Project Description

We propose to use a combination of archival and new observations at infrared, radio, and millimeter/submillimeter wavelengths to identify and characterize "proto-molecular clouds" in the Galaxy. Such a study would have a significant impact on our understanding of the initial conditions of star formation, galactic evolution and the interstellar medium of external galaxies. The proposed work will:

1. Produce a catalog of regions in the Galaxy where molecular cloud formation may be occurring, using archival infrared, CO and HI data.
2. Directly measure the abundance and excitation of H_2, C and CO relative to infrared dust extinction & far-IR dust emission for each candidate "protocloud".
3. Aim to provide initial statistics to determine which mechanism of cloud formation is most prevalent in the Galaxy.
4. Present a "finder chart" of cloud formation for future submm/THz/far-infrared observatories such as SOFIA, ALMA, and Herschel.
5. Provide unique opportunities for public outreach and education, with regard to interactive online content, to programs for local schools, summer camps and (under)graduate student research projects.

1 Introduction

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

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

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

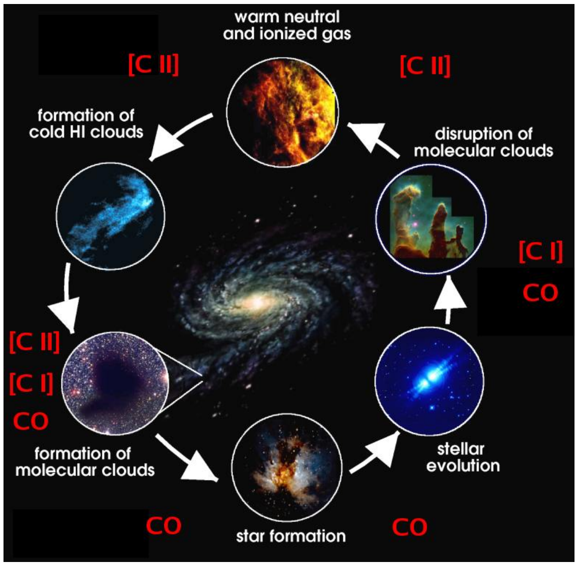

Figure 1: Life Cycles of the ISM

The life cycle of interstellar clouds is summarized pictorially in Figure 1. These clouds are largely comprised of atomic & molecular hydrogen and atomic helium. These species are notoriously difficult to detect under normal interstellar conditions. Atomic hydrogen is detectable via the 21 cm spin-flip transition and provides the observational basis for current models of a multi-phase Galactic ISM (Kulkarni & Heiles, 1987). Its emission is insensitive to gas pressure 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 rarer trace elements. Carbon, for example, is found in ionized form (C^+) in neutral clouds, eventually becoming atomic (C), then molecular as carbon monoxide (CO) in dark molecular clouds (Figure 2).

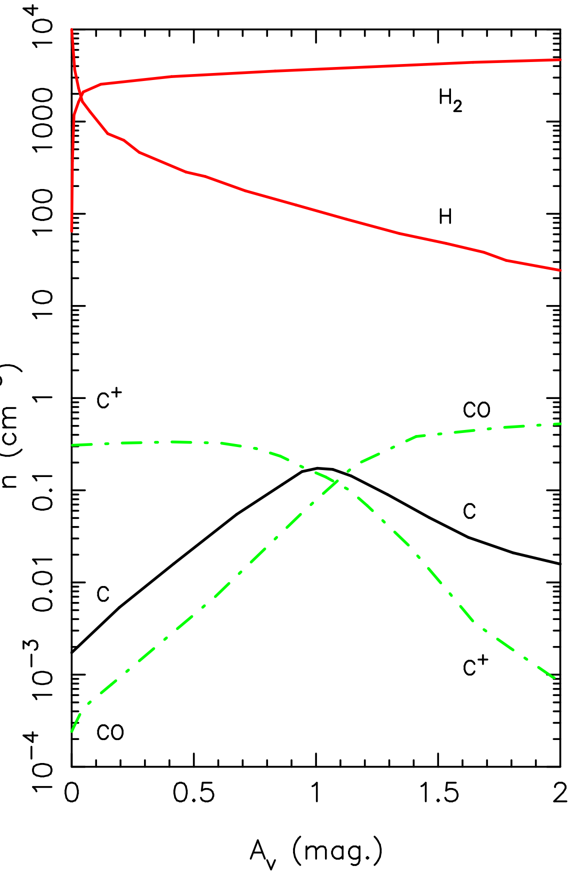

Figure 2: Steady state depth dependence of hydrogen and carbon species abundances in a typical molecular cloud exposed to the local interstellar radiation field. The HI–H_2 interface occurs long before the C^+–C–CO interface, leaving diffuse and translucent material whose hydrogen is fully molecular, but whose carbon is locked up in C^+. **The depth difference between the hydrogen and carbon fronts INCREASES with the external radiation field strength and with decreasing cloud age.**

The latter of these, the CO molecule, is the most prevalent gas-phase tracer of molecular clouds. Since its first measurement via millimeter-wave spectroscopy ∼35 years ago, numerous CO surveys now provide nearly all-sky coverage and are responsible for most of what is known about the distribution, physical structure and kinematics of molecular clouds in the Galaxy.

However, because the abundance of CO stabilizes only at significant cloud depths where hydrogen is already molecular (Figure 2), it makes an ineffective probe of the formative and disruptive stages of a cloud's life cycle. **Thus, despite great efforts and millions of CO spectra, the conclusive birth of a molecular cloud has never been identified!** Indeed, although we are now beginning to understand the formation of stars, the formation, evolution and destruction of their parent molecular clouds still remains (literally) shrouded in uncertainty.

