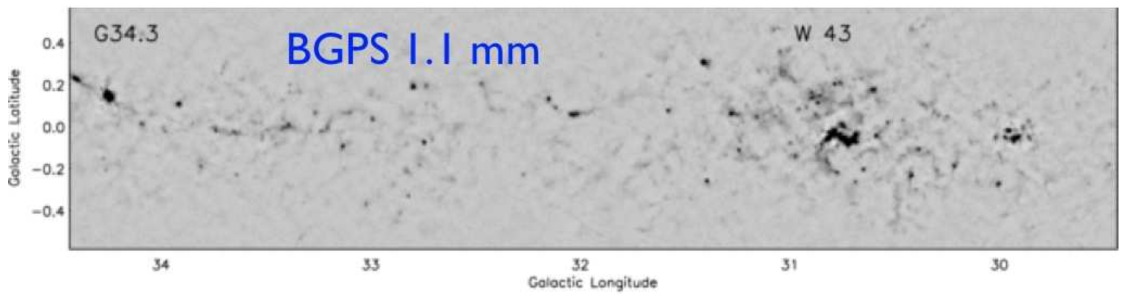

Figure 1: Example of 5 degree section of the first quadrant centered on $l = 32°$ from the Bolocam Galactic Plane Survey (Aguirre et al. 2011). Darker color indicates stronger 1.1 mm continuum emission.

1 A Galactic Plane Mapping Survey of Dense Molecular Gas

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 molecular extragalactic surveys have pushed the spatial resolution of observations of CO to scales of 0.1 kpc in nearby galaxies (see 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 the 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, and when combined with the infrared surveys, can constrain the global star formation relation in the Milky Way. No complete survey of the first quadrant of the Galactic plane in a dense gas tracer currently exists.

In the past decade, continuum surveys at mid-infrared (GLIMPSE; Benjamin et al. 2003), submillimeter (ATLASGAL; Schuller et al. 2009), 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 source in the Galactic plane within 170 square degrees mapped (Rosolowsky et al. 2010; see Fig. X). In 2010, co-I Shirley was awarded a NSF grant to provide spectroscopic follow-up of the BGPS clumps in order to derive kinematic distances and to determine the basic properties (size, mass, luminosity) of the continuum sources. Each BGPS peak continuum position was observed simultaneously in the dense gas tracers HCO^+ and N_2H^+ 3-2. Over 75% of BGPS sources have been detected in HCO^+ 3-2 (Schlingman et al. 2011; Fig. 8) and the complete spectroscopic survey will be released in early 2013. Since the spectroscopic follow-up consists solely of single-pointing observations at the 1.1 mm continuum peaks, we are unable to constrain the distribution of dense molecular gas or the kinematics within individual BGPS clumps. SuperCAM will make it feasible, for the first time, to obtain a complete map of the Galactic plane in a dense gas molecular tracer.

We propose to map HCO^+ 4-3 emission in the first quadrant of the Galaxy with SuperCAM covering ±0.5 deg in galactic latitude. The clumps shown in Figure X clearly display the extended nature of HCO^+ 3-2 emission (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

