Project Description

1 Results from Prior NSF Support

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

In 2010, the PI initiated an NSF-funded (ANT-0944335, 7/2010-6/2014) program to build two 60 cm terahertz telescopes for robotic operation at the summit of the Antarctic high plateau with the dual purpose of site testing and performing leading edge terahertz astronomy. These High Elevation Antarctic Terahertz (HEAT) telescopes operate from 150 to 610 μm and observe the brightest and most diagnostic far-infrared lines in the Galaxy. An international collaboration with Australia's University of New South Wales provided the PLATeau Observatory for Ridge A (PLATO-R), a platform for power and satellite communication. In January 2012, PLATO-R and the first HEAT prototype were deployed to Ridge A and are operational as of this writing (Figure 1). A servicing mission to Ridge A in which the second HEAT telescope will be installed is scheduled for January 2013. HEAT is the first automated telescope on the Plateau with cryogenic receivers; it is showing that the Ridge A site is the best site on the planet from which to perform terahertz observations, with 10× more observing days suitable for 200 μm observations than Chajnantor (e.g. ALMA). Already, a preliminary public data release of 809 GHz (370 μm) [CI] data returned via Iridium satellite has been made[1]. A primary data release in CO J=7-6 and [CI] $^3P_2$ - $^3P_1$ for the first year of operation will take place shortly after the recovery of the raw data in January 2013.

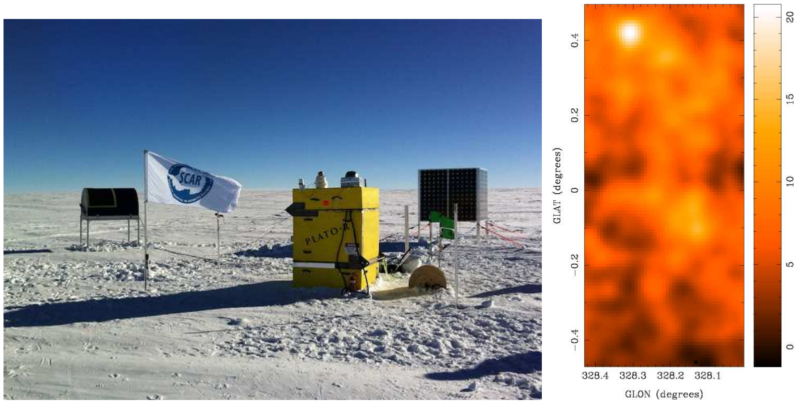


Figure 1: (left) The PLATeau Observatory and 60 cm HEAT telescope at Ridge A, Antarctica installed in January 2012. (right) The first 0.6 sq.deg. integrated intensity map in 370 μm [CI] emission returned by HEAT via onboard data processing and Iridium satellite downlink. The highly extended emission observed directly probes the *dark molecular gas*, i.e. H_2 clouds with little CO emission.

1.2 Bolocam Galactic Plane Survey, CAMPARE, URO

Y. Shirley has been PI or Co-I on three NSF grants; presented here in reverse chronological order.

(1) Astrophysics with the Bolocam Galactic Plane Survey (PI Dr. Y. Shirley, Prof. Jason Glenn is co-I; NSF grant AST-1008577, 8/2010-8/2013): This proposal provides spectroscopic followup of BGPS clumps in the Galactic plane. In the first half of the grant period, Y. Shirley led a team of observers that have completed HHT observations of all BGPS clumps $l > 7.5$ deg in the first and second quadrants of the Galaxy. The complete spectroscopic catalog was released in the fall of 2012. The paper from the pilot spectroscopic survey of 1882 sources was accepted (Schlingman

---

[1] `soral.as.arizona.edu/heat`

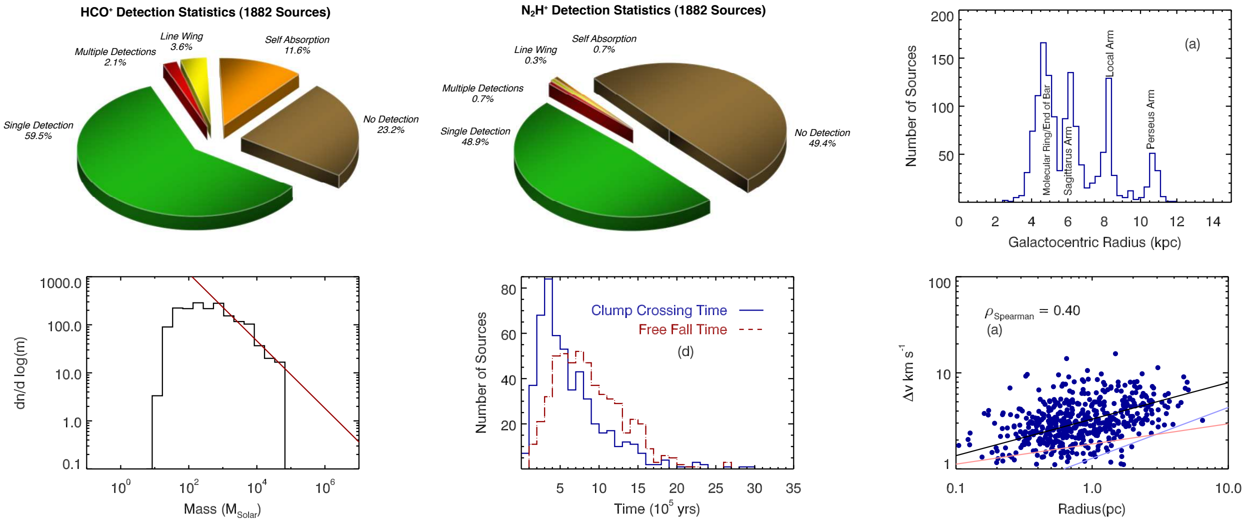


Figure 2: Scientific highlights from the BGPS Spectroscopic followup. CLOCKWISE FROM TOP LEFT: (1,2) Detection statistics for 1882 sources observed in HCO$^+$ and N$_2$H$^+$ 3-2 in the initial spectroscopic followup to the BGPS (Schlingman, Shirley, et al. 2011). Over 3/4th of BGPS continuum sources show emission in HCO$^+$. (3) The distribution of sources with galactocentric radius trace major spiral arm features in the Milky Way. (4) The subset of clumps with the distance ambiguity resolved do not display a size-linewidth relationship. (5) The clump crossing time is slightly less than the free-fall time for BGPS clumps. (6) The clump mass spectrum is steeper (-0.8) than observed for CO clumps (-0.6) in the Galaxy, but flatter than a Salpeter IMF (-1.35).

et al. 2011) and highlights from the characterization of the BGPS clumps properties are shown in Figure 2. Over 75% of clumps were detected in HCO$^+$ 3-2 indicating that kinematic distances will be derived for a significant fraction of BGPS clumps. The Schlingman et al. survey found that the clumps do not obey a size-linewidth relation indicating a breakdown in the supersonic scaling laws (Larson's laws) that apply to larger CO clouds.

(2) California-Arizona Minority Partnership for Astronomy Research and Education (PI is Prof. Alexander Rudolph, Y. Shirley is co-I, NSF AST-0847170, 7/2009 - 7/2014): CAMPARE is an education program designed to give under-represented minorities a hands-on REU experience working at the University of Arizona. The students are selected from California Polytechnic State University. As a co-I, Y. Shirley mentors 1 student each summer. The PI most recently worked with Stephen Jasso, who obtained 12m observations of CS 2-1 & HCN 1-0 toward a sample of dense cores identified through extinction mapping of the cloud (courtesy of Dr. Charlie Lada).

