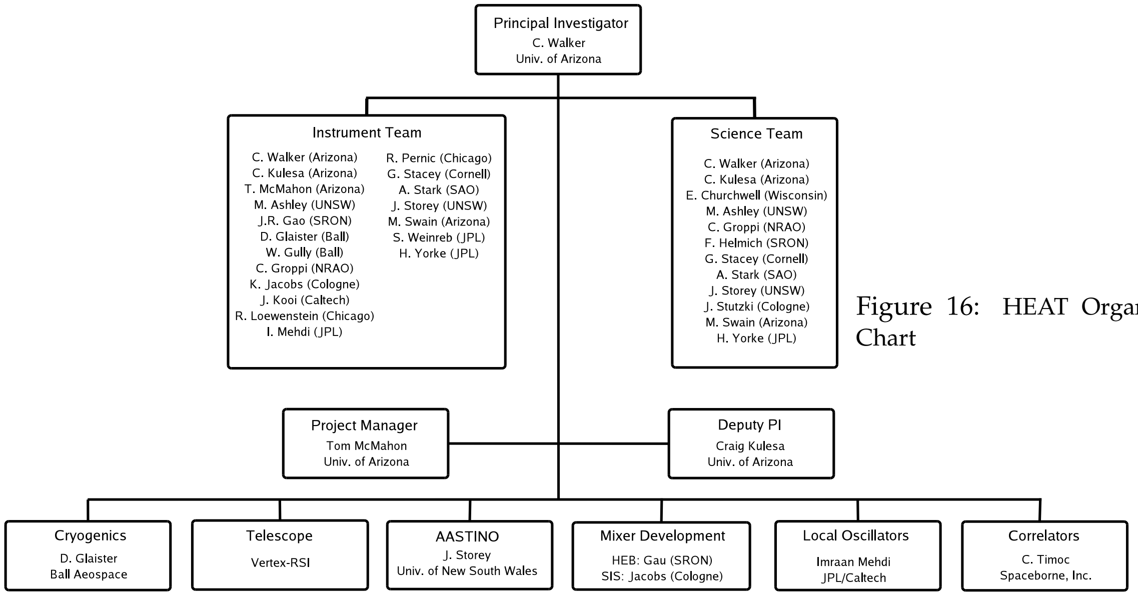

Figure 16: HEAT Organizational Chart

Arizona and New South Wales via (1-3) dedicated Iridium satellite channels. Raw data will be recovered from HEAT each year during maintenance and processed into the released data products.

3.4 Project Organization

HEAT is an exciting, challenging project that requires the coordinated participation of scientists and engineers from several academic institutions and leading-edge companies to succeed. We have developed an organizational structure (shown in Figure 16) to meet this task. Collectively the HEAT team members represent many years of successful telescope and instrument development in Antarctica. The organizational structure of the HEAT project provides effective control of the project while allowing the delegation of authority to be made at the proper level within the organization. The main components of the organization are (1) the PI, who has overall responsibility for the project and coordinates the activities of the participants, (2) the DP-I (Kulesa) who assists the PI and is responsible for instrument control and system integration, (3) the Project Manager (PM-McMahon) who oversees the fiscal realities of the project, and (4) the Science and Instrument Teams who will provide extensive scientific and technical guidance throughout the course of the project. Table 1 provides a listing of the roles and responsibilities of each member in the organization. Postdocs, graduate students, and technical staff at the collaborating institutions will participate in developing the hardware and software for HEAT.

A schedule of key project milestones and tasks is provided in Figure 17. During the first 3 months of the project a reference design for HEAT will be completed, followed by a design review by the instrument and science teams. Procurement of key components will begin soon after following the spending profile outlined in the budget. Integration and test of the receiver system will take place at Ball Aerospace in February-March 2006. Acceptance tests of the telescope will take place in April-May 2006. The receiver and telescope will be shipped to the University of New South Wales in June 2006, where an extended period of integration and testing with the AASTINO module will occur. Our goal is to deploy HEAT at the Amundsen-Scott South Pole base in Nov. 2006, with deployment to Dome A in 2007-2008.