The need to understand the evolution of interstellar clouds in the context of the initial conditions of star formation has become acute – driven by the advent of detailed infrared studies of external galaxies, the expectation of soon detecting the "first light" from primordial star-forming galaxies at high redshift, and the ever-increasing numerical resolution of galaxy simulations requiring better constraints on ISM physics. The National Research Council's most recent *Decadal Survey* has identified the study of star formation as one of the key recommendations for new initiatives in this decade. Similarly, understanding the processes that give rise to star and planet formation represent the central theme of NASA's ongoing Origins program.

1.1 Signposts of Molecular Cloud Formation

Theories of cloud formation are guided and constrained by observations of the atomic and molecular gas components. Based primarily on HI and CO observations, several mechanisms have been proposed to consolidate gas into GMC complexes (Figure 3): (1) gravitational-magnetothermal instabilities within the diffuse gas component, (2) collisional agglomeration of small atomic or molecular clouds, (3) accumulation of material within high pressure environments such as rings and shells generated by OB associations, and (4) compression in the randomly converging parts of a turbulent medium.

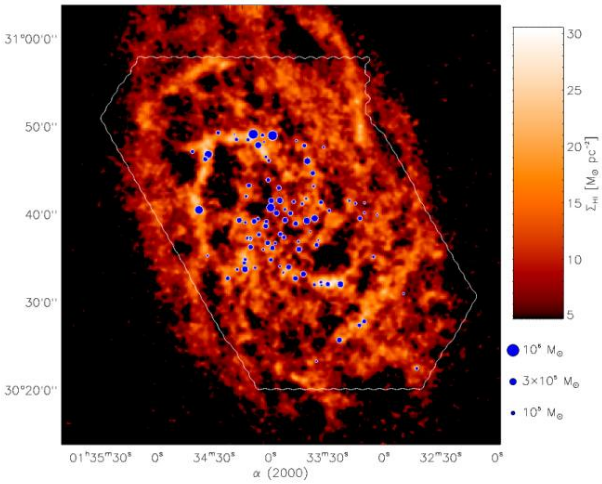

Figure 3: The location of GMCs in the nearby spiral galaxy M33 are overlaid upon an integrated intensity map of the HI 21 cm line (Engargiola, Plambeck, Rosolowsky, & Blitz, 2003). These observations show that GMCs are formed from large structures of atomic gas, foreshadowing the detailed study of GMC formation that this study and future spectroscopic THz followup will provide in the Milky Way.

How might these mechanisms be differentiated? Clearly, a statistically-meaningful assessment of the formation of molecular clouds requires a survey of the Galactic Plane. Then, simply characterizing the Galactic environments of regions identified to be cloud-forming would be sufficient to disentangle the four principal mechanisms for Galactic cloud formation. However, identifying the environmental context of cloud formation requires a high resolution spectroscopic tracer. The role of turbulent flows, spiral arms, winds and shells, and cloud collisions are all kinematic phenomena which cannot be disentangled using continuum emission, but can be distinguished with spectroscopic imaging with ~ 1 km/s resolution.

What would a newly formed molecular cloud look like? Currently the association of diffuse gas (HI) with molecular gas (CO) is difficult owing to the large differences of emitting volumes of the HI and CO lines; that is, HI emission does not differentiate easily between cool atomic clouds and the warm diffuse ISM. However, Figure 2 shows that over a significant depth (which is larger still for newborn clouds), C and C^+ are the dominant carbon species and best spectroscopic probes of H_2 clouds with little CO. Indeed, dust lanes along the inner edges of spiral arms often show neither HI nor CO emission and are therefore likely to be in an intermediate phase; sufficiently dense and self-shielded to harbor H_2, but not CO (Wiklind et al., 1990). **This intermediate phase has received comparatively little recognition, but may play a crucial role in the sculpting of star forming clouds and thus entire galaxies!**

Future THz observatories will be able to survey the pivotal 158μm fine structure line of C^+ that will barometrically distinguish natal molecular clouds not seen in CO from diffuse atomic gas. Joined with CO, HI and infrared surveys, a dedicated THz survey telescope could advance our knowledge of star formation in the Galaxy in the following crucial ways – it would:

1. Map as a function of Galactic position the size and mass distribution and internal velocity dispersion of interstellar clouds in the Galaxy.
2. Construct the first barometric map in the Galactic Plane, the first map of the gas heating rate, and a detailed map of the star formation rate.
3. Probe the relation between the mass surface density (on kpc scales) and the star formation rate, so that we may be able to understand the empirical Schmidt Law used to estimate the star formation rate in external galaxies.
4. Reveal clouds clustering and forming in spiral arms and supershells, and fol-

low the growth of clouds to eventually shield molecules and become gravitationally bound.

5. Answer how the Galactic environment impacts the formation of clouds and stars. What are the specific roles of spiral arms, central bars, infall and other influences from outside the Galaxy?
6. Observe the formation and destruction of clouds throughout the Galaxy, and directly observe the feedback caused by supernovae and the ultraviolet radiation from massive stars.
7. Ultimately construct a Milky Way template connecting the line emission from C^+, N^+, C, CO, and dust continuum to star formation properties and state of the ISM. This template could be applied to nearby star-forming galaxies.