(3) The Arizona Radio Observatory: Surveying the ISM Through Millimeter and Sub-millimeter Spectroscopy (PI is Prof. Lucy Ziurys, Y. Shirley is co-I, NSF 11-529 URO, 4/15/2012 - 03/31/2015): This proposal provides funding for the Arizona Radio Observatory and upgrade of observatory facilities for the next three years. The URO funds thus far have been principally used for engineering development. Work has commenced on designing the proposed 4 mm receiver. Also, preliminary design work for the proposed broad-band spectrometer was begun.

1.3 *Supercam: A 64-beam Heterodyne Array Receiver at 850 μm*

In 2005, this team initiated an NSF-funded (AST-0421499, 1/2005-12/2009, PI: C. Walker) program to design and construct the first integrated heterodyne focal plane array at submillimeter wavelengths: 64 beams in the astrophysically important 850 μm atmospheric window. Supercam was designed to be used at the Arizona Radio Observatory (ARO) 10-meter Heinrich Hertz Telescope (HHT) on Mt. Graham, Arizona to conduct its key project, a Galactic Plane survey in the ^{12}CO J=3→2 line (the purpose of this proposal). Each component of Supercam has been modularized in units of 1×8 rows of the full heterodyne array (Figure 3). Thus, the mixer blocks, bias electronics, IF processors, and digital FFT spectrometers are quantized into modules that provide 8 detector "pixels" each. This one-dimensional integration is crucial to the realization of large format heterodyne arrays and has been successfully completed by the Supercam team (Figure 3).

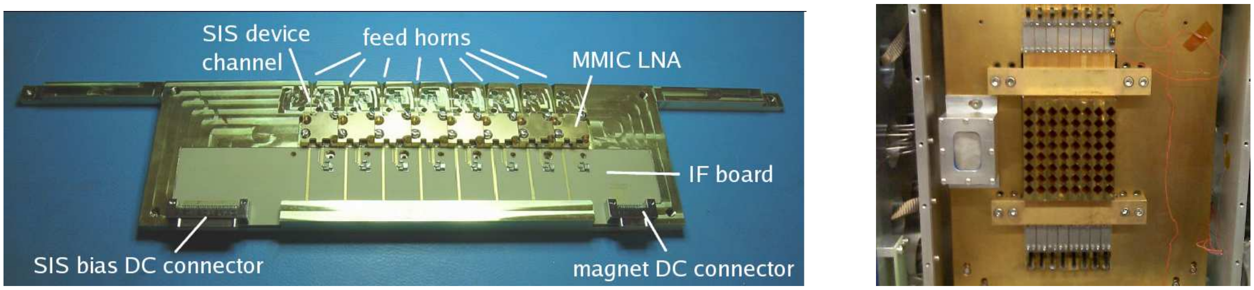


Figure 3: Left: The centerpiece of the Supercam heterodyne array is the integrated mixer block; comprised of 8 feedhorns, SIS mixers, MMIC low noise amplifiers, and nano IF & DC connectors. The final 64-beam focal plane consists of 8 such mixer modules. Right: Zoom-in on the opened Supercam cryostat, showing the fully populated 64 beam focal plane.

The full Supercam instrument was successfully installed on the HHT in May 2012. Despite the comparatively poorer weather near the end of the observing season, Supercam achieved first light and delivered more than 1 million spectra per day. Supercam's relay optics delivered a 23" diffraction-limited beam and 60% beam efficiency in nearly every pixel. Two sample maps from that engineering run are shown in Figure 4. The yield of pixels with good sensitivity (T$_{rec} < 100$K DSB) during the engineering run was approximately 55%. Optimization of devices in the focal plane is underway (Fall 2012), to increase the yield of devices with excellent RF performance, with a target goal of 75%. The expected instrument performance based on laboratory tests is shown in Figure 5(left) and the corresponding mapping speed is shown as a function of frequency in Figure 5(right), dominated by the atmospheric transmission in the 350 GHz band. At the frequencies of interest, near CO J=3-2 and HCO$^+$ J=4-3, the mapping rate is approximately 4-5 hours per square degree, or **5-6 square degrees per day**. This sharply contrasts to the 4-5 days per square degree that is typically expended at (easier) mm wavelengths using the ALMA Band 6 (1.3mm) prototype receiver at the HHT. This is the specific enabling result which motivates the Galactic Plane survey proposed here.

2 Research Activities

Supercam will enable innumerable new astronomical research opportunities as an available PI instrument at the HHT, open to all users. However, its high angular and spectral resolution, cou-

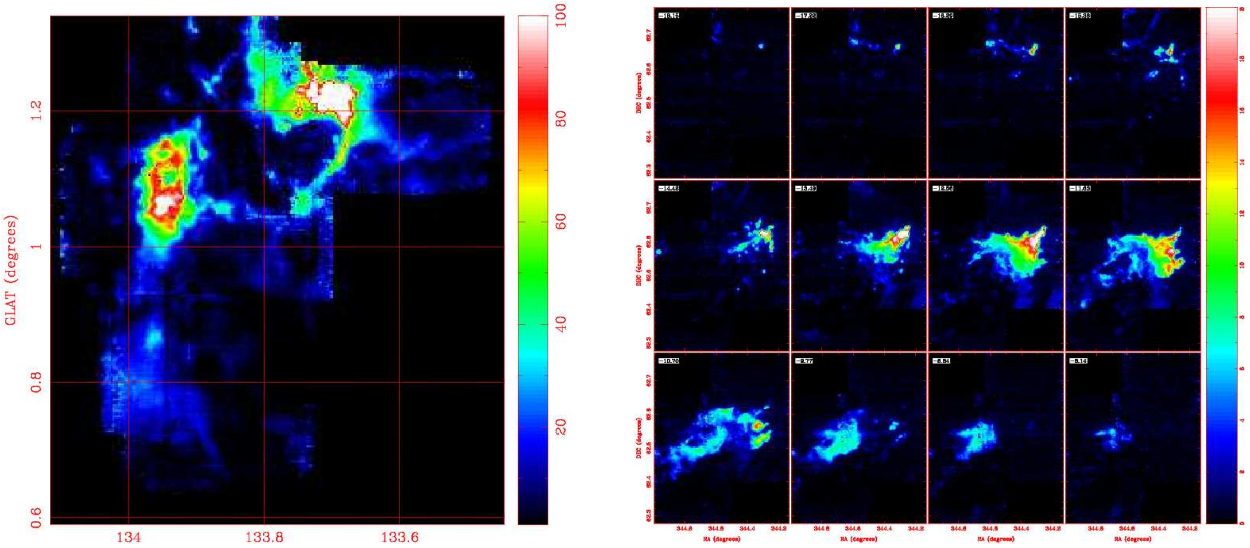


Figure 4: A sample of first light maps at 345 GHz made with Supercam at the HHT in late May, 2012. Left: Integrated intensity map of CO J=3-2 line emission over 40'x40' of the W3 molecular cloud. Right: Channel maps spanning 24'x30' of the Cepheus A molecular cloud show complex kinematics. Each image represents the emission in 1 km/s bins from V_{LSR} = -18 to -6 km/s. Despite the poor early-summer weather and a reduced pixel count, these large-scale maps were made in a few hours each.