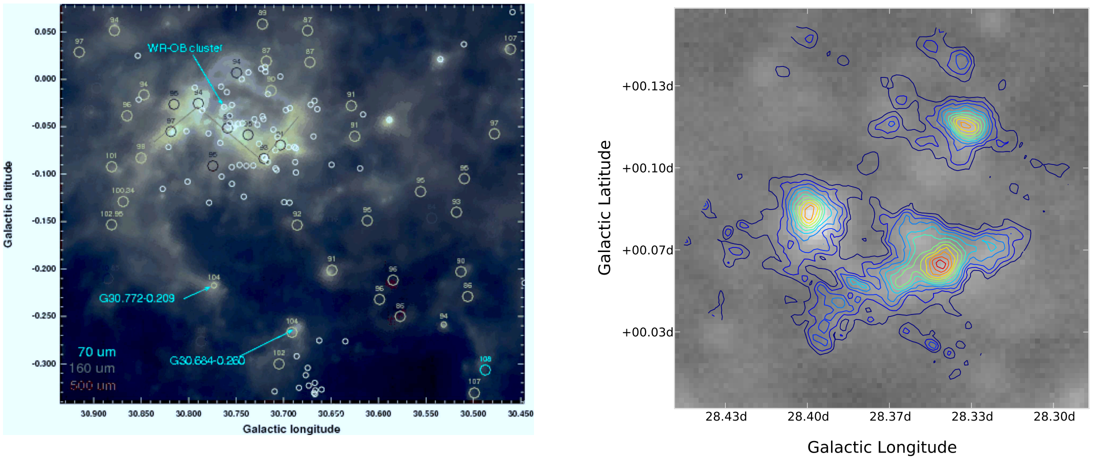

Figure 2: LEFT: Three color *Herschel* image of the W43 region with velocities indicated of clumps associated with the W43 regions determined from spectroscopic follow-up of BGPS clumps (from Bally et al. 2010). RIGHT: Integrated intensity maps ($\int T_{mb}\, dv$, 3σ contours) of G28.37+0.08 in HCO^+ 3-2 obtained with the HHT overlaid on greyscale 1.1mm images (Battersby et al. 2010). Since the excitation conditions for HCO^+ $4-3$ are not drastically different from the $3-2$ transition, we expect the $4-3$ emission to be extended and mapable. The proposed SuperCAM maps will have 25% higher spatial resolution.

in over 2000 individual clumps in this survey.

We shall directly compare molecular emission size with dust continuum sizes as well as molecular-derived virial masses with dust-derived masses (with dust temperatures derived from SED modeling of *Herschel* and BGPS photometry; see Battersby et al. 2012) for the clumps. This will be the largest dense gas to dust comparison made for the Milky Way to date and will answer fundamental questions about the total mass of dense molecular gas in our Galaxy and the stability of the dense clumps probed by the BGPS. Using estimates of size and mass, we will calculate the mass surface density of the cores (Σ grams cm^{-2}); a quantity that have been emphasized by Tan & McKee in their models of stellar accretion rate and formation timescales (2003, 2004; Tan et al. 2012).

The only way to analyze the large-scale kinematics in the clumps is through spectral line mapping observations. We will calculate the first and second moments of the HCO^+ line across the maps to constrain velocity gradients and variations of linewidth. We will also calculate a molecular linewidth-size relation (using the molecular emission to properly define the size of the clumps) for the largest sample of clumps traced by dense molecular gas. The linewidth-size relationship has been an important area of focus in 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).

Another quantity which is of considerable importance in extragalactic studies (e.g., Gao & Solomon 2004a,b, Bussmann et al 2008, Baan et al. 2008) is L' (K km/s pc^2) which is sometimes referred to as the molecular luminosity, but more appropriately it is the source-averaged surface brightness. Extragalactic studies of CO, HCN and HCO^+ emission have found a range of slopes from 0.7 to 1.4 for L_{IR} - L$'$ correlations that appear to depend on the critical density of the tracer (Narayanan et al. 2008, Juneau et al. 2009; Schenck et al. 2011). The popularity of HCO^+ as a dense gas tracer among extragalactic researchers is growing (e.g. Gracia-Carpio et al. 2008). We shall determine the most complete estimate of L' is the Milky Way in a dense gas tracer.

The SuperCAM galactic plane survey will also directly address another major problem in studies of high-mass star formation - the difficulty of identifying a coherent evolutionary sequence for high-mass star formation. While a well developed spectral energy distribution-based (SED) evolutionary sequence (Prestellar, Class 0 - III) exists for low-mass protostars (André et al. 2000), there is still much confusion in interpreting the evolutionary signposts for high-mass star formation. Because high-mass star forming regions are generally more turbulent, more clustered, and less well resolved than nearby low-mass regions, determining the evolutionary state of a high-mass clump requires the synthesis of more information than the SED alone can provide (Motte & Hennebelle 2008). Recently, evolutionary stages have been proposed to categorize the SED shape of high-mass clumps while using combinations of the presence or lack of 24 μm point sources, centimeter radio continuum, extended 4.5 μm emission (EGOs; Cyganowski et al. 2009), and H_2O and CH_3OH masers (Chambers et al. 2009, Battersby et al. 2010). This survey will provide a unique opportunity to study, systematically, how the properties of the dense gas in the cores varies with the evolutionary signposts. The complete sample of mapped cores will be unparalled because it spans a large range of evolutionary stages and represents a much more unbiased sample of core than has ever been previously mapped in dense molecular gas tracers (i.e. Shirley et al. 2003, Beuther et al. 2002).

