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TITLE OF PROPOSED PROJECT **MRI-R2: Development of the Atacama Sub-millimeter Telescope Robotic Observatory (ASTRO)**

REQUESTED AMOUNT	PROPOSED DURATION (1-60 MONTHS)	REQUESTED STARTING DATE	SHOW RELATED PRELIMINARY PROPOSAL NO. IF APPLICABLE
$ 4,882,991	48 months	02/01/10	

CHECK APPROPRIATE BOX(ES) IF THIS PROPOSAL INCLUDES ANY OF THE ITEMS LISTED BELOW

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- ☐ DISCLOSURE OF LOBBYING ACTIVITIES (GPG II.C.1.e)
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- ☐ HIGH RESOLUTION GRAPHICS/OTHER GRAPHICS WHERE EXACT COLOR REPRESENTATION IS REQUIRED FOR PROPER INTERPRETATION (GPG I.G.1)

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Electronic Signature

CERTIFICATION PAGE

Certification for Authorized Organizational Representative or Individual Applicant:

By signing and submitting this proposal, the Authorized Organizational Representative or Individual Applicant is: (1) certifying that statements made herein are true and complete to the best of his/her knowledge; and (2) agreeing to accept the obligation to comply with NSF award terms and conditions if an award is made as a result of this application. Further, the applicant is hereby providing certifications regarding debarment and suspension, drug-free workplace, and lobbying activities (see below), nondiscrimination, and flood hazard insurance (when applicable) as set forth in the NSF Proposal & Award Policies & Procedures Guide, Part I: the Grant Proposal Guide (GPG) (NSF 09-29). Willful provision of false information in this application and its supporting documents or in reports required under an ensuing award is a criminal offense (U. S. Code, Title 18, Section 1001).

Conflict of Interest Certification

In addition, if the applicant institution employs more than fifty persons, by electronically signing the NSF Proposal Cover Sheet, the Authorized Organizational Representative of the applicant institution is certifying that the institution has implemented a written and enforced conflict of interest policy that is consistent with the provisions of the NSF Proposal & Award Policies & Procedures Guide, Part II, Award & Administration Guide (AAG) Chapter IV.A; that to the best of his/her knowledge, all financial disclosures required by that conflict of interest policy have been made; and that all identified conflicts of interest will have been satisfactorily managed, reduced or eliminated prior to the institution's expenditure of any funds under the award, in accordance with the institution's conflict of interest policy. Conflicts which cannot be satisfactorily managed, reduced or eliminated must be disclosed to NSF.

Drug Free Work Place Certification

By electronically signing the NSF Proposal Cover Sheet, the Authorized Organizational Representative or Individual Applicant is providing the Drug Free Work Place Certification contained in Exhibit II-3 of the Grant Proposal Guide.

Debarment and Suspension Certification

(If answer "yes", please provide explanation.)

Is the organization or its principals presently debarred, suspended, proposed for debarment, declared ineligible, or voluntarily excluded from covered transactions by any Federal department or agency? Yes ☐ No ☒

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Certification Regarding Lobbying

The following certification is required for an award of a Federal contract, grant, or cooperative agreement exceeding $100,000 and for an award of a Federal loan or a commitment providing for the United States to insure or guarantee a loan exceeding $150,000.

Certification for Contracts, Grants, Loans and Cooperative Agreements

The undersigned certifies, to the best of his or her knowledge and belief, that:

(1) No federal appropriated funds have been paid or will be paid, by or on behalf of the undersigned, to any person for influencing or attempting to influence an officer or employee of any agency, a Member of Congress, an officer or employee of Congress, or an employee of a Member of Congress in connection with the awarding of any federal contract, the making of any Federal grant, the making of any Federal loan, the entering into of any cooperative agreement, and the extension, continuation, renewal, amendment, or modification of any Federal contract, grant, loan, or cooperative agreement.

(2) If any funds other than Federal appropriated funds have been paid or will be paid to any person for influencing or attempting to influence an officer or employee of any agency, a Member of Congress, an officer or employee of Congress, or an employee of a Member of Congress in connection with this Federal contract, grant, loan, or cooperative agreement, the undersigned shall complete and submit Standard Form-LLL, ''Disclosure of Lobbying Activities,'' in accordance with its instructions.

(3) The undersigned shall require that the language of this certification be included in the award documents for all subawards at all tiers including subcontracts, subgrants, and contracts under grants, loans, and cooperative agreements and that all subrecipients shall certify and disclose accordingly.

This certification is a material representation of fact upon which reliance was placed when this transaction was made or entered into. Submission of this certification is a prerequisite for making or entering into this transaction imposed by section 1352, Title 31, U.S. Code. Any person who fails to file the required certification shall be subject to a civil penalty of not less than $10,000 and not more than $100,000 for each such failure.

Certification Regarding Nondiscrimination

By electronically signing the NSF Proposal Cover Sheet, the Authorized Organizational Representative is providing the Certification Regarding Nondiscrimination contained in Exhibit II-6 of the Grant Proposal Guide.

Certification Regarding Flood Hazard Insurance

Two sections of the National Flood Insurance Act of 1968 (42 USC §4012a and §4106) bar Federal agencies from giving financial assistance for acquisition or construction purposes in any area identified by the Federal Emergency Management Agency (FEMA) as having special flood hazards unless the:

(1) community in which that area is located participates in the national flood insurance program; and
(2) building (and any related equipment) is covered by adequate flood insurance.

By electronically signing the NSF Proposal Cover Sheet, the Authorized Organizational Representative or Individual Applicant located in FEMA-designated special flood hazard areas is certifying that adequate flood insurance has been or will be obtained in the following situations:

(1) for NSF grants for the construction of a building or facility, regardless of the dollar amount of the grant; and
(2) for other NSF Grants when more than $25,000 has been budgeted in the proposal for repair, alteration or improvement (construction) of a building or facility.

AUTHORIZED ORGANIZATIONAL REPRESENTATIVE	SIGNATURE	DATE
NAME Susan Morse	Electronic Signature	Aug 10 2009 4:41PM

TELEPHONE NUMBER	ELECTRONIC MAIL ADDRESS	FAX NUMBER
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* EAGER - EArly-concept Grants for Exploratory Research
** RAPID - Grants for Rapid Response Research

A Project Summary

Funds are requested to develop and deploy the telescope and facility instrument for the Atacama Submillimeter Telescope and Robotic Observatory (ASTRO) to be located on the ALMA site. The facility will be optimized to perform large-scale, high-spectral resolution surveys of the Milky Way and nearby galaxies in astrophysically important lines at submillimeter wavelengths. The telescope will have a 1.7 m aperture and build upon the past success of the Antarctic Submillimeter Telescope and Remote Observatory (AST/RO). The facility instrument will be a self-contained, closed-cycle, 64 pixel SIS receiver with a modular mixer array that may be swapped-out for operation in different atmospheric windows. Molecular and atomic species with lines falling in the 450 micron window ($\sim 600 - 700$ GHz) will be initially targeted. The instrument is made possible by recent advances in mixer, local oscillator, low-noise amplifier, cryogenic, and digital signal processing technologies. The instrument, `SuperCam-2`, will benefit directly from experience gained in the development of the 345 GHz `SuperCam-1` instrument for the Heinrich Hertz Telescope (HHT).

1 What is the intellectual merit of the proposed activity?

ASTRO, with its large format heterodyne imaging array and arcminute resolution, will be able to map hundreds of square degrees of the Galaxy each year at wavelengths not routinely available at other sites. This exceptional mapping speed will make ASTRO a uniquely powerful instrument for probing active regions of star formation and warm gas in our Galaxy and the local Universe. ASTRO surveys will be used to answer fundamental questions about the physics and chemistry of the star formation process, molecular clouds, and evolved stellar envelopes. By comparing ASTRO's surveys to those made at lower frequencies on larger telescopes (e.g. the HHT), the impact of Galactic environment on these phenomena will be realized. ASTRO surveys will also serve as finder charts for focused research (e.g. with ALMA) while simultaneously improving the interpretation and value of numerous contemporary surveys. These developments will put Oberlin and its collaborative institutions at the forefront of research and technology in this wavelength regime for years to come.

2 What are the broader impacts of the proposed activity?

A key project for ASTRO will be to conduct sensitive, large-scale, ^{12}CO and ^{13}CO $J = 6 \rightarrow 5$ surveys of the Galactic Plane, Magellanic Clouds, and nearby galaxies. Definitive and comprehensive science products from these surveys will be made available to the astronomical community via the Web soon after calibrated maps are produced. The anticipated richness of the data set makes delaying web publication for a proprietary period unnecessary and unproductive.

