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

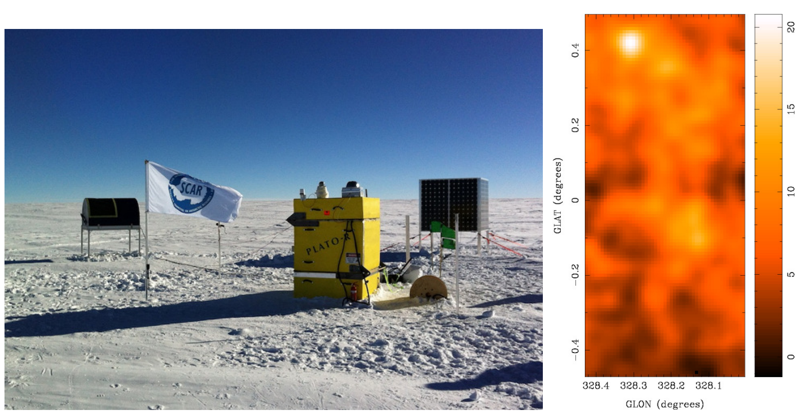

Figure 1: (left) The PLATeau Observatory and 60 cm HEAT telescope at Ridge A, Antarctica installed in January 2012. (right) The first 0.6 sq.deg. integrated intensity map in 370 μm [CI] emission returned by HEAT via onboard data processing and Iridium satellite downlink. The highly extended emission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

1.2 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. Each component of Supercam has been modularized in units of 1$\times$8 rows of the full heterodyne array (Figure 2). 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 2).

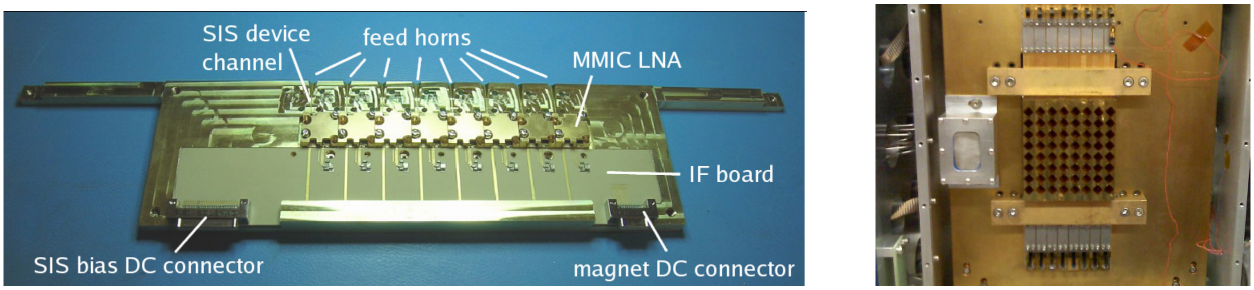

Figure 2: Left: The centerpiece of the Supercam heterodyne array is the integrated mixer block; comprised of 8 feedhorns, SIS mixers, MMIC low noise amplifiers, and nano IF & DC connectors. The final 64-beam focal plane consists of 8 such mixer modules. Right: Zoom-in on the opened Supercam cryostat, showing the fully populated 64-beam focal plane.