The importance of these fundamental measurements to a comprehensive picture of the cold ISM as it relates to star formation cannot be overstated! However the first generation of THz heterodyne instrumentation will have very limited mapping capabilities. For example – although SOFIA and Herschel will be capable of measuring 158μm [C II] spectra, they will possess heterodyne instruments with single diffraction-limited beams of 10-15$''$diameter, making large-scale mapping untenable. Two of the PI's (Walker & Kulesa) are currently performing a detailed design study under the auspices of NSF/OPP for HEAT, the High Elevation Antarctic Terahertz Telescope. A 0.5-meter telescope to be placed on Dome A (the summit of the Antarctic plateau) as early as 2009, HEAT will be dedicated to submm/THz CO, [C I] and [C II] surveys of the Southern Galactic Plane, but will still have a single 1-3$'$ spectroscopic beams at each frequency.

Clearly, in order to make significant progress forward on the topic of molecular cloud formation, it is necessary to focus the first THz observatories on specific regions of the Galaxy where cloud formation may be taking place. These "finder charts" would be based on the wealth of publically-available surveys from ground and space, in concert with new and unique ground-based instrumentation at infrared and (sub)millimeter wavelengths. It is the creation of these finder charts that is the focus of this proposed study.

2 Proposed Research Activity

2.1 *Generating Findercharts for Cloud Formation from Archival Data*

2.1.1 *Molecular Clouds at High Galactic Latitude*

This study will first hone its techniques by searching for molecular material in the diffuse ISM, a rich laboratory of molecule formation and destruction, and the putative medium from which dense molecular clouds are sculpted. The most visually stunning representations of the diffuse ISM are the far-infrared dust continuum maps of interstellar cirrus as first produced by IRAS (Low et al., 1984). Indeed, at high Galactic latitude, IRAS maps of the sky represent the most effective way to compute the combined column density of atomic and molecular hydrogen, $N_H = N(H) + 2N(H_2)$, once corrections for dust temperature, emissivity, and contamination by zodiacal dust have been applied. Such maps currently represent the best method of computing the foreground (Galactic) extinction toward extragalactic sources (Schlegel et al., 1998). After the IRAS mission, several studies aimed to assess the molecular component of high latitude clouds by accounting for the amount of infrared emission attributable to atomic gas via contemporary HI surveys. By subtracting the estimated contribution of HI gas (i.e. its associated dust) to the infrared continuum, molecular material would manifest itself as so-called "infrared excess clouds" (Desert et al., 1988; Reach et al., 1994, 1998). Several studies discovered that infrared excess clouds were fre-

Survey	Product	Location	Resolution
FCRAO Galactic Ring Survey	^{13}CO J=1-0	Galactic Plane, 1st quadrant	$45''$
FCRAO Outer Galaxy Survey	^{12}CO J=1-0	Galactic Plane, 2nd quadrant	$45''$
Bell Labs 7m GPS	^{13}CO J=1-0	Galactic Plane, 1st/2nd quadrants	$3'$
CfA/Columbia CO survey	^{12}CO J=1-0	Galactic Plane, high-z	$>10'$
HI Parkes All Sky Survey	HI 21 cm	Galactic Plane, high-z	$15'$
Southern Galactic Plane Survey	HI 21cm	Galactic Plane, 4th quadrant	$1'$
Canadian Galactic Plane Survey	HI 21 cm	Galactic Plane, 1st/2nd quadrants	$1'$
VLA Galactic Plane Survey	HI 21 cm	Galactic Plane, 1st/2nd quadrants	$1'$
Leiden-Dwingeloo HI Survey	HI 21 cm	northern sky	$30'$
GLIMPSE	3.6-8 μm IR	Galactic Plane	1-$5''$
2MASS	1-2.4 μm IR	All Sky	$3''$

Table 1: Publically-available archival surveys which will be used during the course of this study.

quently devoid of CO (Blitz et al., 1990; Reach et al., 1994; Meyerdierks & Heithausen, 1996; Lee et al., 1999; Onishi et al., 2001) and were interpreted as diffuse H_2 clouds. Indeed, this is also precisely the signature one would expect from natal molecular material!

Thus, we will extend the “infrared excess cloud” analysis of the aforementioned studies. From master maps of IRAS far-infrared emission (and Spitzer, when available), we will subtract the contribution of HI gas and the H_2 gas traced by ^{12}CO J=1-0 where both survey products are available (Table 1). Significant residual infrared excess represents H_2 gas with a comparatively weak or nonexistent CO counterpart – **a necessary signature of a newly-formed molecular cloud** that is either insufficiently UV-shielded or too chemically young to have yet formed much CO. Such residual H_2 clouds will be subdivided into two categories by the relative amplitude of the residual emission. Small excesses are likely to represent diffuse molecular clouds in which the volume and column densities are too low to support significant CO abundance and/or line excitation. Large excesses however, in which the residuals are comparable to the subtracted CO and HI emission, are more indicative of formative and transitional clouds en route to “traditional” CO-rich dark molecular clouds – and are of the greatest interest to this study.

A preliminary study was performed on the Polaris flare, a spur of infrared, CO and HI emission in the near vicinity of the North Celestial Pole. The analysis was compared to that of Meyerdierks & Heithausen (1996), and the results depicted in Figure 4. At left is plotted the CO J=1-0 emission from Dame et al. (2001), at center is the reference hydrogenic column density map of Schlegel et al. (1998), and at right is the column density map after subtraction of both the Meyerdierks & Heithausen (1996) HI map contents and CO. The northernmost clumps of emission are scarcely seen in CO, do not stand out at all above the ambient HI emission plateau, but are strongly visible in the IRAS maps (at 25, 60 and 100 μm). Thus, they remain in the subtracted plot as H_2-only clouds. The northern portion of the cloud, seen at top, has the appearance of being compressed by an old supernova remnant.