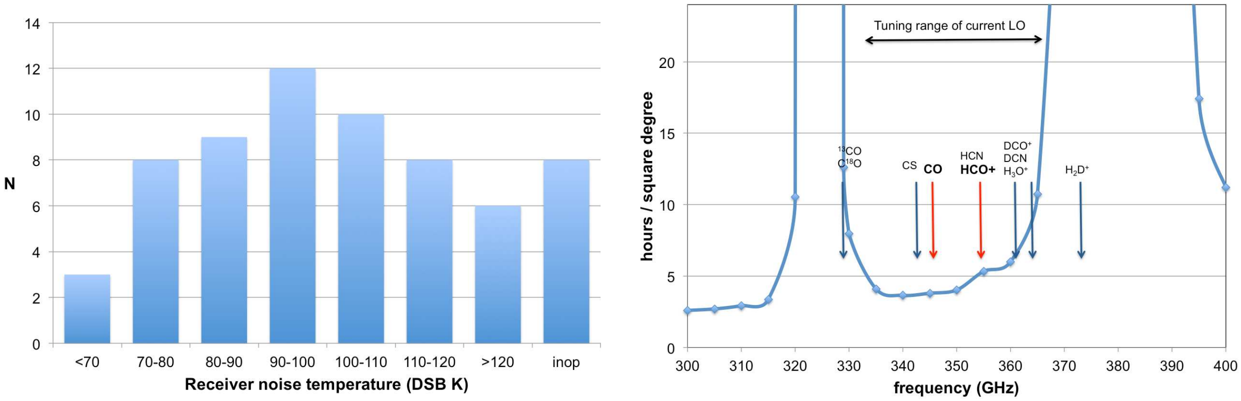


Figure 5: (left) Expected performance of Supercam based on laboratory receiver testing. The mean noise temperature of working devices is 90K DSB and the focal plane yield of good devices is projected to be 75%. (right) Corresponding mapping speeds at the HHT, assuming an rms noise level of 0.2 K km/s in median winter weather at a zenith angle of 30^o. Near the spectral lines of interest, the mapping speed will be approximately 5 square degrees per day.

pled with an exceptional field of view makes it *a truly exceptional Galactic Survey instrument*, which provided the primary motivation for its construction. Here, we outline a first Supercam "key project", a submillimeter CO and HCO^+ survey of the Galactic Plane observable from Arizona.

2.1 Introduction: Critical questions this proposal will address

The evolution of (the stellar population of) galaxies is determined to a large extent by the life cycles of interstellar clouds: their creation, star-forming properties, and subsequent destruction by both natal and dying (massive) stars. (Figure 6).

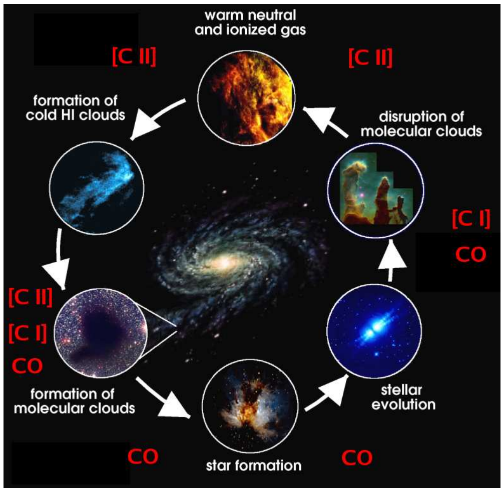


Figure 6: The life cycle of interstellar clouds, observed through carbon lines. The internal evolution of a galaxy is defined by the transformation of dense, neutral interstellar clouds into stars and star clusters, the interaction of the interstellar medium (ISM) with young stars as a regulator of further star formation, and the return of enriched stellar material to the ISM by stellar death, eventually to form future generations of stars.

Although 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 typical interstellar conditions. Atomic hydrogen is detectable in cold clouds via the 21 cm spin-flip transition, but cold (T∼70K) atomic clouds are often indistinguishable from the warm (T∼8000K) neutral medium that pervades 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 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. The dominant ionization state(s) of carbon that accompany each stage of a cloud's life are shown in red in Figure 6. Though 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 as they directly relate to star formation and galaxy evolution has become acute. The most recent decadal survey, "Astro2010: New Worlds, New Horizons", specifically identifies the questions "*What controls the mass-energy-chemical cycles within galaxies*", "*how do stars form*", "*what determines the star formation rates and efficiencies in molecular clouds*", and "*what determines the properties of pre-stellar cloud cores and what is the origin of the stellar mass function*" as among the key questions for radio and (sub)millimeter facilities in this decade. Further, the specific recommendation is made: **"A large-field mapper operating at millimeter and submillimeter wavelengths is required to pave the way for follow-up observations with ALMA"**. Supercam is a direct answer to this recommendation and is ready **now**.

This project aims to increase our understanding of the interactions between stars and the molecular clouds which form them. Stars affect their environments through the direct input of kinetic energy and by radiation which ionizes or heats adjacent molecular gas. This proposed survey will yield major new results targeted at answering specific questions about molecular clouds, star formation, and stellar feedback:

(1) How do molecular clouds form, evolve, and get disrupted? How do typical atoms and grains cycle through the ISM; in particular, how do molecular clouds relate to the atomic hydrogen component of the ISM? Is there statistical evidence that molecular clouds may be formed by colliding streams or filaments of HI as has been shown in hydrodynamical models (Heitsch et al., 2006)?

(2) How and under what conditions do molecular clouds form stars? What role does the underlying physical structure of molecular clouds and their dense cores have on the mass function of stars that result?

(3) What are the effects of HII regions on their associated molecular clouds? To what extent does cloud compression caused by expanding HII regions trigger the formation of dense cores and subsequent star formation? To what extent do the dynamical, heating and ionization effects of OB stars and their HII regions destroy associated molecular clouds?

(4) What is the evolutionary and dynamical state of molecular cloud cores?

(5) 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? Can star formation in the Milky Way be synthesized into a “template” to help interpret star formation in distant, unresolved galaxies?

We will use Supercam, the aforementioned state-of-the-art 64-beam heterodyne array to map a large, 240 square degree region of the Galactic Plane in the J=3-2 transition of CO and the J=4-3 transition of HCO^+ from the HHT. The proposed observations exploit the unique capabilities of Supercam, namely efficient, rapid, high-fidelity spectral mapping over large angular scales. The survey angular resolution, 23”, will yield maps superior in resolution and sensitivity to any other imaging data yet presented over comparably large areas of sky. We will also employ other available data to form as comprehensive a picture as possible of the ISM and the stellar content of Galactic interstellar clouds. With detailed kinematic analyses, it will be possible to compare our data with predictions of numerical hydrodynamical models of the ISM and thereby to constrain the physical mechanisms resulting from stellar energy injection and the resulting feedback which regulates the star formation process. We emphasize that these properties can only be determined from well-sampled large-area maps that cover a wide range of spatial scales. **Single-dish telescopes are key to making high-fidelity images of the ISM with high spectral resolution and spatial dynamic range**. With the advent of ALMA, sensitive, high resolution imaging of relatively small regions is now possible. However, large-scale imaging with ALMA is prohibitively time consuming; this is a task most effectively performed by precision single-dish telescopes outfitted with multi-beam receivers like Supercam.