The SuperCAM HCO^+ Galactic plane survey will be observed from November to March when $\tau_{225} < 0.15$ for 50% of the observing time. Only a fraction of the total 90 square degrees would need to be mapped because the BGPS 1.1 mm emission does not fill the entire first quadrant (see Fig. 4 for an example of one of the more crowded regions). Using the 1.1mm emission to define mapping regions, only $\sim$ 36 sq. deg. needs to be mapped. Using the results from May 2012 SuperCAM tests indicate that for a typical $T_{sys} = 500$ K, a $20' \times 20'$ region may be mapped down to a reasonable limit of 0.1 K rms in 2.5 hours (including moving and calibration overhead). Since many of the BGPS clumps are collected together or clumped within larger filamentary structures, the shape of the mapped region of ≈ 400 square arcminutes will be adjusted to match each region. The entire survey will be completed in 100 observing shifts covering the 15h - 23h LST range. The SuperCAM backend has 1 GHz of bandwidth for each pixel, more than sufficient to detect HCO^+ at all velocities in the Galaxy. Due to scheduling constraints and weather, we expect it will take at least two observing seasons to complete the survey.

2 Results from Prior NSF Support

Y. Shirley has been PI or Co-I on three NSF grants; here they are presented 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 released in the fall of 2012. Co-I Jason Glenn in collaboration with graduate student Tim Ellsworth-Bowers are developing distance probability functions which will be used to statistically characterize the distance ambiguity for BGPS sources with dense molecular gas detections. The paper from the pilot spectroscopic survey of 1882 sources was accepted (Schlingman et al. 2011) and highlights from the characterization of the BGPS clumps properties are shown in Fig. 8. The Schlingman et al. subsample was derived from a flux limited sample of BGPS clumps. 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

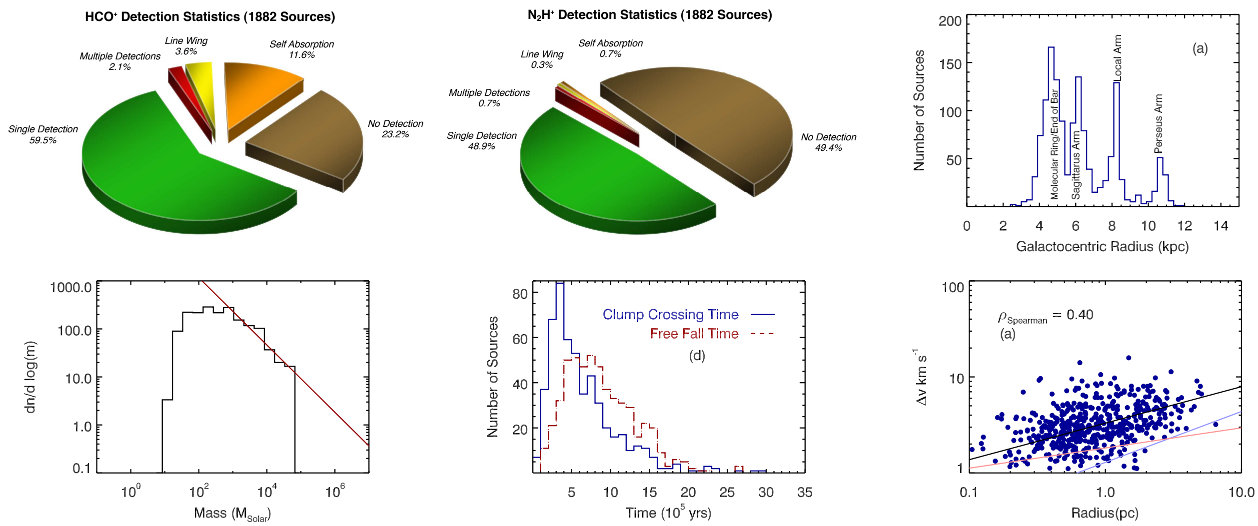

Figure 3: Scientific highlights from the BGPS Spectroscopic followup. CLOCKWISE FROM TOP LEFT: (1,2) Detection statistics for 1882 sources observed in HCO^+ and N_2H^+ 3-2 in the initial spectroscopic followup to the BGPS (Schlingman, Shirley, et al. 2011). Over $3/4^{th}$ of BGPS continuum sources show 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).

CO clouds. The slope of the observed clumps mass spectrum is intermediate between the slopes observed for CO clumps and the Salpeter IMF.

(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 a 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 is most recently worked with Stephen Jasso on a study of the properties of dense molecular gas in the nearby California Molecular Cloud. Stephen obtained 12m observations of CS 2-1 and 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.