Routine communications between project participants is essential. There will be quarterly telecons between Science and Instrument team members to monitor progress, provide insight into solutions to emerging problems, and redefine priorities as needed. There will be weekly telecons and quarterly meeting (primarily through teleconferencing) between the PI, D-PI, PM, and Technical Leads (Storey - AASTINO, Pernic - Telescope, Glaister - Cryogenics, Gao - Mixers, Mehdi - LO's, Weinreb -IF/Correlators, and Loewenstein - IT).

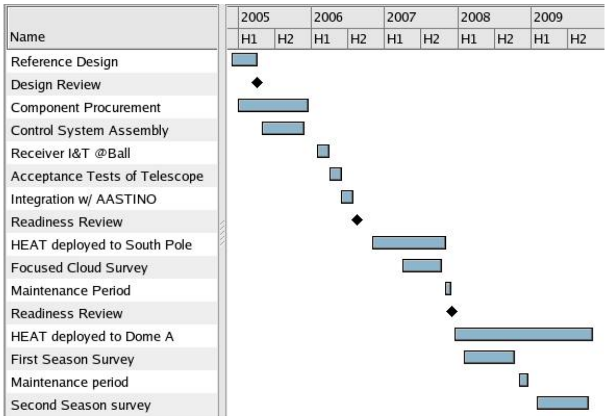

Figure 17: HEAT Organizational Timeline

3.5 *Educational Impact*

The development and establishment of the first astrophysical observatory on Dome A offers many opportunities to tap into the imagination of students of all ages and grade levels. Below we highlight two examples.

3.5.1 *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 the PI'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 5 Ph.D. dissertations and numerous undergraduate research projects. HEAT is a natural extension of these research efforts. In the proposed budget for HEAT, funds for only one graduate student are requested. However, as is customary in the PI's 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.

3.5.2 *K-12 Outreach: Student Radio Telescope*

In support of education and public outreach activities the PI and his students have constructed a fully steerable, 3.5 m Student Radio Telescope (SRT) for observing the HI line in the Milky Way. The SRT has been used as a instructional tool in undergraduate courses (both major and non-major). Recently, the drive system of the SRT has been upgraded and a web-based user interface developed. Students from on and off campus will soon be able to monitor (and in some cases) control observations with the SRT. Unlike optical telescopes, the SRT can be used day and night, making it ideal for classroom instruction. HEAT too is principally a spectroscopic Galactic Plane survey telescope. 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 and use the SRT as a "hands-on" laboratory with the goal of providing students with an intuitive understanding of underlying physical concepts.

3.6 *Global Impact*

HEAT will serve as a prototype for a new class of powerful, automated observatories for the Antarctic plateau and a first step for realizing the scientific potential of Dome A. The astronomical surveys conducted with HEAT will lead to a new, fundamental knowledge of the Life Cycle of the ISM in the Milky Way and serve as a template for understanding processes in the more distant universe. They will serve as a "finder chart" for future, more focused surveys (e.g. with ALMA and Herschel) and markedly improve the interpretation, and enhance the value of numerous contemporary surveys being conducted from ground and spacebased observatories. In particular, HEAT will provide the best corresponding interstellar cloud survey to two Spitzer Legacy programs; Ed Churchwell's GLIMPSE survey, and N. Evans' "Cores to Disks" program. HEAT will account for the dense cloud material that forms stars, cloud interaction with formed stars, and kinematic disruption by mass ejection, outflow, and supernova remnants. The 2MASS survey will be used to construct extinction maps over the entire region to be surveyed by HEAT (25; 1), which will be used to locate regions in the Galaxy where new molecular clouds are being formed.