Nationally and internationally the impacts of this galactic plane survey will coincide with three synergistic surveys: the FCRAO-BU Galactic Ring Survey (GRS), GLIMPSE, a Spitzer Space Telescope Legacy Program, and the Bolocam Galactic Plane Survey (BGPS), along with overlaps on sources in the "Cores to Disks" Spitzer Legacy program and Herschel GTO and Key programs. As has been shown by these groups, tremendous new insights are made possible by large surveys of this kind, and that by freely releasing the data the entire community is energized to explore questions that frequently were not even considered by the original proposers.

The proposed effort is both multi-disciplined and multi-institutional. Our team members have worked closely together both on the AST/RO telescope at the Pole and in the construction of the first `SuperCam-1` instrument. As with these projects, the design and fabrication of ASTRO and `SuperCam-2` will be an interdisciplinary, team effort involving students and faculty from astronomy, physics, optical sciences, and electrical engineering. Astronomical instrumentation is becoming ever more complex, requiring the talents of many individuals to bring projects to fruition. Providing students with both technical training and teamwork experience increases their probability of success not only within astronomy, but society as a whole.

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For font size and page formatting specifications, see GPG section II.B.2.

Appendix Items:

*Proposers may select any numbering mechanism for the proposal. The entire proposal however, must be paginated. Complete both columns only if the proposal is numbered consecutively.

C Project Description

1 Instrument Location

After its development in various locations around the U.S., ASTRO and SuperCam-2 will be placed at the ALMA site on the Atacama Plateau, Chile.

2 Research Activities

The proposed combination of the 1.7-meter ASTRO telescope and SuperCam-1 and SuperCam-2 instruments will provide essential and timely research opportunities to the astronomical community, with survey data made immediately available as it is calibrated. Diffraction-limited arcminute resolution and <0.5 km s^{-1} spectral resolution coupled with a 15-30$'$ instantaneous field of view makes ASTRO a truly exceptional facility for large-scale spectroscopic surveys of the Galaxy.

Here, we outline the initial ASTRO "key project", a submillimeter-wave CO survey of the Galactic Plane observable from Chile. It will complement the northern CO survey to be performed in 2009-2011 with the SuperCam-1 instrument at the Arizona Radio Observatory's Heinrich Hertz Telescope (HHT). The science-driven characteristics of the SuperCam-2 instrument on ASTRO is presented in detail in Section 3.

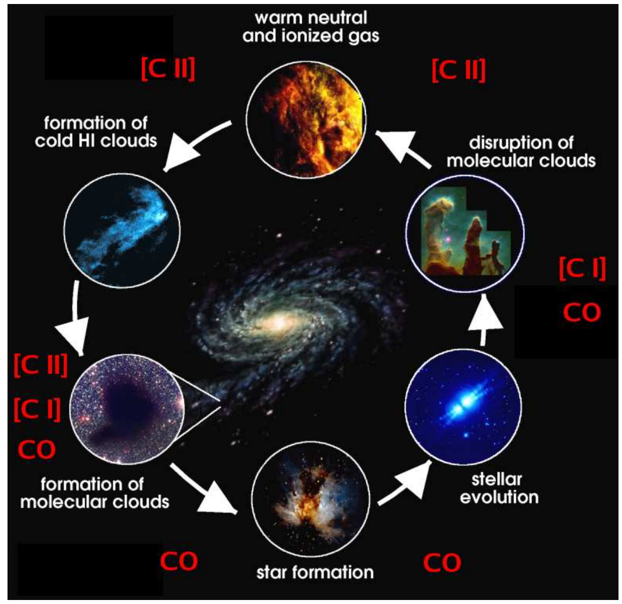

Figure 1: *The ASTRO telescope will observe the most diagnostic submillimeter lines of CO that probe the entire life cycle of dense molecular clouds. In particular, ASTRO will witness the interaction of the interstellar medium (ISM) with the young stars that are born from it, the return of enriched material to the ISM by stellar evolution, and (combined with other surveys) will identify where molecular clouds are forming.*

2.1 Scientific Overview

The internal evolution of all galaxies is determined to a large extent by the life cycles of interstellar clouds, as shown in Figure 1.

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

Although we are 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. These studies have far-reaching impact; 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. ASTRO is designed with the goal of providing insights into the gaps of our knowledge of the interstellar life cycle.

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 and evolve? How are they 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, and infall and other influences from outside the Galaxy?

To answer these questions, we propose a large-scale Galactic Plane survey in the most diagnostic submillimeter-wave lines of CO, with sufficient angular and spectral resolution to disentangle the complicated structural and kinematic processes in interstellar clouds. The extensive mapping coverage of this survey will place star formation and the molecular ISM in a fully Galactic context.

2.2 Properties of the Proposed Survey

> ASTRO with its unique instrumentation will provide the clearest view of star forming clouds in the Galaxy and reference maps for future focused studies with the LMT & APEX telescopes and the SMA, CARMA and ALMA interferometers.

Velocity-Resolved Imaging Spectroscopy Techniques commonly used to diagnose the molecular ISM include submillimeter continuum mapping of dust emission [Hildebrand 1983] and dust extinction mapping at optical and near-infrared wavelengths [Lada *et al.* 1994]. 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, degree-scale maps of submillimeter dust emission associated with molecular material have been made. However, these techniques have limited applicability to the study of the large-scale evolution of molecular clouds due to their complete lack of kinematic information.

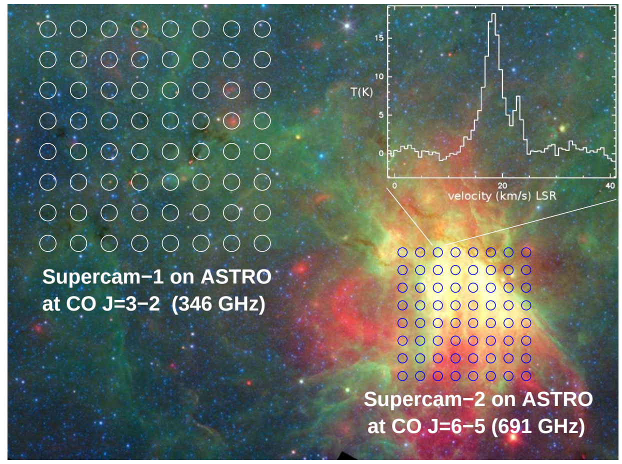

Figure 2: *The 64 beams of* `SuperCam-1` *and* `SuperCam-2` *at 350 and 650 GHz on ASTRO overlaid upon a Spitzer* $1^o \times 0.75^o$ *infrared composite of the M17 star-forming region. Each beam will measure a high-resolution spectrum, a portion of which is shown at upper-right.*

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 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.

CO is second only to H_2 as the most abundant molecule in the ISM, and it remains the most accurate, most sensitive spectroscopic tracer of H_2 on large scales. ASTRO with `SuperCam-1` and `SuperCam-2` will resolve the intrinsic profiles of Galactic CO lines (Figure 2), with a per-channel resolution of $<$0.5 km s^{-1} over 250–500 km s^{-1} of spectrometer bandwidth, comparable to the Galactic rotational velocity.

A Submillimeter-Wave Galactic Survey Molecular line surveys have been performed over the entire sky in the light of the 2.6 millimeter J=1$\rightarrow$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 Galactic molecular clouds is incomplete. Early results were obtained with large beams, e.g., $>9'$ [Dame *et al.* 1987; Dame, Hartmann, and Thaddeus 2001]); were undersampled, e.g., $3'$ for the UMass/Stonybrook survey – [Solomon *et al.* 1987; Scoville *et al.* 1987]; or had limited areal coverage, e.g., the early FCRAO surveys – [Carpenter, Snell, and Schloerb 1995; Stark and Brand 1989; Bally, Langer, and Liu 1991; Miesch and Bally 1994]. The Galactic Ring Survey (GRS) at FCRAO is by far the most comprehensive spectroscopic survey of the inner Galaxy to date [Simon *et al.* 2001]. However, this survey does not span the 4th Galactic Quadrant, the focus of this study, and traces only the J=1→0 line of ^{13}CO, which is less sensitive to warm, low-opacity, high velocity gas such as produced by outflows, photodissociation regions (PDRs), and shocks. This point is illustrated in Figure 3, with images of a synthetic model cloud constructed in the integrated light of different spectral lines of CO. The model cloud is externally illuminated by a B-type star and cloud excitation, temperature and chemical abundances are determined self-consistently using Monte Carlo and Coupled Escape Probability methods [Elitzur and Asensio Ramos 2006]. The integrated spectral line images show that the heated portion of the cloud is traced best by the J=3→2 and J=6→5 lines. Almost 40% of the molecular mass would be missed by examining the J=1→0 alone.