2.2 Properties of the Proposed Survey

The following properties represent a definitive survey that would not only provide the clearest view of the star forming clouds in the Galaxy, but also serve as the definitive reference for focused follow-up studies with the SMA, CARMA and ALMA interferometers and LMT.

2.2.1 High Resolution Spectroscopic Imaging

Techniques commonly used to diagnose the molecular ISM include submillimeter continuum mapping of dust emission (Hildebrand, 1983) and dust extinction mapping at optical and near-infrared wavelengths (Lada, Lada, Clemens, & Bally, 1994). Large format detector arrays in the infrared

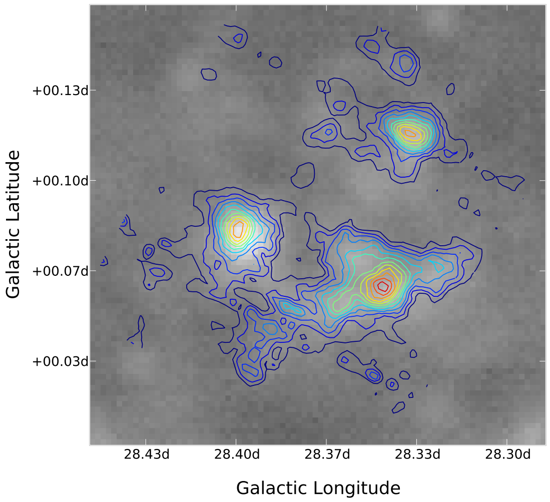


Figure 7: Integrated intensity maps ($\int T_{mb}\, dv$, 3σ contours) of G28.37+0.08 in HCO$^+$ J=3-2 obtained with the HHT overlaid on greyscale 1.1mm images (Battersby et al. 2010). Since the excitation conditions for HCO$^+$ J=4-3 are not drastically different from HCO$^+$ J=3-2, we expect the J=4-3 emission to be extended and mappable.

are now commonplace, and with the advent of bolometer arrays like SCUBA at the JCMT and BOLOCAM at the CSO, both techniques have performed large area maps of molecular material. In the past decade, continuum surveys at mid-infrared (GLIMPSE & MIPSGAL; Benjamin et al. 2003), submillimeter (Hi-GAL; Molinari et al. 2010), and ATLASGAL; Schuller et al. 2009, Contreras et al. 2012), and millimeter wavelengths (BGPS, Aguirre et al. 2011) have cataloged dense star forming clumps throughout the Galaxy. The Bolocam Galactic Plane Survey (BGPS) has discovered over 8400 sources in the Galactic plane (Rosolowsky et al. 2010). 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. Supercam will make it feasible, for the first time, to obtain a complete spectral map of the Galactic plane in a moderate (CO J=3-2) and dense (HCO$^+$ J=4-3) gas molecular tracer, for direct comparison with these surveys.

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 of 1 km s^{-1} or better, a cloud's kinematic location can be distinguished from other phenomena that alter the lineshape, such as turbulence, rotation, and local phenomena 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.

Supercam resolves the intrinsic profiles of Galactic CO and HCO$^+$ lines, with a per-channel resolution of 0.2 km s^{-1}. Supercam's IF center frequency will be adjusted to allow simultaneous observations of both lines, CO 3-2 in the lower sideband and HCO$^+$ 4-3 in the upper sideband. Supercam's mixers are optimized for double sideband operation, with a sideband ratio of $\sim$1. The spectral bandwidth will scale with the known CO velocity dispersion (Dame, Hartmann, & Thaddeus, 2001): for the Outer Galaxy ($l > 40^o$), all 64 pixels will observe both spectral lines simultaneously, with 110 km s^{-1} of bandwidth each. In the Inner Galaxy ($l < 40^o$), all 64 pixels will observe CO J=3-2, and 16 of them will observe both lines simultaneously, with 220 km s^{-1} of bandwidth each (comparable to the Galactic rotational velocity). Local Oscillator (LO) doppler tracking will ensure that the Galactic emission profiles stay within their spectral bandpasses.

2.2.2 A Submillimeter Survey in CO and HCO$^+$

CO is second only to H_2 as the most abundant molecule in the ISM, and it remains the most accurate, most sensitive tracer of H_2 on large scales. 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 Galactic molecular clouds is incomplete. Early results were obtained with large beams (Dame et al., 1987; Dame, Hartmann, & Thaddeus, 2001), were undersampled (Solomon, Rivolo, Barrett, & Yahil, 1987; Scoville et al., 1987); or had limited areal coverage, e.g., the early FCRAO surveys – (Carpenter, Snell, & Schloerb, 1995; Stark & Brand, 1989; Bally, Langer, & Liu, 1991; Miesch & Bally, 1994). The Galactic Ring Survey (GRS) at FCRAO is by far the most comprehensive survey of the inner Galaxy to date (Simon et al., 2001). However, this survey 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.

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 gas probed by higher-J transitions is best suited to addressing the proposed survey's driving 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 line surveys like Supercam's are also needed to properly interpret basic properties of clouds derived from existing CO J=1-0 observations.

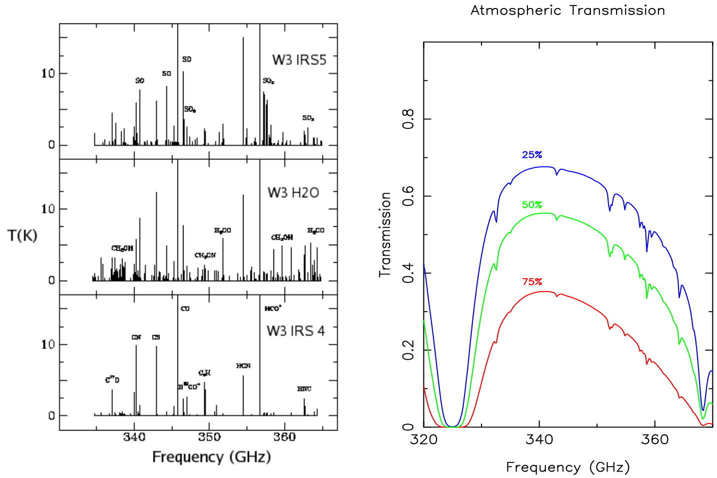
The CO J=3-2 transition at 345.8 GHz ($n_{crit} = 1.5 \times 10^4$ cm^{-3}) yields the lowest-lying line that significantly departs from the behavior seen in J=1-0 emission at 2.6mm, making it an ideal probe of the denser, more energetic portions of clouds. Similarly, HCO$^+$ J=4-3 is among the best tracers of high density gas ($n_{crit} = 2 \times 10^6$ cm^{-3}). In the 350 GHz atmospheric window, it has more accessible excitation characteristics than CS J=7-6 or HCN J=4-3. It is expected to be often subthermally-excited and optically-thick; radiative trapping reduces its effective excitation density to $n \sim 10^5$ cm^{-3}. HCO$^+$ also has a straightforward chemistry that is closely connected to CO. Observing both species is therefore highly synergistic.