2.2 *Molecular Clouds in the Galactic Plane*

The advent of sensitive, large-scale CO J=1-0 observations to complement single-dish and interferometric HI surveys has enabled the all-sky mapping of molecular clouds and constitutes most of what is known about the overall physical structure and distribution of molecular gas in the Galaxy (Dame et al., 2001; Heyer et al., 1998; Lee et al., 2001; Jackson et al.,

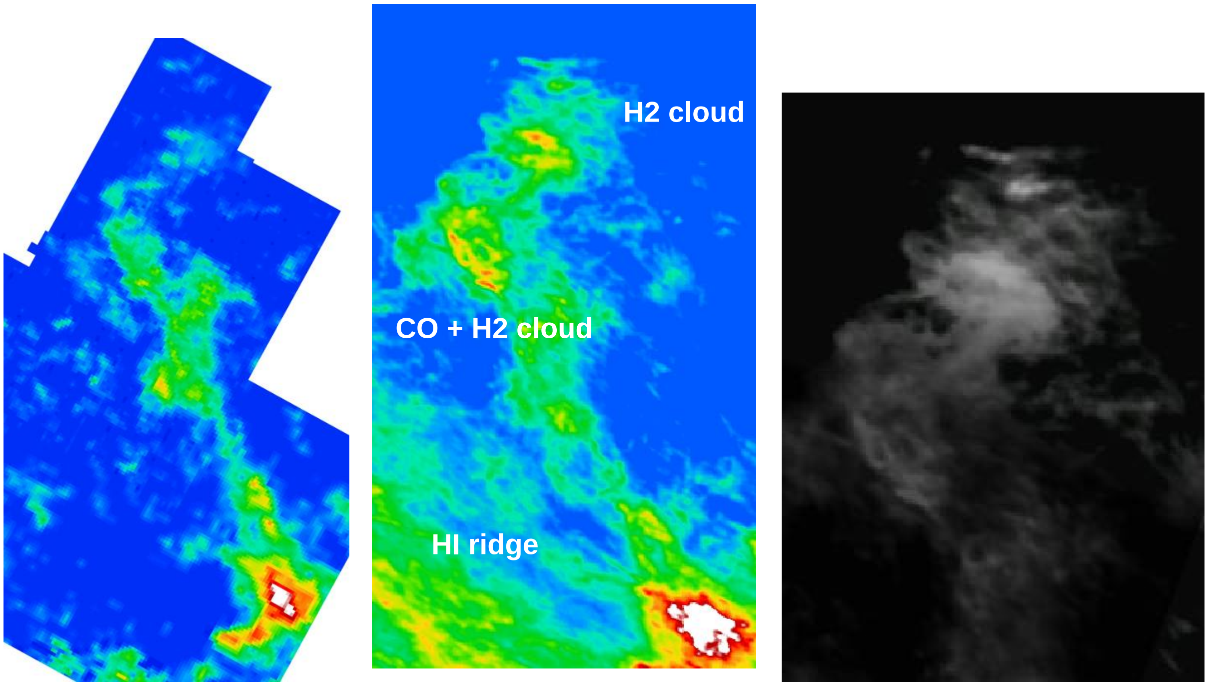

Figure 4: [LEFT] CO J=1-0 map of the Polaris Flare from the Milky Way survey of Dame et al. (2001). [CENTER] Column density map derived from the IRAS 100 μm survey (Schlegel et al., 1998), with results of preliminary analysis annotated; the peak intensity corresponds to $A_v = 7$. [RIGHT] Subtraction of HI and CO components from the column density map; leaving a residual of H_2 gas ($A_v \sim 2$) with little CO – the signature of molecular cloud formation that we will pursue in less diffuse environments elsewhere in the Galaxy.

2006). Yet, understanding how dense molecular clouds are formed from a more diffuse atomic substrate is not observationally clear, despite millions of CO spectra! Figure 2 suggests that the answer lies in the low-visual extinction (A_v) molecular component not traced by CO, since it is in an intermediate state between diffuse atomic gas and dark clouds. Thus, we will search for H_2 clouds using a similar strategy as that adopted for high latitude clouds, above. However, we will need to start with a "master hydrogen map" optimized for studies in the Galactic Plane. Although far-infrared continuum emission from IRAS and Spitzer is still applicable, systematic uncertainties in emissivity and dust temperature make the translation to gas column density problematic. However, the GLIMPSE imaging survey of the Galactic Plane from Spitzer (Benjamin et al., 2003) and the 2MASS all-sky near-infrared survey (Skrutskie et al., 2006) allows infrared extinction maps using the NICE(R) algorithm (Lada et al., 1994; Alves et al., 2001) to be directly computed and translated to gas column density via canonical extinction laws (Rieke & Lebofsky, 1985). Once derived, the highest resolution Galactic Plane survey data of HI and CO can then be applied to and subtracted from these column density maps and a residual computed. In principle, this will lead to identification of regions where both CO and HI underrepresent the state of the cold ISM and the existence of H_2 clouds with little CO can be verified. However, the plane of the Galaxy is kinematically complex – it is difficult enough to correlate CO and HI emission profiles, much less reference both quantities to an infrared-derived extinction that blindly measures the *total* absorbing column of all clouds along a given line of sight.