A more comprehensive view of molecular clouds can therefore be gleaned from measurement of the *submillimeter* lines of CO and its isotopes, in combination with existing millimeter-wave observations. The proposed CO surveys will be orders of magnitude larger than existing submillimeter line surveys. The gas probed by higher-J transitions is of greatest interest to our posed questions – it is the *energetic* 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. Higher-J lines are also needed to properly interpret even basic properties of clouds derived from existing CO 1→0 observations.

Due to the prevailing physical conditions in the interstellar medium, the 850 and 450 μm (350 and 650 GHz) atmospheric windows are among the richest in the electromagnetic spectrum [Helmich and van Dishoeck 1997; Schilke *et al.* 1997]. At these wavelengths, ASTRO has high aperture efficiency (80%) and excellent atmospheric transmission more than 75% of the year at 350 GHz and 50% of the Austral winter at 650 GHz (Figure 4). These prospects make the design of a large format multi-beam receiver in these atmospheric windows very attractive.

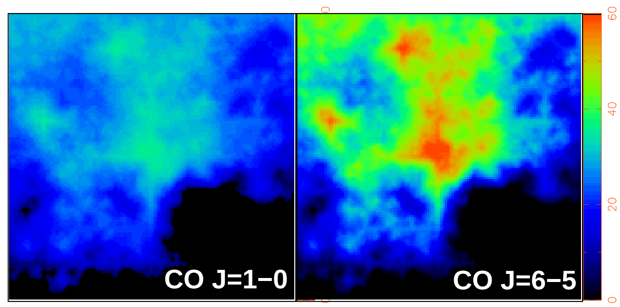

Figure 3: **The need for a submillimeter survey***: Simulated image of a fractal molecular cloud in two CO transitions. The energetic gas that dynamically interacts with stars is far better probed by submillimeter CO lines, which are needed to extract a comprehensive understanding of cloud properties, dynamics, and evolution.*

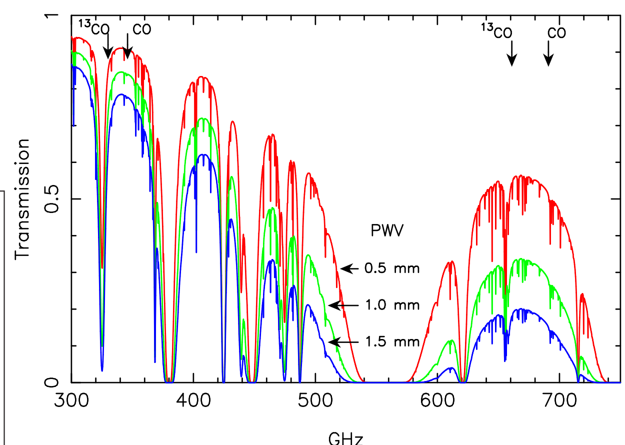

Figure 4: *Modeled submillimeter atmospheric transparency for the ASTRO on the ALMA site on Chajnantor in in 75 percentile (bottom), median (middle), and 25 percentile (top) atmospheric conditions, derived from 183 GHz and 860 GHz tipping radiometer measurements accumulated over the past decade [Radford* et al. *2008]*

Angular Resolution Angular resolution is a critical aspect of improvement for a new Galactic survey. Figure 5 depicts the model cloud of Figures 3, projected to a distance of 7 kpc. Clearly, disentangling different clouds and cloud components can only be accomplished with arcminute angular scales. The angular resolution of ASTRO is 1.0′ at 690 GHz and 2.1′ at 345 GHz.

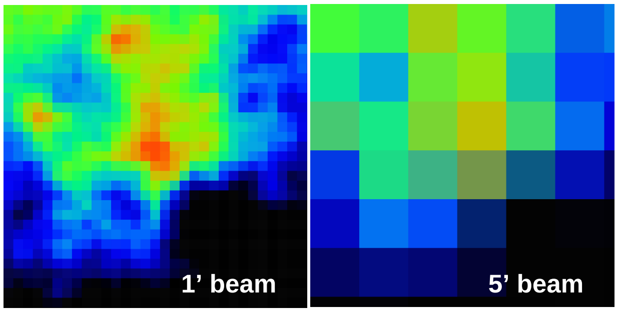

Figure 5: **The need for sufficient angular resolution:** *The synthetic cloud from Figure 3 is projected to a distance of 7 kpc, and observed in ^{12}CO 6→5 with beam sizes of 1′ (left) and 5′ (right). The structure of the cloud is essentially lost in the largest beam. In order to probe cloud structure and excitation over the entire Galactic disk, arcminute angular resolution is vital.*

High Sensitivity CO survives in the ISM in part because of the UV shielding from dissociation provided by H_2; thus CO's survivability depends upon a molecular, H_2-dominated environment. For typical molecular clouds, the sharp transition from H to H_2 typically occurs by a visual extinction of ∼1 magnitude in the local interstellar radiation field, or $N(H) = 1.8 \times 10^{21}$ cm^{-2}. We therefore aim to detect all CO down to this hydrogen column density limit. This corresponds to a 3σ detection limit of $N(^{12}CO) \sim 10^{15}$ cm^{-2}, which implies an integrated intensity for cool gas (20K $< T_k <$ 40K) of 1.5 K km s^{-1} in the J=3→2 transition. For ^{12}CO J=6→5, an intensity limit of 0.6 K km s^{-1} is reached at a gas density of $n_H = 10^4$ cm^{-3} and T_k=50K. The J=3→2 sensitivity limit is achievable (5σ) within 5 seconds of integration time per independent beam in the poorest 75%-ile atmospheric conditions (PWV=1.5mm, $T_{sys} \sim$450K) on Atacama. With 64-beams on `SuperCam-1`, 1.5 square degrees can be readily mapped per hour with 30″ grid spacing. The J=6→5 sensitivity limit in the best 25%-ile weather conditions in winter/fall/spring (PWV=0.5mm, $T_{sys} \sim$2000K) will be achieved within 200 seconds per independent beam, for a 64-beam mapping rate of 18 hours per square degree. Detection of (or limits on) either J=3→2 or J=6→5 in that time would constrain the gas temperature and density, based upon the line brightness of millimeter wave transitions.

Large-Scale Coverage of the Galactic Plane Figure 6 demonstrates the proposed sky coverage of the `SuperCam-1` and `SuperCam-2` submillimeter-wave Galactic plane surveys. 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. We propose therefore to probe the entire Galactic plane as seen from Chile ($-120^o < l < 30^o$). Previous surveys have shown that the scale height of CO emission toward the inner Galaxy is less than one degree [Dame *et al.* 1987; Dame, Hartmann, and Thaddeus 2001]. Within $l = 100^o$, a *completely unbiased survey* will be undertaken, covering 260 square degrees ($-1^o < b < 1^o$). This Galactic Plane survey will coincide with three synergistic surveys: the FCRAO-BU Galactic Ring Survey (GRS), GLIMPSE, a Spitzer Space Telescope Legacy Program [Benjamin *et al.* 2003], and the Bolocam Galactic Plane Survey (BGPS) [Nordhaus *et al.* 2008]. The remaining 40 square degrees will be distributed among clouds at higher Galactic latitude and will follow the CO 1→0 distribution [Dame *et al.* 1987; Dame, Hartmann, and Thaddeus 2001] while maximizing synergies with the “Cores to Disks” Spitzer Legacy program [Evans *et al.* 2003] sources and Herschel GTO and Key programs.

The proposed combination of the ASTRO telescope and the `SuperCam-1` and `SuperCam-2` arrays exceeds all of these needs as well as current capabilities elsewhere (Table 1) and constitutes the ideal Galactic survey facility.

2.3 Survey Activities

Mapping Strategy The most efficient mode of data collection with a focal plane array and 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 (typically 4×/beam). The primary advantage of OTF mapping with an array is that a given position on the sky is observed by all pixels in the array. This redundancy removes any

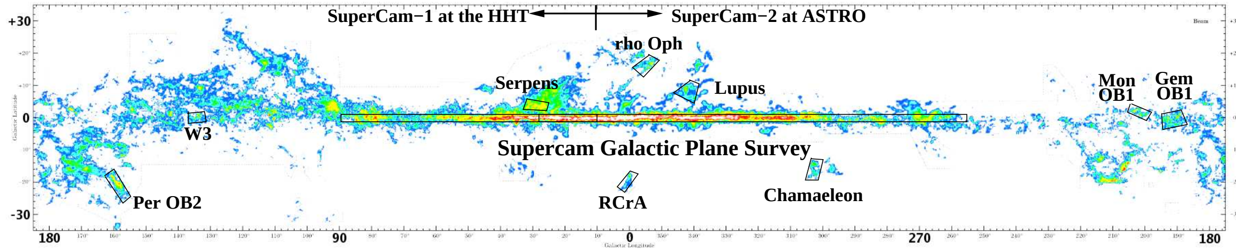

Figure 6: *The power of ASTRO with* `SuperCam-2`*: a definitive chemical and kinematic survey of star forming clouds in ^{12}CO & ^{13}CO J=3-2 and J=6-5 can be performed in less than 2 calendar months per spectral line at 350 GHz, and 8 months total at 650 GHz. No other facility has the capability of performing such an expansive survey.*

Array (#pix)	Telescope	deg^2/day (@freq)
`SuperCam-2` (64)	ASTRO	30 (@350)
		3 (@690)
`SuperCam-1` (64)	HHT	5 (@350)
HARP (16)	JCMT	0.3 (@350)
SMART (8)	NANTEN	2 (@460)
		0.1 (@810)
CHAMP+ (7)	APEX	0.01 (@690)

Table 1: *Spectroscopic mapping speed of current submillimeter heterodyne array systems. Tabulated is the time needed to sample one square degree to 3σ=1 K* km s^{-1} *sensitivity per beam.* `SuperCam-2` *on ASTRO exceeds the mapping speed of any other heterodyne array by an order of magnitude.*

noise and gain inhomogeneities between pixels and reduces the degree to which the data are correlated, as a singular off-source measurement is distributed to on-source data.