While HCO$^+$ emission will be more concentrated than CO, bright BGPS sources such as those shown in Figure 7 clearly show that HCO$^+$ emission is often extended (Battersby et al. 2010). Based on the brightness of HCO$^+$ 3-2 emission and the typical gas kinetic temperature measured with NH_3 observations toward BGPS clumps ($< T_k > \sim 15$ K; Dunham et al. 2011), we expect to map extended HCO$^+$ $4 - 3$ emission in ~1600 individual clumps in a first quadrant survey alone. The MALT90 survey (Foster et al., 2011) in HCO$^+$ J=1-0 will provide a significant lever arm to constrain physical conditions in dense clumps that both surveys share in common.

The design of a 350 GHz spectroscopic survey is attractive; at this frequency the HHT has high aperture efficiency and good atmospheric transmission more than 50% of the winter (Figure 8-b).

2.2.3 Large Area Mapping: A Galactic Plane Survey

A complete picture for how star formation proceeds throughout the Galaxy can only be accomplished through Galactic plane surveys. Studies of star formation in other galaxies have derived a fundamental relationship between the surface density of dense gas and the star formation rate (i.e. the Kennicutt-Schmidt Law, Kennicutt 2007, Gao& Solomon 2004a,b, Bussmann et al. 2008, Baan et al. 2008, Juneau et al. 2009, Lada et al. 2012, Kennicutt & Evans 2012). The most recent



a) b)

Figure 8: a) The 345 GHz spectral line survey toward three positions in the W3 molecular cloud by Helmich & van Dishoeck (1997) shows a rich diversity of spectral diagnostics. b) Modeled sub-millimeter atmospheric transparency for the HHT on Mt. Graham in 75 percentile (top), median (middle), and 25 percentile (bottom) atmospheric conditions, derived from 24 hour 225 GHz radiometer measurements over the last 10 years.

molecular extragalactic surveys have pushed the spatial resolution of observations of CO to scales of 0.1 kpc in nearby galaxies (Bigiel et al. 2011). Over the next few years, ALMA observations will probe smaller scales and also trace the more relevant dense gas from which stars form with high efficiency using molecular tracers such as HCO$^+$ and HCN. A simultaneous effort is needed within our own Galaxy to build-up to the scales probed by extragalactic observers to determine a star formation relationship within the Milky Way. Galactic plane surveys in dense molecular gas tracers can provide the needed information on the surface density and fraction of dense molecular gas throughout the Galaxy. When combined with infrared surveys, they can constrain the global star formation relation in the Milky Way. No complete survey of the first quadrant of the Galactic plane currently exists in a submillimeter-wave, dense gas tracer.

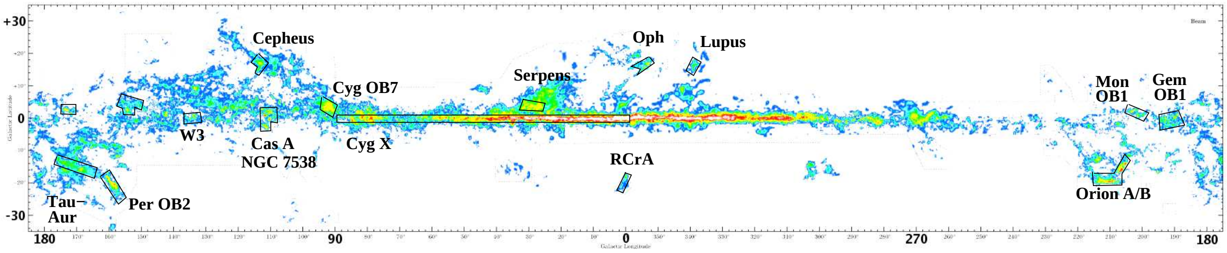


Figure 9: The power of SuperCam: a definitive chemical and kinematic survey of star forming clouds in ^{12}CO J=3-2 and HCO$^+$ J=4-3 over 240 square degrees of the sky can be performed in 4 months of observing in median winter weather. A corresponding survey with a single pixel receiver would take 100% of the HHT's observing time for 5 years.

Figure 9 shows the proposed sky coverage of the SuperCam submillimeter-wave 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 (Dame et al., 1987; Dame, Hartmann, & Thaddeus, 2001). The 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 Arizona ($0 < l < 240^o$). Below $l = 90^o$, a *completely unbiased survey* will be undertaken, covering 180 square degrees ($-1^o < b < 1^o$). This "inner" Galaxy survey will coincide with several synergistic surveys (Section 3.2), such as the FCRAO-BU Galactic Ring Survey (GRS), GLIMPSE, a Spitzer Space Telescope (SST) Legacy Program (Benjamin et al., 2003), and Hi-GAL (Molinari et al., 2010). Above $l = 90^o$, most of the CO emission is located at higher Galactic latitude; 60 square degrees will be distributed according to the Dame, Hartmann, & Thaddeus (2001) survey to follow the CO J=1-0 distribution, while maximizing synergies with the C2D and GLIMPSE(360) Spitzer programs (Evans et al., 2003), cloud cores seen by BGPS, and and other Spitzer & Herschel programs (Figure 9). Further discussion of the survey regions may be found in Section 2.3.1 and the data management document.

2.2.4 High Angular Resolution

Angular resolution is a critical aspect to the science return of a new Galactic plane survey. Figure 10 depicts a synthetic model cloud projected to distances of 500 pc and 5 kpc. Clearly, disentangling different clouds and cloud components can only be accomplished with sub-arcminute angular scales. The angular resolution of Supercam in CO J=3-2 on the HHT is 23″, equivalent to 0.9 pc at the distance of the Galactic Center.

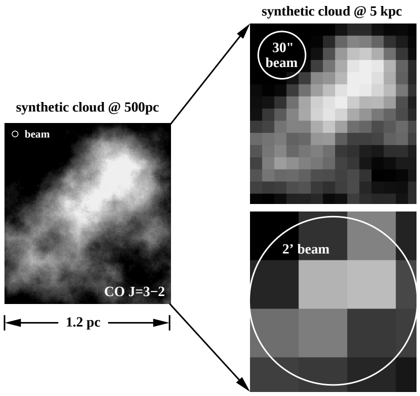


Figure 10: **The need for high angular resolution:** A synthetic model cloud seen in the ^{12}CO $J = 3 - 2$ transition at a distance of 500 pc (left) and at 5 kpc, with beam sizes of $30''$ (top) and $2'$ (bottom). The structure of the cloud is essentially lost in the larger beam. In order to probe cloud structure and excitation over the entire Galactic disk, high angular resolution is vital.

2.2.5 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 occurs by a visual extinction of $\sim$1 magnitude in the local interstellar radiation field, N(H)=1.8×10^{21} cm^{-2}. We therefore aim to detect all CO down to this hydrogen column density limit. This corresponds to a 5σ detection limit of N(CO)=10^{15} cm^{-2}, which implies an integrated intensity for cold gas (T$_{kin}$=10-50K) of 1 K km s^{-1} in the $J = 3 \rightarrow 2$ transition at a gas density of $n_H = 10^4$ cm^{-3}. This sensitivity limit is achievable (at 5σ) within 12 seconds of integration time per independent beam in *median* atmospheric conditions (T$_{sys}$ $\sim$700K) at the HHT, or 5 hours per square degree, with 10" spatial pixels. Detection (or limits) on J=3$\rightarrow$2 in that time would constrain the gas density, based upon the line brightness of millimeter wave transitions. In the same period of time, Supercam would also reach a 5σ limit of 1 K km s^{-1} in HCO$^+$ J=4-3, which would detect around 65% of the BGPS clumps observed by Schlingman et al. (2011) in HCO$^+$ J=3-2. Targeted follow-up HCO$^+$ observations with Supercam toward sources with a wide range of evolutionary stages are expected in year 3 of the proposed effort.