How will we bridge the fundamental differences between these survey data-types? First, interpreting color-color diagrams for the purpose of extinction measurements is much cleaner than at visible wavelengths, since the locus of points spanning unobscured stars is much more restricted. This makes differentiation of *intrinsic color* versus *color excess* more straightforward (Lada et al., 1994). This is particularly true when one adds the thermal infrared bands from GLIMPSE/Spitzer to the traditional J/H/K bands from 2MASS. Thus, lines of sight passing through multiple distinct spiral arms with dusty obscuration will lead to a color-color diagram with potentially distinguishable stellar loci that may be referenced kinematically to CO and HI emission. Secondly, we will accept that many regions along the Galactic Plane will be hopelessly confused and will not attempt to interpret them – the tangent arms at $l \sim 100^o$ and near the Galactic Center are likely to rank highest among these regions. We will concentrate on specific cloud complexes in the Outer Galaxy in coordination with Co-PI Bieging's ongoing CO surveys being performed at the HHT, and on regions of the Inner Galaxy with $30^o < |l| < 70^o$ and $|b| < 2^o$ where we can sample both "northern" and "southern" spiral arms and interarm regions, to help evaluate the role of the Galactic environment on potential sites of cloud formation. Finally, we will definitively differentiate gas and dust properties along complex lines of sight using ground-based high resolution infrared absorption line spectroscopy; discussion will follow in Section 2.3.1.

2.3 *Ground-Based Studies of Candidate Cloud Formation Regions*

Pathfinding studies using archival data surveys of CO and HI line emission coupled with near- and far-infrared continuum maps will provide a sample of regions suggestive of molecular cloud formation. Future THz observatories will be able to observe [C II] line emission toward these regions and, with knowledge of the contribution of hot ionized gas to the [C II] line intensity, will directly measure the interstellar pressure of H_2 clouds with little CO. These measurements will yield not only diffuse clouds with H_2 but will also yield the direct observation of bound molecular clouds forming from an atomic substrate.

However, the archival catalog of "protoclouds" can be improved in quality with selected ground-based observations that supplement and calibrate the rather disparate archival survey products, and provide fundamental new constraints on molecular cloud structure. We aim to do this in two diverse ways using unique instrumentation developed (in part) by this team of proposers at the University of Arizona:

1. Infrared absorption line spectroscopy will relate dust extinction to a directly-measured abundance of CO and H_2 for lines of sight spanning diffuse, translucent, and dense clouds throughout the Galaxy.
2. (Sub)millimeter wave mapping of higher excitation CO lines at the Arizona 10-meter Heinrich Hertz Telescope (HHT) will provide a complete excitation analysis that will dramatically enhance the interpretation of CO line emission and will improve upon the archival datas' angular resolution by up to an order of magnitude in many cases.
3. Measurement of carbon recombination lines at both infrared and submillimeter wavelengths will allow the fine structure level populations of C^+ to be measured – yielding *in advance of THz observations* the expected brightness and abundance of C^+ emission toward the most favorable lines of sight.

Figure 5: [LEFT] The purple imager and green spectrometer halves of ARIES, the `Arizona Infrared Imager and Echelle Spectrometer`, slated for first light at the adaptive optics focus of the 6.5-meter MMT in December 2006. [RIGHT] `Supercam`, a 64-beam heterodyne receiver operating in the 345 GHz atmospheric window, slated for the HHT. Both instruments are one-of-a-kind and dovetail into the proposed science program.

2.3.1 *Infrared Spectroscopy of Protoclouds*

Although most interstellar molecules have been detected through millimeter-wave emission-line spectroscopy, this technique is inapplicable to non-polar molecules like H_2 (among others) which are central to our understanding of the structure and contents of molecular clouds and interstellar chemistry. **Thus high-resolution infrared spectroscopy plays an important but often unrecognized role in interstellar studies: significant non-polar molecules like H_2 can be directly observed alongside "common" molecules like CO, and their abundances and excitation conditions can be referred to the same "pencil-beam" absorbing column that gives rise to interstellar extinction.** With sufficient resolution and sensitivity, the long-sought relation connecting extinction, H_2, ^{12}CO and ^{13}CO can be conclusively and *directly* measured in dense clouds (Scoville et al., 1983; Black et al., 1990; Lacy et al., 1994; Kulesa & Black, 2002, 2006) as it has been in diffuse clouds (Bohlin, Drake & Savage, 1978). Figures 6 and 7 demonstrate the absorption line measurements of ^{12}CO and H_2 that this study will undertake.

ARIES, the Arizona Infrared Imager and Echelle Spectometer, is nearing completion as an adaptive optics instrument for the Arizona/SAO 6.5-meter MMT (McCarthy et al., 1998) and has the unique blend of high resolution ($\lambda/\Delta\lambda = 30,000 - 60,000$) and broad (cross-dispersed) simultaneous wavelength coverage needed for this project. The PI of this effort is on the ARIES instrument team. ARIES will be used at the 6.5-meter MMT to perform 1-5 μm absorption line spectroscopy of a sample of lines of sight through diffuse, translucent and dense (formative) clouds in the Galaxy. Near the Galactic Plane, extinction measurements through complex lines of sight will be kinematically distinguished in H_2 and ^{12}CO line absorption at 2.1-2.3 μm with 5 km s^{-1} resolution, and directly comparable