The broad coverage of the Galactic Plane Survey lends itself naturally to efficient, 24-hour/day mapping. With 64 pixels at 345 GHz, `SuperCam-1` can reach the requisite sensitivity of 1σ=0.3K over a full square degree in <1 hour. At 690 GHz `SuperCam-2` can reach this limit in 8 hours, but additional sensitivity is needed to reach A_V=1 (see Section 2.2). We will therefore use a total of 12 months of observing time over two years to perform the baseline survey; the first year of observing will be devoted to ^{13}CO and ^{12}CO J=3$\rightarrow$2 mapping (331-346 GHz), and 300 square degrees will be mapped in both spectral lines. The second year will be devoted to ^{13}CO and ^{12}CO J=6$\rightarrow$5 mapping (661-691 GHz), during which at least 100 square degrees will be mapped in both spectral lines. Additional mapping coverage in the J=6$\rightarrow$5 lines will be sought after this proposal's performance period. *`SuperCam-1` and `SuperCam-2`'s wide instantaneous IF bandwidth (ultimately 8 GHz; see Section 3 for details) also allows measurement of the 850 and 450 μm dust continuum emission.* Thus, we will also simultaneously record total power scans and construct dust continuum maps, particularly where the ^{13}CO lines become optically thick.

Science Products and Dissemination The primary challenge of OTF mapping is data management, which becomes particularly acute with an array for which the data rates are typically 100 times larger. We therefore plan to adopt the scheme developed at FCRAO for OTF mapping with the 32 pixel SEQUOIA array (see http://www.astro.umass.edu/~fcrao/library/manuals/), where 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 a 300 square degree map, gridded to 30″ spacing, with 1024 spectral points per grid position, is 20 GB. The total disk requirements for the survey will be less than 100 GB. This volume can be readily handled by a single computer with a redundant disk array for data integrity. The greater scientific community can access these data products through a Java-based web browser interface that will interface with the FITS data cubes. In addition to data products, released science products include the following:

Source Catalogs: 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. They will be cross-referenced against other surveys (e.g. stellar sources from GLIMPSE and mm-wave continuum sources from the BGPS). An unbiased survey of Galactic outflows, and their energy inputs to the ISM will be tabulated.

CO Analysis Package and Cloud Models: Numerous tools used to extract physical properties of clouds, such as volume density and temperature, will be released. These tools will include statistical equilibrium calculations, radiative transfer codes based upon LTE, Coupled Escape Probability (CEP), and Monte Carlo techniques, a basic chemical network capable of following hydrogen and carbon chemistries, and foundational models of molecular clouds and photodissociation regions.

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 in the photometric J, H, and K bands, to be compared with the measured CO emission and used to search for molecular cloud formation in the Galaxy: regions where large amounts of gas have become molecular, but CO has not yet formed. The ideal probe of nascent H_2 is the 158 μm fine-structure line of the C^+ ion, owing to its intensity and utility as a densitometer [Kaufman *et al.* 1999]. The Stratospheric Terahertz Observatory (STO, Walker PI) will perform mapping of this fine structure line in 2009–11 with similar resolution to ASTRO at 650 GHz. *The combination of 21 cm HI, submillimeter CO, and far-IR C^+ measurements will enable the crucial first measurement of the formation of Galactic molecular clouds.*

Systematic calibration of the dataset: Co-PI 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 the ^{12}CO and ^{13}CO abundances relative to a precisely measured column density of H_2 [Kulesa 2003]. These pointed measurements will be used to calibrate the submillimeter dust continuum maps and molecular line observations provided by ASTRO, the infrared extinction maps from the 2MASS survey, and the mm-wave continuum from the BGPS.

All science tools, packaged reduction software, data products and science products will be made available from the `SuperCam-2` survey's web page with no proprietary period.

2.4 Results from Prior NSF MRI and non-MRI Support

AST/RO AST/RO, which will be dramatically enhanced by this proposal, received support from the NSF in a variety of ways (with PI and Co-I participation from various members of this project: A. Stark, C. Martin, C. Walker, & C. Kulesa). Prior to February 2002, the observatory was funded as part of the Center for Astrophysical Research in Antarctica (CARA), an NSF Science and Technology Center, supported by Cooperative Agreement OPP89-20223 to the University of Chicago. Starting in May 2002, core observatory functions were supported directly by a grant to the Smithsonian Astrophysical Observatory (part of the Harvard-Smithsonian Center for Astrophysics) from the NSF Office of Polar Programs, grant ANT-0126090 "Continuing Operation of the Antarctic Submillimeter Telescope and Remote Observatory (AST/RO)" (PI: A. Stark, May 2002–2006, $2,588,889), with additional awards for specific sub-fields including (ANT-0338150) "Middle Atmospheric Dynamics by Sub-Millimeter Radiometry" (PI: C. Martin, Sept. 2004–2008, $60,419). Numerous students and post-docs were trained by working with the AST/RO telescope (including the PI and two Co-Is (C. Groppi and C. Kulesa)) and over 100 publications (a sampling: [Stark *et al.* 1997; Stark *et al.* 2001; Stark 2003; Chamberlin and Bally 1994; Lane 1998; Stark *et al.* 2001; Chamberlin *et al.* 2003; Kulesa 2002; Groppi 2003; Bolatto *et al.* 2000; Ingalls *et al.* 1997; Kulesa *et al.* 2004; Groppi *et al.* 2004; Martin *et al.* 2003; Tieftrunk *et al.* 2001; Burrows, Martin, and Roberts 2007]), demonstrating the transformative power of successful NSF funding.

University of Arizona Over the past ten years, Co-PI Walker's team at the University of Arizona has constructed three spectroscopic heterodyne array receivers; `PoleSTAR`, a 4 pixel 810 GHz receiver that operated at the 1.7 m AST/RO telescope at the South Pole, `DesertSTAR`, a 7 pixel 345 GHz array receiver for the 10-meter Heinrich Hertz Telescope (HHT) on Mt. Graham, Arizona (Figure 7), and `SuperCam-1`, a 64 pixel 345 GHz array also for use on the HHT. `PoleSTAR` was completed in 2000 and offered excellent receiver performance on all 4 pixels [Kulesa *et al.* 2005]. `PoleSTAR` was funded by the NSF Office of Polar Programs (A. Stark–PI: OPP-0126090), and `DesertSTAR` development was 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).

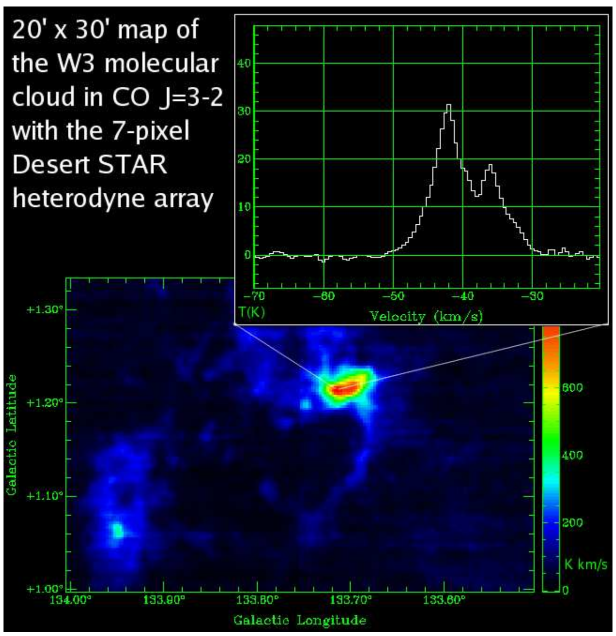

Figure 7: *Map of the W3 molecular cloud taken with the* `DesertSTAR` *instrument on the HHT.*

In 2004 a multi-institutional team led by Co-PI Walker was awarded an NSF MRI grant, (AST-0421499) "Development of a Submillimeter-wave Superheterodyne Camera (SuperCam) for the Heinrich Hertz Telescope" (PI: C. Walker, Sept. 2004–Dec. 2009, $2,148,007), to construct `SuperCam-1`, a 64 pixel, heterodyne array for the Heinrich Hertz Telescope [Groppi *et al.* 2008]. `SuperCam-1` represents the cutting edge of heterodyne array development technology in terms of integrated mixer and low noise amplifiers [Pütz *et al.* 2006], and scalable IF processor and spectrometer technology. `SuperCam-1` will be commissioned at the HHT in the autumn of 2009. The design of `SuperCam-1` is readily scalable to operate in the 450 μm atmospheric window being targeted in this proposal.