2.3 *Survey Activities*

2.3.1 *Mapping Strategy*

The most efficient mode of data collection with a focal plane array that produces high 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 sufficent rate to eliminate aliasing and beam smearing. 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 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. Mapping projects at the HHT routinely and efficiently use the OTF technique.

The broad coverage of the Galactic Plane Survey lends itself naturally to efficient, 24-hour/day mapping. Only the regions defined by $0 < l < 40^o$ enters the 30^o Sun-avoidance circle in December, and $150 < l < 210^o$ during May-June. With 64 pixels, SuperCam can reach the requisite sensitivity of 1σ=0.2 K km/s over a full square degree in 5 hours (Section 2.2.5). A visibility diagram (Figure 11) shows the nominal observing strategy in which the entire survey can be accomplished in 4 months of observing time– total; two month-long campaigns in each of two years. A corresponding survey with a single pixel receiver would take 100% of the HHT's observing time for 5 years. The observing time required for the proposed survey was guaranteed by Steward Observatory in the original Supercam MRI proposal (see letter from P. Strittmatter).

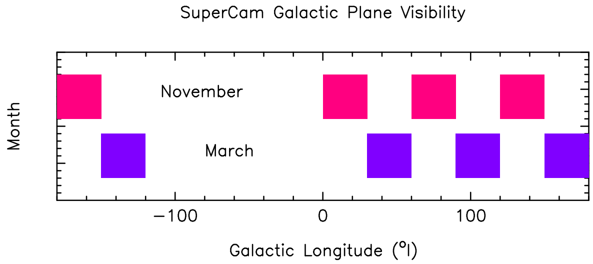


Figure 11: The entire Galactic Plane survey can be accomplished in 4 months of observing time total; two month-long campaigns in each of two years. This visibility diagram denotes how the Galactic Plane will be partitioned for efficient observing.

2.3.2 *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 100x larger than normal. We have adopted the strategy developed at FCRAO for OTF mapping with the 32 pixel SEQUOIA array, whereby coadded and regridded data are written as a FITS cube, and headers for each scan are written into a SQL relational database. This approach facilitates efficient logging and retrieval of the data. Our storage requirements for a 240 square degree map, gridded to $10''$ spacing, with 1024 spectral points per grid position, is $\sim$100 GB. The total disk requirements for the raw data will be about 6 TB. This volume can be readily handled by a single computer with a redundant disk array for data integrity. Open access to these data products (with no proprietary period) will be provided through a web browser interface that will parse the SQL database and FITS data cubes.

All science tools, packaged reduction software, data products and science products will be made available from the Supercam survey's web page, at `soral.as.arizona.edu/supercam`

2.3.3 Survey Science Analysis Strategy

To extract physical information from the Supercam survey data, in combination with copious ancillary data already available, we will employ a variety of analysis tools and integrative activities.

1) Coupled escape probability (CEP) (Elitzur & Asensio Ramos, 2006) and Monte Carlo (MC) (Bernes, 1979) **radiative transfer models** will be used to constrain kinetic temperature, hydrogen (molecule) particle density, and total column density. Observed line ratios and intensities can be compared to CEP model grids that can be used to estimate the average physical conditions of each observed point. For HCO^+ J=4-3, application of Monte Carlo radiative transfer will be used to check the CEP solutions when applicable. Applicable codes have already been developed by the proposing team (CEP: Kulesa, MC: D. Narayanan).

2) **Photodissociation region (PDR) models** aim to reproduce the physics, chemistry, and emergent spectra of the surfaces of molecular clouds exposed to energetic stellar radiation. PDR codes were originally developed to model the interstellar clouds subject to intense UV fields, like those in massive star forming regions (Tielens & Hollenbach, 1985; van Dishoeck & Black, 1988). We will use modified versions of CLOUDY (Ferland, Korista & Verner, 1998) and the Meudon PDR code (Le Petit et al., 2012) in combination with the radiative transfer models cited above, to derive physical models of the observed regions, allowing the radiative impact on any cloud to be derived.

3) **Dynamical analyses.** Besides the effects of their radiation, stars influence clouds by depositing kinetic energy in protostellar outflows, stellar winds, and shocks from supernovae. This energy input is expected to drive turbulent linewidths in clouds, but the nature of this link is poorly established. To extract this kinematic information from the data set, we will first perform moment analyses of the CO and HCO^+ spectral line profiles. Centroid maps outside the line cores constitute the standard technique for finding high velocity gas such as shocks and outflows (Walker, Carlstrom, & Bieging, 1993; Groppi et al., 2004). The line width provides a measure of the velocity components coincident within a telescope beam and sets an upper limit on the turbulent velocity field. Secondly, we will extract kinematic information through a principal component analysis (PCA), a statistical approach that emphasizes the underlying patterns and regularities within complex data sets while minimizing inferences derived from incidental features (Heyer & Schloerb, 1997). Brunt & Heyer (2002) have demonstrated that PCA can recover the true 3-dimensional statistics of the velocity field, distinguishing incompressible, eddy-like flows from strong compressible motions that create shocks and generate density enhancements like cloud cores. These analyses will allow us to define the inertial range in molecular clouds and the variation of turbulence within molecular clouds and dense cores.

4) **Development of a Milky Way Template**. At high-redshift, (sub)mm-observations of molecular gas in galaxies are typically restricted to higher-rotational quantum number transitions ($J \geq 3$). Because the ground state transition is the principal tracer of star-forming molecular gas (H_2), some assumption invariably has to be made regarding the excitation of CO. This can dominate the error budget in determining the gas mass of the galaxy, driving uncertainty in baryonic gas fraction determinations of high-z galaxies. In the era of ALMA, these quantities are routinely being measured in galaxies from z=0-6 in order to understand the baryon cycle in galaxies that governs gas accretion from the intergalactic medium, conversion into stars, and subsequent expulsion due to stellar feedback. Our high-resolution CO (J=3-2) survey of the Galactic plane will reduce this uncertainty. By comparing Supercam data to the FCRAO CO and ^{13}CO J=1-0 surveys of the Milky Way, we will be able to construct CO (J=3-2)/(J=1-0) line ratio maps across the Galaxy at parsec

scales. Comparisons of this data to young stellar object counts for nearby clouds will allow us to parameterize the excitation in terms of the star formation rate surface density, the observable quantity most likely to correlate with molecular excitation, and most readily observable for high-z galaxies. This comparison will also establish the Galactic Kennicutt-Schmidt Law. We will compute Star Formation Rate to the surface brightness of CO J=3-2 and HCO^+ J=4-3 relation for gas in a large range of physical conditions, determining the most complete estimate of the Milky Way's molecular luminosity in a dense gas tracer. This strongly connects the Milky Way to observations of other galaxies. These templates will allow our team to not only inform future observations, and help constrain the cosmic evolution of the baryonic gas fraction in galaxies. With observations and cosmological simulations showing dramatic differences in the predicted gas fractions of high-z galaxies (Narayanan, Bothwell & Dave, 2012), the construction of these templates will be timely.