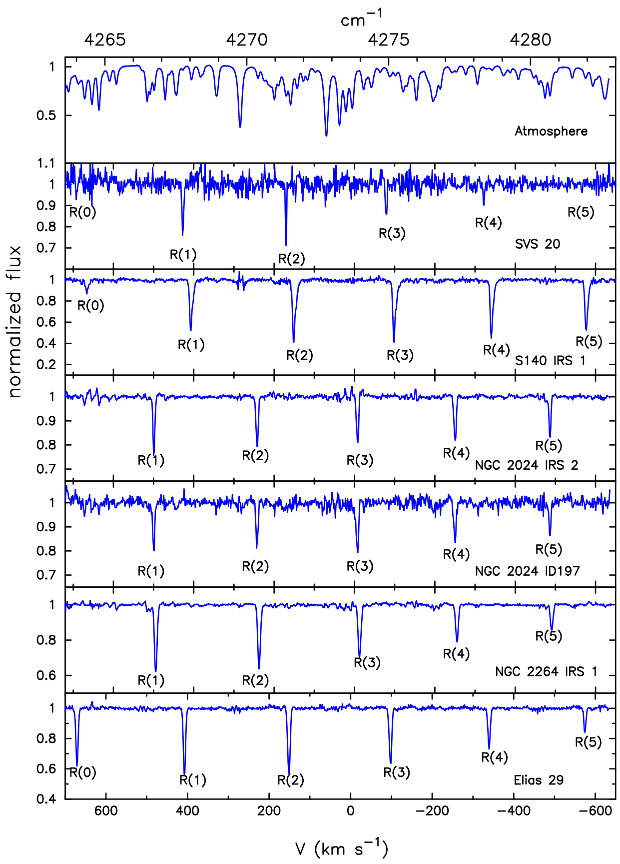

Figure 6: Spectra of ^{12}CO in the (2,0) R-band; R(0) through R(5). The uppermost spectrum is a typical comparison spectrum of the B2V star β_1 Sco that depicts the atmospheric transmission. The spectra are the ratioed (corrected) spectra of obscured (young) stellar objects that demonstrate prominent ^{12}CO absorption. The observed velocity shifts are due to the orbital motion of the Earth along the line of sight. These data were taken with the NOAO Phoenix spectrometer on the KPNO 2.1-meter telescope.

with radio measurements of CO and HI emission. Toward diffuse lines of sight where the intrinsically weak H_2 lines cannot be measured, ^{12}CO can still be observed in its fundamental ro-vibrational bands at 4.6 μm and compared with its radio counterpart (Mitchell et al., 1989).

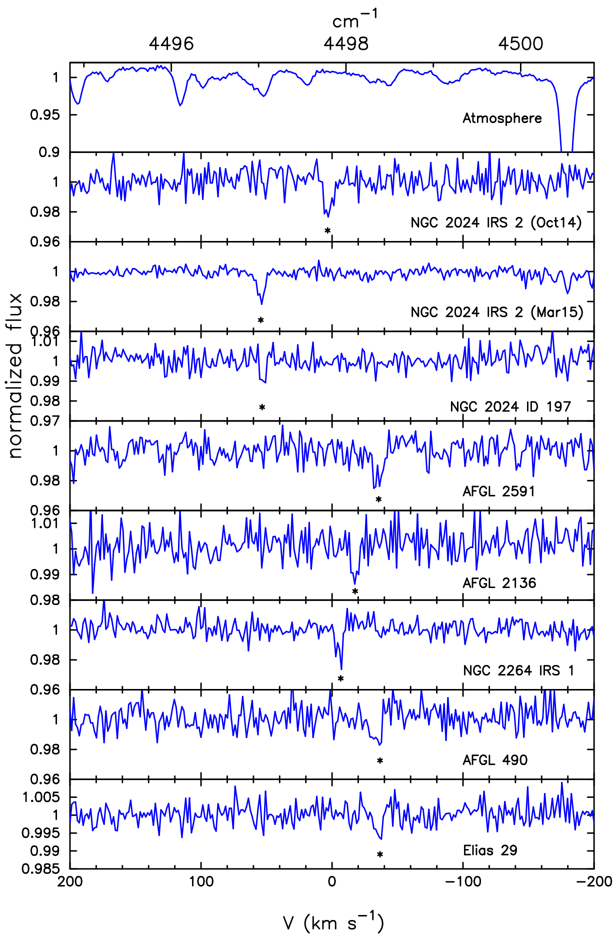

Figure 7: Direct measurements of H_2 line absorption in dark molecular clouds: the top plot represents the atmospheric transmission, ratioed astronomical spectra follow. The quality of the spectra obtained toward NGC 2024 IRS 2 at two different epochs can be compared to the landmark observations performed by Lacy et al. (1994). Asterisks show the $V_{\rm LSR}$ of CO absorption in each source.

2.3.2 *Submillimeter Spectroscopy of Protoclouds*

Molecular line surveys have been performed over the entire sky in the light of the 2.6 millimeter J=1-0 lines of ^{12}CO and ^{13}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, since the J=1-0 lines are much less sensitive to warm, low-opacity, high velocity

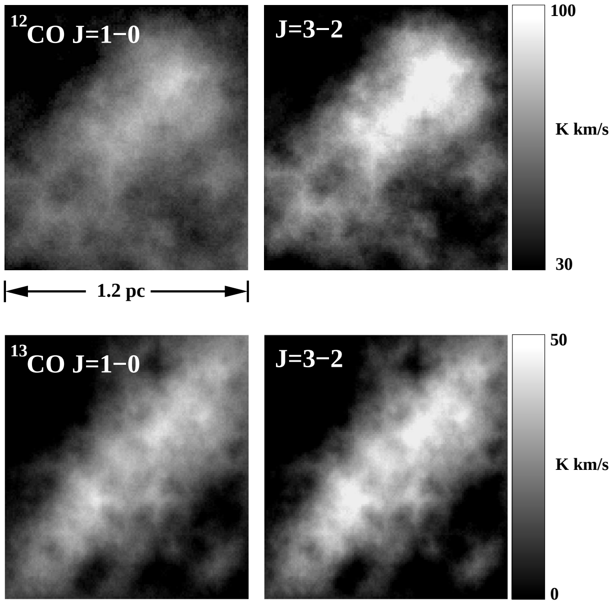

Figure 8: Simulated image of a fractal molecular cloud in several CO transitions shows the need for submillimeter CO lines. The energetic gas that interacts with stars is far better probed by the $3-2$ lines, however both $1-0$ and $3-2$ lines are needed together to extract a comprehensive understanding of cloud properties, dynamics & evolution.