In 2006 funding was obtained through NSF/OPP (ANT-0538665: Walker-PI, Kulesa-CoPI) to perform a design study for the High Elevation Antarctic THz Observatory (`HEAT`). In 2007 an NSF-SGER proposal was funded (ANT-0735854: Walker-PI, Kulesa-CoPI) to construct `Pre-HEAT`, a 450 μm tipper and spectrometer. `Pre-HEAT` was constructed and successfully deployed to Dome A with the University of New South Wales' PLATeau Observatory (`PLATO`) in January 2008. The effort was an international collaboration between the US, China, UK and Australia. It set a new record for high-powered autonomous operation on the Antarctic plateau. Pre-HEAT's principal science products are submillimeter atmospheric transmission data and Galactic spectra of the ^{13}CO $J = 6 \rightarrow 5$ line [Kulesa *et al.* 2008].

Finally Co-I C. Groppi has participated in ATM-0723239, "MRI: Development of the Active Temperature Ozone and Moisture Microwave Spectrometer (ATOMMS) cm and mm-wave Occultation Instrument" (PI: E. Kursinski, Sept. 2007–2010, $1,883,695). This project is in the process of building an airborne radio occultation system for water and ozone lines in the Earth's atmosphere [Kursinski *et al.* 2007; Kursinski *et al.* 2008].

3 Description of the Research Instrumentation and Needs

ASTRO Telescope The Atacama Submillimeter Telescope and Robotic Observatory will re-use the primary mirror and steel structure of the Antarctic Submillimeter Telescope and Remote Observatory (AST/RO). The telescope structure is shown in Figure 8 and documented in Stark *et al.* 1997 and 2001. In its original form, the telescope operated at the NSF Amundsen-Scott South Pole Station from 1994 until 2005. The telescope worked reliably for many years, and completed some of the largest submillimeter-wave line surveys ever made [Martin *et al.* 2004]. The most significant operating problems were: (1) the need for liquid cryogens in the receivers, (2) pointing inaccuracies due to thermal variations in the telescope foundation, (3) drive motor and gear failure, and (4) computer disk failure. These issues will be resolved by the hardware improvements described below.

The new Atacama telescope will be optically similar to the South Pole version: a 1.7 meter diameter offset Gregorian capable of observing at wavelengths between 200 μm and 1.3 mm. The unblocked aperture gives a good beam with high forward spillover and scattering efficiency ($\eta_{fss} > 0.95$). This simplifies data calibration. The design pointing accuracy of the telescope is $3''$ [Stark *et al.* 2001].

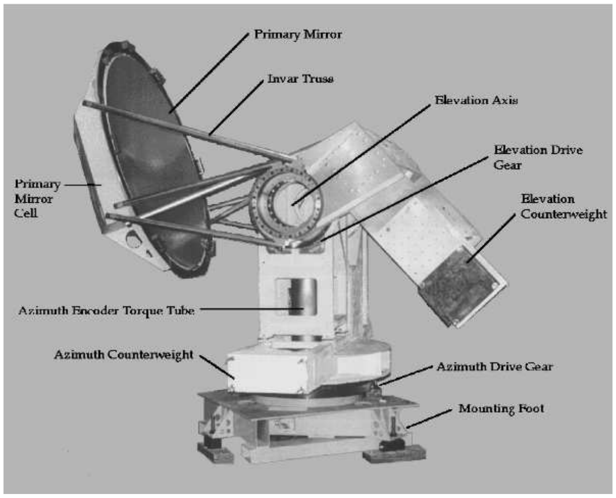

Figure 8: *The ASTRO telescope structure. In the foreground is the Nasmyth focus where* `SuperCam-2` *will be mounted.*

In the South Pole version of AST/RO, the receivers were located underneath the telescope at a Coudé focus. This allowed the receiver to operate in a laboratory environment. Waste heat from the instrument room beneath the telescope was used to keep the drive motors and electronics mounted within the telescope structure warm. This was necessary as the minimum outside temperature in winter was as low as -83 C. At the Pole, the telescope was installed on an insulated steel tower, floating atop large timber rafts buried in the snow. Pointing shifts caused by flexing of the mount were of the same order as the intrinsic pointing accuracy.

From the beginning, AST/RO was designed to allow remote operation. Complex observational programs often ran unattended for days at a time. At the South Pole, however, the need to refill the receivers with liquid cryogens meant that a winterover scientist had to be physically present at the telescope several times a week.

Atacama Implementation: AST/RO → ASTRO For its relocation to Atacama, the optics and mechanical parts of the AST/RO telescope will be refurbished to meet or exceed the original specifications given in [Stark *et al.* 1997]. Additionally, telescope systems will be upgraded to allow completely unattended operation, and to address shortcomings of the original AST/RO telescope, as determined by a decade's experience in Antarctica.

Liquid cryogens will no longer be required as `SuperCam-2` will use closed-cycle coolers. This is described below in the section on the array cryostat.

The major structural change is that the heterodyne array instruments will be placed in a small enclosure at the Nasmyth focus on the side of the telescope. At the Pole, this focus was used for the SPIFI array receiver [Oberst *et al.* 2006] The Coudé focus will not be used. This allows mounting the telescope on a wide but short steel platform. The more rigid support will give better pointing accuracy.

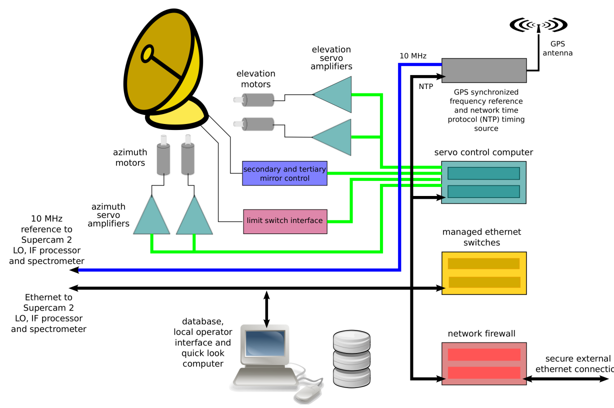

Figure 9: *Simplified block diagram of the ASTRO drive system and telescope control. The firewall, control computer and ethernet switch are redundant pairs configured for automatic fail-over if a fault occurs.*

Another major upgrade will be in the telescope control system. A simplified block diagram is shown in Figure 9. The design philosophy is to eliminate unreliable components and avoid single points of failure. For example, the computers which control the servo motors have no hard disks, only solid state memory. There are two control computers, one acting as a "hot spare". In the event of a failure, the redundant computer will automatically "fail-over", taking control and restarting the observation. The control system is also responsible for providing time and frequency distribution to the receiver and backend electronics.

Recognizing that remotely operated scientific equipment can be an "attractive nuisance" to so-called "hackers", the entire telescope control and data system is isolated behind redundant firewalls, allowing encrypted access only to authorized persons.

ASTRO will reside in a commercially available (Middough Inc.), 20 ft. diameter, dome. The roof of the dome slides open under computer control, giving the telescope full access to sky (see Fig. 10). A converted, 40 ft. shipping container will be located beside the dome. The container will be divided into sections and house support electronics, compressors, UPS, and an on-site control room and laboratory. Electrical power for ASTRO will be provided by diesel generators until such time as power from the local grid becomes available (see ALMA support letter).