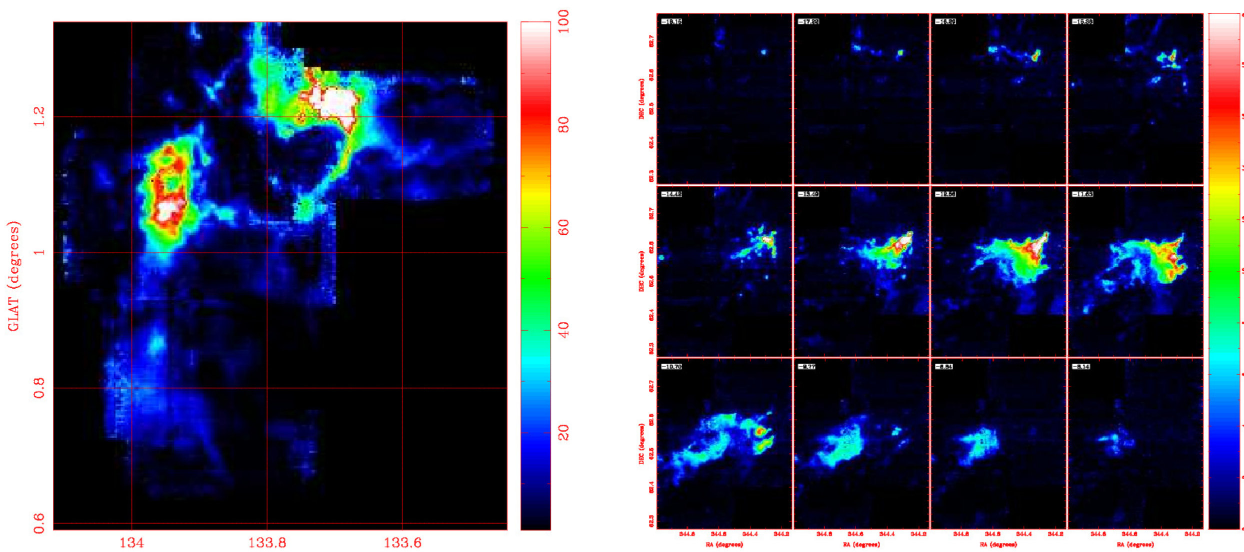

Figure 3: A sample of first light maps at 345 GHz made with Supercam at the HHT in late May 2012. Left: Integrated intensity map of CO J=3-2 line emission over 40'x40' of the W3 molecular cloud. Right: Channel maps spanning 24'x30' of the Cepheus A molecular cloud show complex kinematics. Each image 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.

The full Supercam instrument was successfully installed on the HHT in May 2012. Despite the comparatively poor 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 3. 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 took place in Fall 2012 and Spring 2013, and the focal plane now achieves the desired uniformity and sensitivity. Only the few (8) remaining bad 'pixels' will be replaced before the proposed work effort begins. The current instrument performance is shown in Figure 4(left) and the corresponding mapping speed is shown as a function of frequency in Figure 4(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. *Rapid, high fidelity spectroscopic mapping at submm wavelengths is the specific enabling result which motivates the Galactic Plane pilot survey proposed here.*

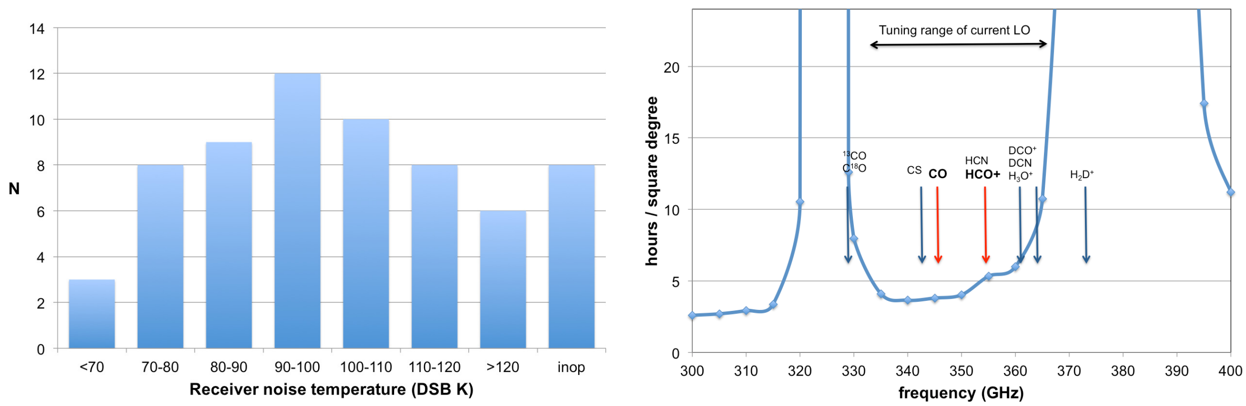

Figure 4: (left) Expected performance of Supercam based on laboratory receiver testing. The mean noise temperature of working devices is 90K DSB and the focal plane yield of good devices is 75%. (right) Corresponding mapping speeds at APEX, assuming an rms noise level of 0.2 K km/s in median summer weather at a zenith angle of 30^o. Near the spectral lines of interest, the mapping speed will be approximately 5 square degrees per day.