References

[1] Alves, J., Lada, C. J., & Lada, E. A. 1999, "Correlation between Gas and Dust in Molecular Clouds: L977", ApJ, 515, 265

[2] Bennett, C. L., et al. 1994, ApJ, 434, 587

[3] Benjamin, R. A. et al. 2003, "GLIMPSE. I. An SIRTF Legacy Project to Map the Inner Galaxy", PASP, 115, 953

[4] Carpenter, J. M., Snell, R. L., & Schloerb, F. P. 1995, "Star Formation in the Gemini OB1 Molecular Cloud Complex", ApJ, 450, 201

[5] G. Chattopadhyay, E. Schlecht, J. Gill, S. Martin, A. Maestrini, D. Pukala, F. Maiwald, and I. Mehdi, "A Broadband 800 GHz Schottky Balanced Doubler," IEEE Microwave and Wireless Components Letters, vol. 12, no. 4, pp. 117-118, April 2002.

[6] Dame, T. M. et al. 1987, "A composite CO survey of the entire Milky Way", ApJ, 322, 706

[7] Dame, T. M., Hartmann, D., & Thaddeus, P. 2001, "The Milky Way in Molecular Clouds: A New Complete CO Survey", ApJ, 547, 792

[8] Engargiola, G., Plambeck, R. L., Rosolowsky, E., & Blitz, L. 2003, ApJS, 149, 343

[9] Evans, N. J. et al. 2003, "From Molecular Cores to Planet-forming Disks: A SIRTF Legacy Program", PASP, 115, 965

[10] Gaidis, M., et al., 2000, IEEE Trans. Microwave Theory Tech. 48, 733.

[11] Gao, J. R., Hajenius, M., Baselmans, J., Klawijk, P., de Korte, Voronov, B., and Gol'tsman, G., 2004, "NbN Hot Electron Bolometer Mixers with Superior Performance for Space Applications", International Workshop on Low Temperature Electronics, 23-24 June 2004, (invited paper).

[12] Gershenzon, E. M., et al., 1990, Superconductivity, 3, 1582.

[13] Giannini, T. et al. 2000, A&A, 358, 310

[14] Gillespie, A. R. & Phillips, T. G., 1979, "Array Detectors for Millimetre Line Astronomy", A&A, 73, 14.

[15] Goldsmith, P., in "Quasioptical Systems", pub. IEEE Pressm 184.

[16] Groppi, C. E. et al. 2003, "DesertSTAR: a 7 pixel 345 GHz heterodyne array receiver for the Heinrich Hertz Telescope", SPIE, 4855, 330

[17] Hildebrand, R. H. 1983, "The Determination of Cloud Masses and Dust Characteristics from Submillimetre Thermal Emission", QJRAS, 24, 267

[18] Kaufman, M. J., Wolfire, M. G., Hollenbach, D. J., & Luhman, M. L. 1999, "Far-Infrared and Submillimeter Emission from Galactic and Extragalactic Photodissociation Regions", ApJ, 527, 795

[19] Kennicutt, R. C. 1998, ApJ, 498, 541

[20] Kooi, J., 2004, private communication.

[21] J.W. Kooi, G. Chattopadhyay, S. Withington, F. Rice, J. Zmuidzinas, C.K. Walker, and G. Yassin, "A Full-Height Waveguide to Thin-Film Microstrip Transition with Exceptional RF Bandwidth and Coupling Efficiency", International Journal on Infrared and Millimeter Waves, Vol24, No. 3, 2003.

[22] J.W. Kooi, C.K. Walker, and J. Hesler, "A Broad Bandwidth Suspended Membrane Waveguide to Thinfilm Microstrip Transition", 9th Int. Conference on Teraherz Electronics, 15th - 16th October 2001.