Participant	**Affiliation**	**Partipation Activity**
Craig Kulesa	U. Arizona	PI: Reviews & approves operations plans and execution Reviews and approves science data products Coordinates collaborative followup observations.
Chris Walker	U. Arizona	Co-PI (Supercam PI): Leads science advising effort with students Responsible for instrument viability Shares responsibility for science operations, & data products
Yancy Shirley	U. Arizona	Co-PI: Lead responsibility for dense gas mapping in HCO^+ Shares student advising effort
John H. Bieging	U. Arizona	Integration of SuperCam data with 1.3mm HHT survey
Ed Churchwell	Wisconsin	Advisor: Synergy with GLIMPSE survey
Paul Goldsmith	JPL	Advisor: Synergy with Herschel $GOTC^+$ survey
Alyssa Goodman	Harvard	Advisor: Synergy with C2D & COMPLETE surveys
Chris Groppi	Arizona State	Participates in science operations & instrument upgrades
Mark Heyer	U. Mass	Advisor: Synergy with GRS survey, PCA analysis
Desika Narayanan	U. Arizona	Theoretical modeling, construction of Milky Way template
Gopal Narayanan	U. Mass	Advisor: Galactic Surveys & Star formation regions

Table 1: Activities of the Supercam Science Team

2.3.4 Roles of the Collaboration Participants

Senior personnel who will use the Supercam instrument in this first "key" program at the HHT are listed in Table 1. *In addition, numerous students will participate in the science development at the University of Arizona and participating organizations.*

3 Project Impact

3.1 Educational Impact

The training of students in the development and use 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 occuring 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 team's lab (SORAL: Steward Observatory Radio Astronomy Laboratory), we have been fortunate to have had a number of talented students pursue their research. Over the past 10 years the lab has produced 9 Ph.D.'s and numerous undergraduate senior projects. Most of the Ph.D.'s are still pursuing astronomical research and a number of the undergraduates have gone on to receive Ph.D's at other institutions. In recent years research in the lab has drawn an increasing number of students from other departments, particularly optical sciences and electrical engineering. It is interest in astronomy and the interdisciplinary nature of the research that attracts them to the SORAL lab. In an effort to reach this population of students, the Co-PI's and fellow faculty members in other departments are seeking to establish an interdisciplinary program in astronomical instrumentation. Two of Co-PI Walker's past Ph.D. students have received majors and minors in different departments. Co-PI Walker currently has 4 graduate and 2 undergraduate students participating in interdisciplinary studies.

In the proposed budget, funds for only one graduate student are requested. The use of Supercam on the HHT will be the focus of the student's research. However, as is customary in the SORAL lab, many other students will also participate in making the program a success. Indeed, one of the most important aspects of training students is the experience gained in working in teams. Astronomical science and 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.

3.2 Global Impact: Survey Synergies

The proposed Galactic Plane survey with Supercam will serve as a "finding chart" for future, focused surveys with ALMA and markedly enhance the value of numerous contemporary surveys. These data will be released openly to the astronomical community, with no proprietary period.

3.2.1 BGPS and ATLASGAL continuum surveys

The 1.3mm Bolocam Galactic Plane Survey and 850 μm ATLASGAL survey from APEX represent the most comprehensive long-wavelength continuum surveys of high column density, cold dust in the Galaxy. As previously described in Section 2.2.3, we will map the kinematics and column of HCO^+ toward $\sim 10^3$ cold dust condensations, and expect to map extended HCO^+ emission towards many of them. With Supercam's survey of dense gas, a linewidth-size relationship can be computed, which is critical to studies of turbulence and basic scaling laws for star formation. Approximately 12% of HCO^+ detections from Schlingman et al. (2011) showed a self absorption profile (Figure 9) indicating that we will also identify many potential infall candidates (see Reiter et al. 2011). Co-PI Shirley will coordinate efforts to maximize the scientific return from Supercam's dense gas surveys in combination with the BGPS.

3.2.2 GLIMPSE, MIPSGAL, and Hi-GAL

The Spitzer Space Telescope Legacy program GLIMPSE, headed by E. Churchwell, provided a thermal infrared survey of the Galactic plane that provides a complete census of star formation, the stellar structure of the molecular ring, will map the warm interstellar dust, constrain extinction laws as a function of galactocentric radius and will detect all young embedded O and B stars. MIPSGAL extended the wavelength coverage to Spitzer's 24 μm band, and Herschel's Hi-GAL program is mapping 720 sq.deg. of the Galactic Plane in 5 bands from 60 to 600 μm. Supercam's 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. Collaborator E. Churchwell will provide guidance in interpreting Spitzer data for comparison with the Supercam survey.

3.2.3 From Molecular Clouds to Young Stars

A second Spitzer Legacy proposal, "From Cores to Disks", or "C2D", 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 (Ridge et al., 2006) provided a reference study of the mm wave dust continuum emission and 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 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. Collaborator Alyssa Goodman (CfA) will provide guidance in comparing COMPLETE data with the Supercam survey.

3.2.4 Galactic Ring Survey

The FCRAO Galactic Ring Survey led by J. Jackson provided the most sensitive study of the inner Galaxy to date, but only mapped the ^{13}CO $J = 1 \rightarrow 0$ line. This proposed study will improve upon the GRS resolution by up to a factor of 4 in area and yield the crucial higher-J lines that make proper interpretation of existing CO surveys possible. Collaborator Mark Heyer (U.Mass) is a member of the GRS team and will provide guidance interpreting the GRS & Supercam data.

4 Project Management

Transitioning Supercam from an instrument development to a scientific workhorse is an exciting prospect that our team has been working towards for years. Collectively the Supercam team members represent many years of successful instrument development and observing experience. As related by Table 1, the main components of the organization are the PI, who has overall responsibility for the project and coordinates the activities of the participants; Co-PI's Walker and Shirley, who share in these responsibilities and lead the student advising efforts; and the distributed members of the science team who act as an advisory council to the PI and Co-PIs to ensure that the project stays on course. A schedule of key project milestones and tasks is provided in Figure 12. Routine communications between project participants is essential. There will be monthly science team telecons to monitor progress and provide insight into solutions to emerging problems, and redefine priorities as needed. A Supercam wiki at Arizona will provide a resource for team communications and documentation.

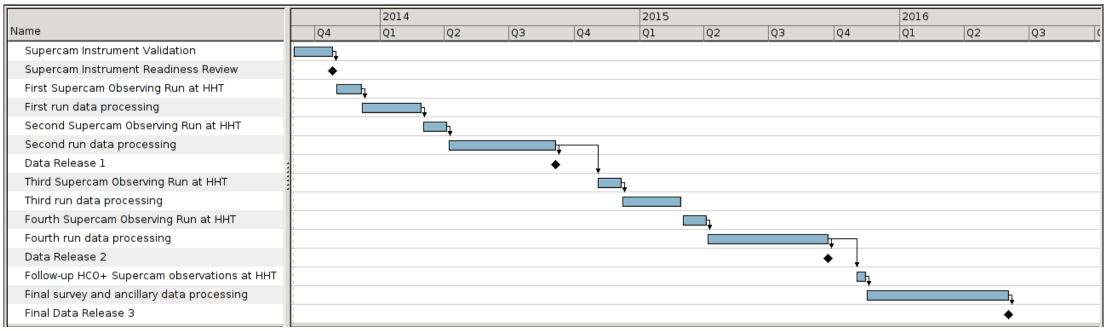


Figure 12: Supercam Science Operations Timeline

References

Aguirre, J. E., Ginsburg, A. G., Dunham, M. K., et al. 2011, “The Bolocam Galactic Plane Survey: Survey Description and Data Reduction”, ApJS, 192, 4