gas such as produced by outflows, photodissociation regions (PDRs), and shocks. This point is illustrated in Figure 8, 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 star and cloud excitation, temperature and chemical abundances are determined self-consistently using Monte Carlo methods. The integrated spectral line images show that the heated portion of the cloud is largely missed by the J=1-0 lines, but captured by the J=3-2 lines. Reconstruction of the cloud based on observation of the ^{13}CO J=1-0 line alone recovers only 60% of the total cloud mass, whereas the combination of J=1-0 and J=3-2 lines recovers 90% of the H_2 mass.

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 of greatest interest to our posed questions – it is the *energetic* gas that 1) participates in disruptive 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 provide the dynamic range of excitation needed to interpret cloud properties from existing CO J=1-0 observations.

Unique new (sub)millimeter instrumentation offers new capabilities for mapping candidate regions. Walker and Kulesa are PI and Co-PI (respectively) of the *Supercam* instrument, a 64-beam heterodyne array for spectroscopic imaging in the 345 GHz atmospheric window (Groppi et al., 2006). When Supercam is completed in 2007, it will be the largest submillimeter heterodyne array in the world and will be capable of mapping CO J=3-2 with unprecedented speed and sensitivity (e.g. 3 hours per square degree of coverage). On the 10-meter Heinrich Hertz Telescope (HHT), Supercam will have angular resolution of $20''$ per diffraction-limited beam.

The HHT is now home to the world's most sensitive 230 GHz receiver. Equipped with prototype Band 6 ALMA mixers from NRAO, the facility receiver now offers simultaneous detection of the ^{12}CO and ^{13}CO J=2-1 lines with many times the sensitivity of the previous receiver system. System temperatures of 100K (SSB) have been measured in moderate weather conditions on Mt. Graham.

Using such unique instrumentation, we will map candidate cloud formation regions in ^{12}CO and ^{13}CO J=2-1 and 3-2 line emission much more sensitively, and with much higher angular resolution than provided by archival survey data. For high latitude clouds, these measurements of minute quantities of CO will directly measure the temperature and density of the cloud regions and confirm whether the molecular gas is likely to be diffuse and tenu-

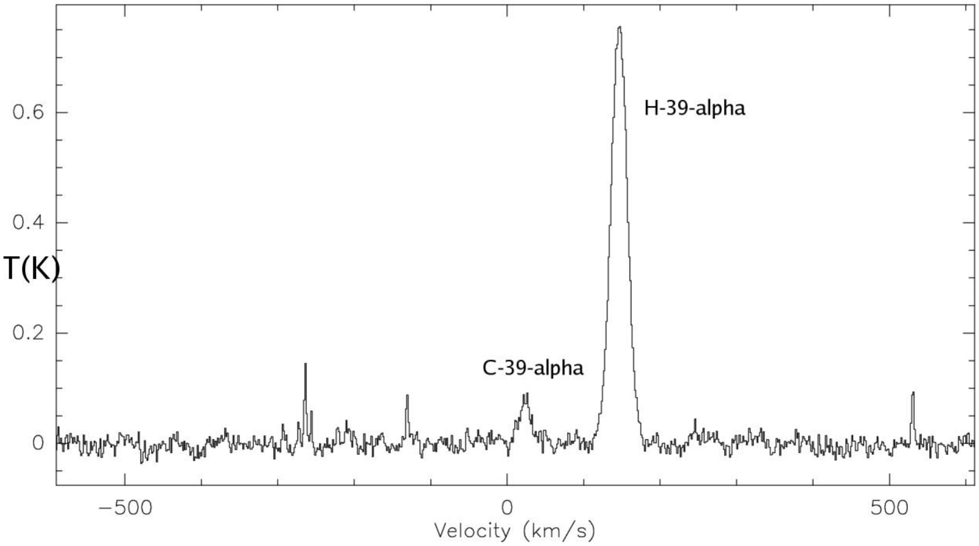

Figure 9: First detected carbon recombination line spectrum at mm-wavelengths, taken toward the northernmost edge of the Orion Molecular Cloud. The 39α lines of hydrogen and carbon are observed adjacent to each other in this spectrum at 106.8 GHz = 2.8 mm, taken at the Arizona (formerly NRAO) 12-meter. Analysis of multiple recombination lines allows reverse-construction of the C^+ level populations and 158 μm line intensity.

ous, or transitioning toward more dense and self-gravitating clouds. Toward the Galactic Plane, the higher excitation conditions of the (sub)millimeter lines will better diagnose the translucent surfaces of molecular clouds, reveal the full excitation and column density of CO and thereby better constrain its formative state.