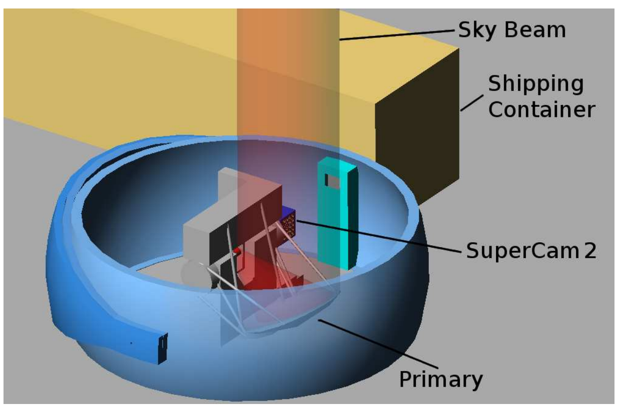

Figure 10: *Schematic of ASTRO and* `SuperCam-2` *inside of a 20-foot diameter automated retractable dome on the Atacama plateau, with a standard shipping container behind containing compressors, electronics and other support equipment.* `SuperCam-2` *(dark blue) is located at the Nasmyth focus on the right side of the telescope structure.*

`SuperCam-1` (330–370 GHz) is a 64 pixel array incorporating leading-edge technology. `SuperCam-2` (660–695 GHz) will be a scaled version of `SuperCam-1`.

Array Receiver Development

Overview The scientific objectives described in the previous sections require observations of hundreds of square degrees of the Milky Way in submillimeter-wave transitions at high spectral resolution. This requirement can only be met using large format heterodyne array receivers. Unlike the situation with bolometric detectors, heterodyne receiver systems are coherent, retaining information about both the amplitude and phase of the incident photon stream. From this information a high resolution spectrum of the incident light can be obtained without multiplexing. *Each pixel of a heterodyne array* typically provides $\sim$ 1,000 simultaneous spectral measurements. High resolution spectroscopy can, in principle, be performed in this same wavelength regime using incoherent detectors together with frequency dispersive quasi-optical devices such as gratings and Fabry-Perot interferometers. However, the size requirement of quasi-optical devices and/or the need to scan in order to construct a spectrum make them too cumbersome or insensitive for the scientific objectives of the proposed study.

Over the past decade our team members have led the development of 3 heterodyne array receiver systems. The first to be deployed was `PoleSTAR`, a 4 pixel, 810 GHz array for the AST/RO telescope at the South Pole. The second system was `DesertSTAR` a 7 pixel, 345 GHz array receiver for the HHT. The latest generation instrument is `SuperCam-1`, a 64 pixel, array receiver designed to work throughout the 870 micron atmospheric window. A block diagram of `SuperCam-1` is shown in Figure 11. `SuperCam-1` is constructed by stacking eight, 1x8 rows of fixed tuned, SIS mixers. The IF output of each mixer is connected to a low-noise, broadband MMIC amplifier integrated into the mixer block. The instantaneous IF bandwidth of each pixel is 2 GHz, with a center frequency of 5 GHz. A spectrum of the central section of each IF band is produced by sixteen, subdivided, 1 GHz wide, A/D converters feeding FFT digital signal processors. Mixer, magnet, and MMIC bias of each mixer are optimized under computer control. Local oscillator power is provided by frequency multipliers whose output is divided between the pixels by using a broadband, 64-way waveguide power divider and a single dielectric beam splitter for LO injection. The mixer array is cooled to 4 K by a closed-cycle Sumitomo cryocooler. A second cryocooler is used to absorb the heat load of the 64 stainless steel coax cables leading from the mixer array to connectors on the cryostat vacuum housing. Each pixel provides a diffraction limited beam on the sky.

`SuperCam-1` will begin the northern CO $J = 3 \rightarrow 2$ survey of the Milky Way on the HHT in October 2009. Here we propose to:

1. install `SuperCam-1` on ASTRO at the ALMA site once the northern survey is complete (May 2012). It will then be used to perform the southern half of the survey.
2. construct `SuperCam-2`, a 64 pixel, heterodyne array based on `SuperCam-1` technology optimized for the 450 micron atmospheric window. `SuperCam-2` will be used to conduct a CO $J = 6 \rightarrow 5$ survey of the Milky Way, first on ASTRO and then on the HHT.

`SuperCam-1` was specifically designed to allow a straightforward scaling to higher frequencies. In the following sections we describe how `SuperCam-2` will be constructed.

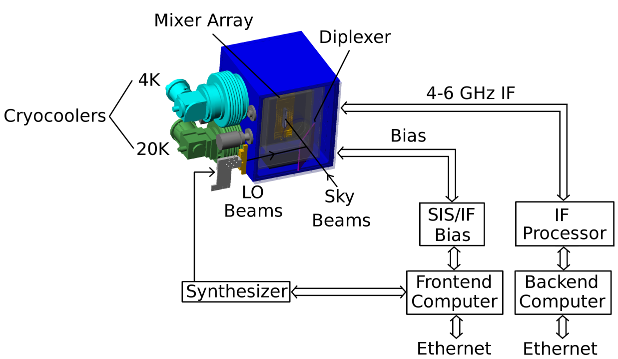

Figure 11: *System Block Diagram of the 64 pixel `SuperCam-1` heterodyne array*

Receiver Design The `SuperCam-2` instrument will build on the successful `SuperCam-1` splitblock mixer design as shown in Figure 12. This mixer module integrates eight single-ended SIS mixers, low noise amplifier (LNA) modules, individually biased electromagnets and bias distribution into a single splitblock module [Groppi *et al.* 2008]. Simple, single-ended mixers with integrated feedhorns are used to maximize reliability and to eliminate the need for cold optics inside the cryostat. The module, equipped with blind-mate RF and DC electrical connectors, slides on rails into a receptacle in the cryostat with mating connectors. This receptacle also provides the heat conduction path for cryogenic cooling of the module. The modules will be fabricated at Arizona State University using a state-of-the-art micromilling system similar to the system used to fabricate the original `SuperCam-1` mixers. Dr. Christopher Groppi, who was responsible for the fabrication of the `SuperCam-1` mixer modules, will lead the development and fabrication of the `SuperCam-2` modules. The SIS mixers in `SuperCam-1` were designed by Dr. Jacob Kooi and fabricated at the University of Virginia by Dr. Arthur Lichtenberger. `SuperCam-2` will use the same team for fabrication of similar 660 GHz devices. The design of the original 350 GHz `SuperCam-1` mixers, fabricated on 3 micron thick SOI (silicon on insulator) membrane, was specifically designed to allow straightforward scaling to higher frequencies [Kooi 2008]. These new devices will be integrated into a similar mixer block, with identical pixel spacing. The `SuperCam-1` design and components will be re-used wherever possible, with cryo-mechanical and electrical refinements based on our team's past experience.

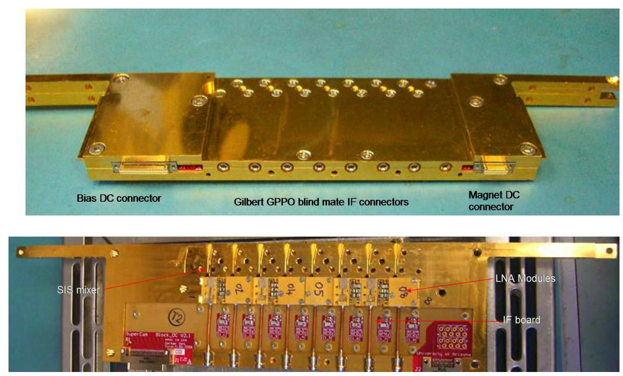

Figure 12: *1x8 `SuperCam-1` mixer module with integrated LNA modules and electromagnets.*

For the deployment of ASTRO and `SuperCam-2` on the Atacama plateau, only the Nasmyth focus will be used for mounting the heterodyne array receivers. This configuration is shown in Figure 10.

Integrated IF Amplifiers A critical component for the ASTRO receiver are the cryogenic IF amplifiers described in Figure 13. Fortunately, these amplifiers were developed by Caltech for the 64-pixel `SuperCam-1` receiver and are available for use in ASTRO without change in the design. Caltech has made provisions to sell cryogenic amplifiers to other research institutions and 80 amplifiers (includes spares) will be provided to the ASTRO program as purchased parts.

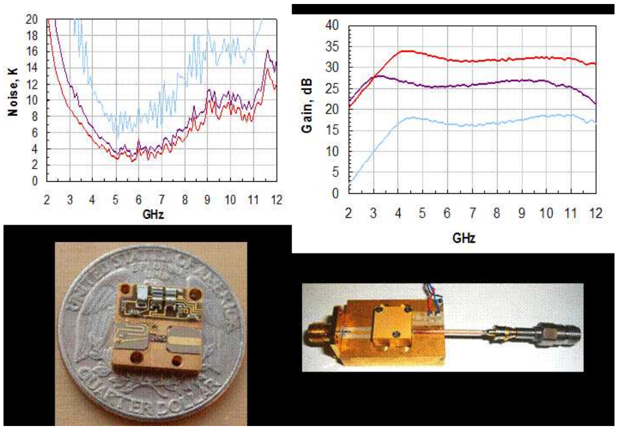

Figure 13: *IF amplifier for ASTRO. The noise and gain vs. frequency at 20K for 3 bias settings (0.6V, 21.1mA; 0.4V, 10.7mA, and 0.2V, 5.8mA) are shown at the top. The amplifier module shown on the quarter is 10mm square with a 2 x 0.7 mm InP chip bonded between two transmission lines. The input transmission lines contain a DC block and SIS bias tee and bond directly to the SIS junction. The module with cover and output coaxial cable is shown at lower right in a test fixture.*

Local Oscillators The LO power for the array will be provided by two solid-state, synthesizer-driven sources available from Virginia Diode Inc (quote provided). One LO chain will be optimized for observations of the ^{13}CO $J = 6 \rightarrow 5$ line at 660 GHz and the other for the CO $J = 6 \rightarrow 5$ line at 690 GHz. The active multiplier chains consist of high power solid-state amplifiers followed by a series of tunerless broadband multipliers. There are no mechanical tuners, so the output frequency simply tracks the synthesized input frequencies. The chains utilize a series of broadband varactor doublers and/or triplers that have been developed at Virginia Diode Inc. Each LO chain will produce $>$ 3mW of output power, more than sufficient to drive the SIS mixers. A similar 345 GHz VDI LO chain is used to pump all 64 SIS receivers in the existing `SuperCam-1` array.