Alves, J., Lada, C. J., & Lada, E. A. 1999, “Correlation between Gas and Dust in Molecular Clouds: L977”, ApJ, 515, 265

Baan, W. A., Henkel, C., Loenen, A. F., Baudry, A., & Wiklind, T. 2008, “Dense gas in luminous infrared galaxies”, A&A, 477, 747

Bally, J., Langer, W. D., & Liu, W. 1991, “Infrared dust and millimeter-wave carbon monoxide emission in the Orion region”, ApJ, 383, 645

Benjamin, R. A. et al. 2003, “GLIMPSE. I. An SIRTF Legacy Project to Map the Inner Galaxy”, PASP, 115, 953

Bernes, C. 1979, “A Monte Carlo approach to non-LTE radiative transfer problems”, A&A, 73, 67

Bigiel, F., Leroy, A., & Walter, F. 2011, “Scaling Relations between Gas and Star Formation in Nearby Galaxies”, Computational Star Formation, 270, 327

Brunt, C. M., & Heyer, M. H. 2002, “Interstellar Turbulence. I. Retrieval of Velocity Field Statistics”, ApJ, 566, 276

Bussmann, R. S., Narayanan, D., Shirley, Y. L., et al. 2008, “The Star Formation Rate-Dense Gas Relation in Galaxies as Measured by HCN(3-2) Emission”, ApJL, 681, L73

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

Contreras, Y., Schuller, F., Urquhart, J. S., et al. 2012, “ATLASGAL - Compact source catalogue: $330 < l < 21$ degrees”, arXiv:1211.0741

Dame, T. M. et al. 1987, “A composite CO survey of the entire Milky Way”, ApJ, 322, 706

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

Elitzur, M., & Asensio Ramos, A. 2006, “A new exact method for line radiative transfer”, MNRAS, 365, 779

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

Ferland, G. J., Korista, K. T., & Verner, D. A. 1998, “CLOUDY 90: Numerical Simulation of Plasmas and Their Spectra”, PASP, 110, 761

Foster, J. B., Jackson, J. M., Barnes, P. J., et al. 2011, “The Millimeter Astronomy Legacy Team 90 GHz (MALT90) Pilot Survey”, ApJS, 197, 25

Gao, Y., & Solomon, P. M. 2004, “The Star Formation Rate and Dense Molecular Gas in Galaxies”, ApJ, 606, 271

Gao, Y., & Solomon, P. M. 2004, “HCN Survey of Normal Spiral, Infrared-luminous, and Ultraluminous Galaxies “, ApJS, 152, 63

Gillespie, A. R. & Phillips, T. G., 1979, “Array Detectors for Millimetre Line Astronomy”, A&A, 73, 14.

Goldsmith, P., in “Quasioptical Systems”, pub. IEEE Pressm 184.

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

Groppi, C. E., Kulesa, C., Walker, C., & Martin, C. L. 2004, “Millimeter and Submillimeter Survey of the R Coronae Australis Region”, ApJ, 612, 946

Heitsch, F., Slyz, A. D., Devriendt, J. E. G., Hartmann, L. W., & Burkert, A. 2006, “The Birth of Molecular Clouds: Formation of Atomic Precursors in Colliding Flows”, ApJ, 648, 1052

Helmich, F. P. & van Dishoeck, E. F. 1997, “Physical and chemical variations within the W3 star-forming region. II. The 345 GHz spectral line survey”, A&AS, 124, 205

Heyer, M. H., & Schloerb, F. P. 1997, “Application of Principal Component Analysis to Large-Scale Spectral Line Imaging Studies of the Interstellar Medium”, ApJ, 475, 173

Hildebrand, R. H. 1983, “The Determination of Cloud Masses and Dust Characteristics from Submillimetre Thermal Emission”, QJRAS, 24, 267

Juneau, S., Narayanan, D. T., Moustakas, J., et al. 2009, ApJ, “Enhanced Dense Gas Fraction in Ultraluminous Infrared Galaxies”, 707, 1217

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

Kennicutt, R. C., Jr., Calzetti, D., Walter, F., et al. 2007, “Star Formation in NGC 5194 (M51a). II. The Spatially Resolved Star Formation Law”, ApJ, 671, 333

Kennicutt, R. C., & Evans, N. J. 2012, “Star Formation in the Milky Way and Nearby Galaxies”, ARA&A, 50, 531

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

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

Lada, C. J., Forbrich, J., Lombardi, M., & Alves, J. F. 2012, “Star Formation Rates in Molecular Clouds and the Nature of the Extragalactic Scaling Relations”, ApJ, 745, 190

Le Petit, F., Roueff, E., Le Bourlot, J., & Nehmé, C. 2012, “Meudon PDR: Atomic & molecular structure of interstellar clouds”, Astrophysics Source Code Library, 5010

Miesch, M. S. & Bally, J. 1994, “Statistical analysis of turbulence in molecular clouds”, ApJ, 429, 645

Molinari, S., Swinyard, B., Bally, J., et al. 2010, “Hi-GAL: The Herschel Infrared Galactic Plane Survey”, PASP, 122, 314

Narayanan, D., Bothwell, M., & Davé, R. 2012, “Galaxy gas fractions at high redshift: the tension between observations and cosmological simulations”, MNRAS, 426, 1178

Reiter, M., Shirley, Y. L., Wu, J., et al. 2011, “The Physical Properties of High-mass Star-forming Clumps: A Systematic Comparison of Molecular Tracers”, ApJS, 195, 1

Ridge, N. A., Di Francesco, J., Kirk, H., et al. 2006, “The COMPLETE Survey of Star-Forming Regions: Phase I Data”, AJ, 131, 2921

Roshi, D. A., Kantharia, N. G., & Anantharamaiah, K. R. 2002, “Carbon recombination lines near 327 MHz. I. “Diffuse” C II regions in the Galactic Disk”, A&A, 391, 1097

Rosolowsky, E., Dunham, M. K., Ginsburg, A., et al. 2010, “The Bolocam Galactic Plane Survey. II. Catalog of the Image Data”, ApJS, 188, 123

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

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

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

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

Schlingman, W. M., Shirley, Y. L., Schenk, D. E., et al. 2011, “The Bolocam Galactic Plane Survey. V. HCO+ and N2H+ Spectroscopy of 1.1 mm Dust Continuum Sources”, ApJS, 195, 14

Stark, A. A. & Brand, J. 1989, “Kinematics of molecular clouds. II - New data on nearby giant molecular clouds”, ApJ, 339, 763

Tielens, A. G. G. M., & Hollenbach, D. 1985, “Photodissociation regions. I - Basic model. II - A model for the Orion photodissociation region”, ApJ, 291, 722

van Dishoeck, E. F., & Black, J. H. 1988, “The photodissociation and chemistry of interstellar CO”, ApJ, 334, 771

Walker, C. K., Carlstrom, J. E., & Bieging, J. H. 1993, “The Detection of [CI] in Molecular Outflows Associated with Young Stellar Objects”, ApJ, 402, 655