[23] Krauss, J., "Radio Astronomy", 1966, Mcgraw-Hill, NY

[24] Kulesa, C. A. & Black, J. H. 2002, Chemistry as a Diagnostic of Star Formation, 60

[25] Lada, C. J., Lada, E. A., Clemens, D. P., & Bally, J. 1994, "Dust extinction and molecular gas in the dark cloud IC 5146", ApJ, 429, 694

[26] Lawrence, J. S., 2004, "Infrared and sunmillimetre atmospheric characteristics Of high Antarctic plateau sites", PASP, in press.

[27] Martin, C. L. & Kennicutt, R. C. 2001, ApJ, 555, 301

[28] Nakagawa, T., Yui, Y. Y., Doi, Y., Okuda, H., Shibai, H., Mochizuki, K., Nishimura, T., & Low, F. J. 1998, ApJS, 115, 259

[29] Neilson, J. M., "An Improved Multimode Horn for Gaussian Mode generation at Millimeter and Submillimeter Wavelengths", 2002, IEEE Transactions on Antennas and Propogation, 50, 1077

[30] Pütz, Glenz, R., Tils, T., Honingh, N., Jacobs, K., Hedden, A., Kulesa, C., Groppi, C., Walker, C., "High Sensitivity 810 GHz SIS Receivers at AST/RO", SPIE, 2004, in press

[31] Sakamoto, S., Hasegawa, T., Hayashi, M., Handa, T., & Oka, T. 1995, "The Five College Radio Astronomy Observatory CO Survey of the Outer Galaxy", ApJS, 100, 125

[32] Schmidt, M. 1959, ApJ, 129, 243

[33] Scoville, N. Z., Yun, M. S., Sanders, D. B., Clemens, D. P., & Waller, W. H. 1987, "Molecular clouds and cloud cores in the inner Galaxy", ApJS, 63, 821

[34] Simon, R., Jackson, J. M., Clemens, D. P., Bania, T. M., & Heyer, M. H. 2001, "The Structure of Four Molecular Cloud Complexes in the BU-FCRAO Milky Way Galactic Ring Survey", ApJ, 551, 747

[35] Solomon, P. M., Rivolo, A. R., Barrett, J., & Yahil, A. 1987, "Mass, luminosity, and line width relations of Galactic molecular clouds", ApJ, 319, 730

[36] E. Schlecht, G. Chattopadhyay, A. Maestrini, A. Fung, S. Martin, D. Pukala, J. Bruston, and I. Mehdi, "200, 400, and 800 GHz Schottky diode substrateless multipliers: Design and Results," 2001 IEEE, MTT-S International Microwave Symp. Digest, Phoenix, Az, pp. 1649-1652, May 2001.

[37] Stark, A. A. & Brand, J. 1989, "Kinematics of molecular clouds. II - New data on nearby giant molecular clouds", ApJ, 339, 763

[38] C. K. Walker, J. Kooi, M. Chan, H. G. LeDuc, P. L. Schaffer, J. E. Carlstrom, and T. G. Phillips, 1992, "A low noise 492 GHz SIS waveguide receiver", Int. J. of IR and MM Waves, vol. 15, no. 3, pp. 477-492.

[39] Walker, C. K., Carlstrom, J. E., & Bieging, J. H. 1993, ApJ, 402, 655

[40] Walker, C. K., Hungerford, A., Narayanan, G., Groppi, C., Bloomstein, T., Palmacci, S., Stern, M., & Curtin, G., "Laser Micromachining of Silicon: A New Technique for Fabricating TeraHertz Imaging Arrays", Proc. SPIE, 3357, 45.

[41] Walker, C. K., Groppi, C., d'Aubigny, C., Kulesa, C., Hungerford, A., Jacobs, K., Graf, U., Schieder, R., & Martin, C., 2001, PoleSTAR: A 4-Pixel 810 GHz Array Receiver for AST/RO, "Proceedings of the 12th International Symposium on Space TeraHertz Technology", San Diego, CA, Eds. Mehdi & McGrath, JPL.