`SuperCam-1` uses a hybrid waveguide and quasioptical LO multiplexing and injection scheme. A waveguide power divider takes the output of a single LO chain and divides it into 64 beams in an 8x8 array spaced by 11mm. An image of the `SuperCam-1` LO power divider's measured power pattern is shown in Figure 14.

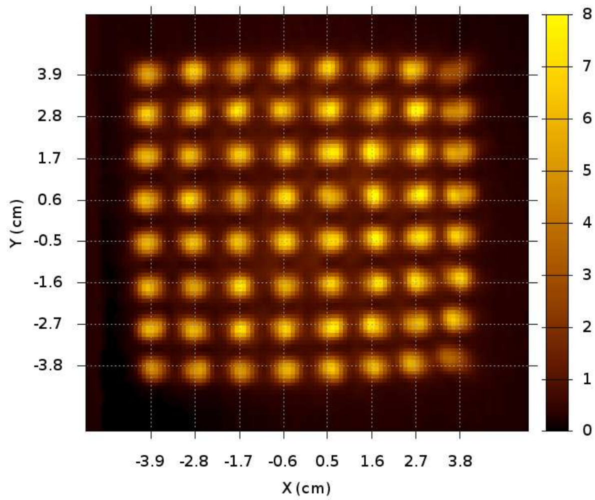

Figure 14: *LO Beam map of* `SuperCam-1`*. 64 beams are formed by a waveguide power divider feeding an array of diagonal feedhorns.*

A diagonal feedhorn array identical to the focal plane modules launches the 64 LO beams through a refractive relay optics system. A simple Mylar beamsplitter then diplexes the LO and signal beams. We plan to use a largely identical scheme for `SuperCam-2`. A similar waveguide circuit will be fabricated by Dr. Patricio Mena at the University of Chile for `SuperCam-2`. Mena's team will optimize the splitter design for 660 GHz and machine it using their Kern micromilling system (identical to the one used to machine `SuperCam-1` waveguide components).

IF Processor Conversion of the sixty-four 5 to 6 GHz band into inputs for the digital spectral processor will be accomplished at low risk and cost by a copy of the downconverter system developed at Caltech for the `SuperCam-1` system. A photograph is shown in Figure 15.

The IF processor designed for `SuperCam-1` provides 64 independent down conversion chains from an intermediate frequency of 5 GHz to a baseband signal to drive the spectrometer digitizers. The processor can also provide integrated total power measurements from each pixel. The design allows for selection between two IF bandwidths, up to 1000 MHz wide. Therefore, the same design can be used with minimal modifications to support bandwidths of 500 MHz and 1000 MHz for `SuperCam-2`.

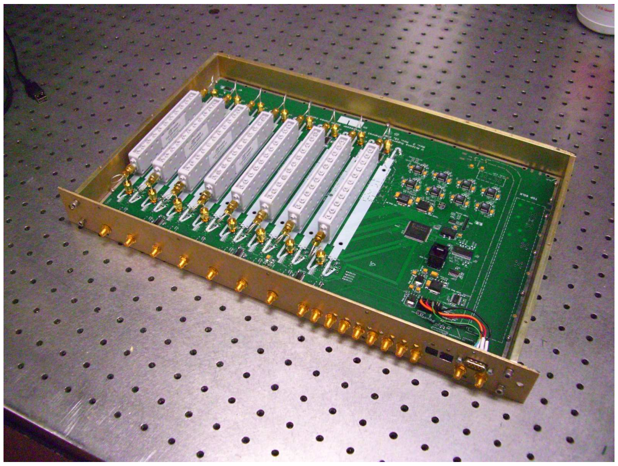

Figure 15: *Chassis with 8 IF converters as constructed for `SuperCam-1`.*

Figure 16: *The assembled 8-board, 16 GHz FFT spectrometer from Co-PI Walker's `SuperCam-1` project is no larger than a rack-mounted PC and requires only 200 watts of input power. One additional spectrometer module will be purchased for ASTRO.*

Spectrometer The ASTRO Galactic Plane surveys require both fine kinematic resolution ($<$0.5 km s^{-1}) to disentangle cloud components and wide instantaneous bandwidth ($\geq$200 km s^{-1}) to span the velocity dispersion of the Galaxy. Recent gains in high-speed ADCs and FPGAs have made such a wide bandwidth, direct-digitization spectrometer economically feasible. The baseband output of the IF processors is fed into two direct digitization spectrometer boards, each board with four IF inputs. For each IF input, the spectrometer board provides 0.5 GHz of instantaneous bandwidth at 0.25 MHz resolution. The resulting velocity coverage (up to 500 km/s at a resolution $\leq$ 0.25 km/s) enables CO lines to be resolved and observed throughout the Milky Way. Omnisys Inc. has already designed and delivered 8 of these boards for the Co-PI Walker's `SuperCam-1` array project, which perform admirably (Figure 16). The measured Allan variance (spectroscopic stability) time of the combination of IF-processor and FFT spectrometer is 650 seconds. Funds are requested to purchase an additional spectrometer unit to accommodate the increase in bandwidth needed to support 690 GHz operations.

Array Cryostat The cryostat developed for the original `SuperCam-1` instrument has proven to be both successful and reliable (see Figure 17). The `SuperCam-2` cryostat will be based largely on this design, with refinements based on our experience with `SuperCam-1`. The same Sumitomo 4K cryocooler, with 1.5W capacity will be used, driven by an air cooled compressor. The supplementary 15K cryocooler will also be sourced from Sumitomo.

Figure 17: *`SuperCam-1` instrument with LO injection system.*

4 Impact on Research and Training Infrastructure

Institutional Impact The combination of ASTRO and `SuperCam-2` will provide an order of magnitude leap in the mapping speed available in the astrophysically important 450 micron atmospheric window. ASTRO will be the most powerful instrument in the southern hemisphere for probing the history of star formation on Galactic scales and serve as a finders scope for investigations on ALMA. It will put Oberlin (and the Co-PIs) at the forefront of research and technology in this wavelength regime. This will in turn attract more highly qualified physical science students, technical staff, and faculty to the participating institutions. The substantial technological spinoffs from the project will place the partners in an excellent position to propose for future instruments and facilities.

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

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. Many of these labs are under the supervision of our ASTRO team members. A number of students (both graduate and undergraduate) have participated in the development of submm-wave instrumentation in these labs. This work, and the astronomy that has come from it, has led to 9 Ph.D. dissertations at the Univ. of Arizona alone and the basis of numerous undergraduate research projects. ASTRO is a natural extension of these research efforts. Funding for ASTRO will help support the research efforts of graduate and/or undergraduate students at Oberlin, the Univ. of Arizona, Arizona State Univ., the Univ. of Virginia, and Caltech. These students will interact with each other directly through weekly telecons and (when possible) in face-to-face meetings. 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 and the long-term progress in the entire field. This is especially true for the ASTRO project, where direct collaborations between students and faculty at several universities will be ongoing.

Web-based Outreach The broadest impact of the proposed research may be drawn from the use of these surveys as educational and outreach tools. More people rely on the Internet for news, information, and entertainment than ever before; a trend which is unlikely to change soon. Thus, providing online outreach tools that are accessible and interesting is an excellent way to reach a wide range of people. Distributed software should be operable on multiple platforms and be open source, so that others in the online community can embrace and extend what is provided within the confines of this study. A practical application would be to present a view onto the multi-wavelength Universe using existing planetarium software (*e.g.* Stellarium, `http://www.stellarium.org/`).