2 Research Activities

Supercam will enable pivotal astronomical research opportunities as an available PI instrument at APEX. For the November 2014 run, use of Supercam was opened to all users and observing time was oversubscribed by a factor of over 4:1 for ESO time. Its high angular and spectral resolution, coupled 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 pilot study, a submillimeter CO survey of a crucial portion of the Galactic Plane ideally observed from Chile. The benefits to US Astronomy are substantial:

1. 20 square degrees of the Galactic Plane will be mapped by our observing proposal in 2014, with another 10-20 square degrees possible if an April 2015 run is granted.
2. Provides the ultimate wide-field spectroscopic survey for detailed followup with ALMA. Data to be made available immediately with no proprietary period.
3. Overlaps with surveys from High Elevation Antarctic Terahertz (HEAT) telescope (ANT-0944335) supported by PLR and AST, and the Stratospheric Terahertz Observatory supported by PLRs Long Duration Balloon facility at McMurdo Station (joint w/ NASA).
4. All other awarded Supercam/APEX programs have at least one US Co-Investigator.

5. 50% of the awarded Supercam programs are lead by a US PI.

6. Over 320 hours of APEX time were awarded to Supercam in 2014. April 2015 is pending.

2.1 Justification for a RAPID response

The installation of Supercam on the APEX telescope is a timely, once-in-an-instrument's-lifetime event. The November 2014 (and potentially April 2015) observing windows for Chilean, ESO and Swedish time are available for Supercam's use, and fully endorsed by the APEX collaboration. Proposals for Supercam time were publicly requested and submitted in Spring 2014. The respective TACs responded favorably and have publicly committed essentially all of the observing time in the Nov/Dec APEX run to Supercam. As the German partners in APEX have their own multi-beam receiver in development, Supercam's readiness creates a unique window of opportunity for 2014-15 that is very unlikely to repeat. This time-critical access to a needed facility makes RAPID the most appropriate avenue for support.

Minimal RAPID funds from NSF are requested to take Supercam instrument development "the last mile" to make this opportunity a reality. Investing $30k to deliver the scientific benefits behind NSFs $2.5M instrument development effort is an exceptional return! All of the facilities available will be fully utilized to make this instrument development and observing run a success.

The established excellence of the APEX telescope and site, combined with the readiness of the Supercam instrument creates a compelling and unique opportunity to leverage NSF's major investment in the world's first integrated submillimeter-wave imaging spectrometer.

2.2 Critical questions this pilot study 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. 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 ultimately 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 suggested in hydrodynamical models?

(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 pilot, 20+ square degree region of the Galactic Plane (Galactic longitudes 310-330 degrees) in the J=3-2 transition of CO. The proposed observations exploit the unique capabilities of Supercam, namely efficient, rapid, high-fidelity spectral mapping over large angular scales. The survey angular resolution at APEX, 18", 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.

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. The PI is in fact a byproduct of this educational facility! 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.

3.2 Global Impact: Survey Synergies

The proposed Galactic Plane survey with Supercam will serve as the ultimate "finding charts" 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. The data management section provides details of the Supercam data flow and archival plan.

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. The main components of the organization are the PI, who has overall responsibility for the project and coordinates the activities of the participants; Co-PI Walker who shares in these responsibilities and lead the student advising efforts; and the distributed members of the science team who act as an advisory council to the PI and Co-PIs to ensure that the project stays on course. 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.

A **first-draft Interface Control Document (ICD)** that outlines the interfaces between Supercam and the APEX telescope is provided in Supplementary Documents. Questions that this document was designed to raise will be answered during an on-site visit by the Supercam instrument team in late July 2014.