K-12 Outreach: A Student Radio Telescope In support of education and public outreach activities, Co-PIs Walker and Groppi and their students have constructed a remotely operable, steerable, 3.5 m Student Radio Telescope (SRT) for observing the H I line in the Milky Way. Like ASTRO, the SRT is a spectroscopic Galactic Plane survey telescope. During development and operation of ASTRO, we will develop instructional modules for various age groups that focus on the science and technology of ASTRO and use the SRT as a "hands-on" laboratory with the goal of providing students with an intuitive understanding of underlying physical concepts.

Global Impact: Synergies with Contemporary Surveys

GLIMPSE: a Spitzer Legacy Program The Spitzer Space Telescope Legacy program GLIMPSE, headed by E. Churchwell, provides a thermal infrared survey of the Galactic plane that provides a complete census of star formation, shows the stellar structure of the molecular ring, maps the warm interstellar dust, constrains extinction laws as a function of galactocentric radius and detects all young embedded O and B stars. The proposed Galactic Plane survey will provide the best corresponding molecular cloud survey that 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.

Cores to Disks: a Spitzer Legacy Program A second SST Legacy proposal, "From Cores to Disks", or "C2D", has surveyed a sample of giant molecular clouds and complexes in infrared continuum emission to provide a complete base for nearby star formation and to follow the transition from starless cloud cores to low-mass disks. The COMPLETE survey of Alyssa Goodman provides a reference study of the millimeter wave dust continuum emission in these clouds, and their molecular line survey will support the $J = 1 \rightarrow 0$ lines of CO and ^{13}CO using the FCRAO Sequoia array. Our target surveys of Outer Galaxy and high latitude GMC's add significant value to the baseline by providing higher-J CO data critical for the study of star forming regions where many excitation components are often present and cannot be disentangled with only one spectral line.

BU-FCRAO Molecular Ring Survey The ongoing FCRAO Molecular Ring Survey led by J. Jackson will provide the most sensitive study of the inner Galaxy to date, but only maps the ^{13}CO $J = 1 \rightarrow 0$ line. This proposed study will yield the crucial higher-J lines that make proper interpretation of existing CO surveys possible.

Bolocam Galactic Plane Survey The Bolocam Galactic Plane Survey (BGPS) is a 1.1 mm continuum survey of the Galactic Plane made using a bolometric camera on the Caltech Submillimeter Observatory. Millimeter-wavelength thermal dust emission reveals the repositories of the densest molecular gas, ranging in scale from cores to whole clouds. By pinpointing these regions, the connection of this gas to nascent and ongoing star formation may be explored. The BGPS coverage totals 170 square degrees (with 33" FWHM effective resolution). The proposed ASTRO/`SuperCam-2` survey will provide the spectroscopic follow-up to over 8000 mm-wave condensations and hundreds of molecular cloud complexes. The northernmost part of the BGPS will be covered by the northern `SuperCam-1` survey from the HHT.

2MASS & Formation of Molecular Clouds The 2 Micron All Sky Survey (2MASS) has imaged the northern and southern hemisphere skies in the photometric J, H, and K bands from 1–2.5 μm. This survey will be used to construct extinction maps over the entire region to be surveyed by ASTRO and `SuperCam-2` [Lada *et al.* 1994; Alves, Lada, and Lada 1999], which will be used to locate regions in the Galaxy where new molecular clouds are being formed; i.e. where gas has become molecular (i.e. H_2), but CO has not yet formed. These measurements will enable the crucial first measurement of the formation of Galactic molecular clouds, and will leverage the investment of the 2MASS survey in an innovative way.

5 Management Plan

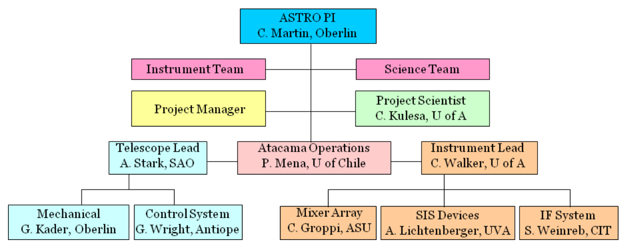

Figure 18: *ASTRO project organizational chart*

The development and deployment of ASTRO and its facility instrument `SuperCam-2` is a challenging, multi-institutional project that requires a high degree of coordination between its team members. Collectively the proposal team members represent many years of successful telescope/instrument development and observing experience. We have defined an organizational structure (shown in Figure 18) to meet this task. The organizational structure is optimized to pull on each team member's experience and institutional strength, while allowing the delegation of authority to be made at the proper level within the organization. The PI (Chris Martin) has extensive experience operating and maintaining the AST/RO telescope and instrumentation from his time in Antarctica. He has conducted one of the largest surveys of the Milky Way at submillimeter-wavelengths [Martin *et al.* 2004] and, more recently, is serving as the PI on a multi-national, *Herschel* key project. He will oversee all aspects of the project and be ultimately responsible for its success. The ASTRO Project Scientist (Co-PI Kulesa) has extensive experience in submillimeter-wave, infrared, and optical astronomy and their associated instrumentation. He will

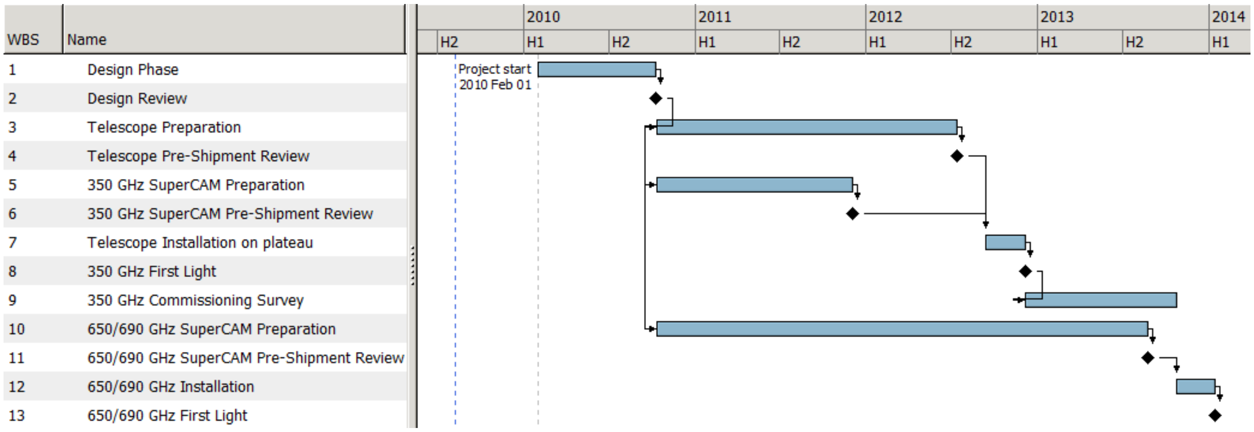

Figure 19: *ASTRO project key milestones and timeline. The telescope and receiver systems are developed in parallel, until the telescope structure ships to the Atacama plateau in year 3. At that point it will be commissioned with* `SuperCam-1` *and then outfitted with* `SuperCam-2` *when it is ready the following year.*

work with the PI and team members to design, coordinate, and fulfill ASTRO's key science program. Co-PI Stark was PI of the AST/RO telescope at the South Pole and will oversee its refurbishment and deployment at the ALMA site. Co-PI Walker is PI on the `SuperCam-1` project for the HHT and will lead the `SuperCam-2` development effort. The integration and testing of `SuperCam-2` will take place in his laboratory at the University of Arizona. Prof. Patricio Mena at the University of Chile has extensive experience developing receiver systems for ALMA. He and his team will participate in the development of `SuperCam-2` and be responsible for the on-site operation of the telescope/instrument. A Project Manager will aid the PI and Co-PI's in overseeing the fiscal and logistical aspects of the project. The Science and Instrument Teams (to be assembled in early 2010) will provide extensive scientific and technical guidance throughout the course of the project. A schedule of key project milestones and tasks is provided in Figure 19. 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 (either in person or through teleconferencing) between the PI, Co-PI's, PM, and Mixer Array lead Groppi (ASU), IF technical lead Weinreb (CIT) and Device technical lead Lichtenberger (UVa) along with active participation by associated postdocs and students.

Atacama Operations ASTRO will be optimized for unattended, remote operation on the ALMA site. Observing programs will be downloaded and data retrieved from ASTRO by the PI at Oberlin on a daily basis. Project Scientist Kulesa will work with the PI to formulate the observing programs and process incoming data. Co-PI's Stark and Walker will routinely monitor the health and performance of the telescope and receiver system. Prof. Patricio Mena and his team at the University of Chile will oversee site operations and perform routine maintenance on the facility. ASTRO will be visited routinely (at least quarterly) by the PI and one or more of the Co-I's and their students. The sharing of infrastructure (*e.g.* power, telecommunications) between ASTRO and ALMA will be coordinated by the PI and a preliminary agreement with ALMA has been reached (see attached letter).

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