Finally, toward regions that seem to possess all of the proper characteristics of newborn molecular clouds, we will attempt to ascertain the state of carbon in forms *other* than CO. We will measure the fine structure line of atomic carbon in its (^{3}P) J=1-0 transition at 492 GHz and measure multiple radio recombination lines of carbon from 70 GHz (using the Arizona 12-meter) to 230 GHz (using the HHT). Just as optical recombination lines of hydrogen (e.g. H-α) probe *hydrogen-ionized regions*, radio recombination lines of carbon can probe *carbon-ionized regions* in which the hydrogen may be fully molecular but the carbon has had insufficient time or UV-shielding to transform into CO. Although the radio recombination lines are at least one order of magnitude less sensitive than far-infrared spectroscopy of 158 μm [C II] emission, both line emission strengths are density-sensitive and will therefore be able to discern H_2 *clouds* from *diffuse* H_2 *gas*. Thus, it may be possible to ascertain the state of C^+ and the internal pressure of the cloud in advance of regular THz observations – at least toward the most favorable lines of sight. The PI has performed test observations of the technique toward the northernmost portion of the Orion Molecular Cloud using the Arizona 12-meter; the first millimeter-wave detection of carbon recombination lines is shown in Figure 9. The direct measurement of hydrogen recombination lines in the same bandpass allows the warm ionized gas component of the C^+ emission to be directly measured and corrected for.

3 Summary

This study aims to advance the observational study of cloud formation in the Galaxy in advance of the first focused THz observatories which, coupled with this work, should soon be able to address these questions even more directly and conclusively. The results of this study will be a finder chart of candidate "protoclouds" that will be well-characterized with fundamental and new observations of dust extinction, CO and H_2. These additions will dramatically advance our knowledge of the molecular ISM in their own right. This study bears important implications for the theoretical/numerical modeling of galaxy evolution and to unresolved cloud and star formation in distant galaxies, highlighting its broad applicability to topics that are both fundamental and timely.

4 Educational Outreach and Broader Impact

The broadest impact of the proposed research however may be drawn from the use of these surveys as educational and outreach tools. The visage of the dusty lanes of the Milky Way has inspired artistic and scientific imaginations for generations. Indeed, a project that encompasses so much of the entire sky offers numerous opportunities to capture the imagination of students of all ages and persuasions. 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. Specifically, this proposal will target (1) web-based and local (ex. grade school) public outreach, (2) guiding undergraduate students toward a greater appreciation and hands-on understanding of science and its methods, and (3) training graduate students through innovative research, and presentation of research results to the general public and astronomical community. These notions are outlined below.

4.1 Web-based Outreach

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 would be a useful, if indirect way of reaching the widest 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 in the confines of this study. A practical application would be, for example, to present a view onto the multi-wavelength Universe using existing planetarium software. For example, Stellarium (`http://www.stellarium.org/`) is a visually stunning, 3D, open source planetarium package for Linux/BSD Unix/Macintosh/Windows (Figure 10. Writing a plugin to allow the user to put on different wavelength "glasses" to view the IRAS 100 μm sky in place of the visible one – or CO J=1-0 or HI 21 cm emission, is a tractable possibility and could be used to visualize the Galaxy in new ways with a minimum of distracting software efforts.

4.2 Summer Outreach Programs for Teens

The PI is a long-time counselor for the University of Arizona Alumni Association's Astronomy Camp for adults and teens (`http://www.astronomycamp.org/`). In particular, the advanced teen camps in the summer present a gender-balanced group of $\sim$30 motivated high school students with the opportunity of becoming real astronomers for a week; they live in astronomer's dorms at the summit of Mt. Lemmon Observatory, devise astronomical research programs, write telescope proposals, perform observations, reduce their data and present their results to the group. Many of them continue their research

Figure 10: Open source planetarium software such as `stellarium` represent useful tools with which maps of the sky at other wavelengths can be rendered.

long after Camp concludes. Some of the earliest teen campers from the early 1990's have completed their Ph.D's in astronomy and other scientific fields! In concert with this study, we would integrate archival data of HI, CO and extinction into a uniform MySQL database that students could query and implement in their own projects – just as the investigators will do for the principal science program!

4.3 Undergraduate and Graduate Student Guidance and Training

The formal education of undergraduate students occurs through both the traditional classroom setting and through undergraduate research. However, the crucial role of creative inquiry in the development of a scientist is often better served outside the classroom. Since archival data is already pre-reduced, one can concentrate on more creative science-oriented problems; tasks particularly well suited for undergraduates or even first-year graduate students who are also new to astronomy. Similarly, advising graduate students is an essential role of University educators, because it is here where the next generation of professional scientists is prepared. This grant will support a portion of a graduate student's salary. Travel to scientific meetings is particularly important for graduate students – thus funding is requested to take a graduate student to at least one national meeting in the 2nd and 3rd years.

5 Prior NSF Support

This is the first proposal that PI Kulesa has authored to NSF/AST. He is a Co-PI on two ongoing instrumentation programs; *Supercam*, a 64-beam heterodyne array for the HHT (C. Walker, PI) funded through an NSF MRI grant (2004-2007), and the High Elevation Antarctic Terahertz Telescope (HEAT), a design study for an automated 0.5-meter THz telescope for Dome A, the summit of the Antarctic plateau, funded (only) for 2006 through NSF's OPP program. Both programs are ongoing and play an integral role in the definition of this proposed scientific endeavor.

References

Alves, J. F., Lara, C. J., & Lada, E. A., "Internal structure of a cold dark molecular cloud inferred from the extinction of background starlight", 2001, Nature, 409, 159

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

Black, J. H., van Dishoek, E. F., Willner, S. P., & Woods, R. C., "Interstellar absorption lines toward NGC 2264 and AFGL 2591 - Abundances of H2, H3(+), and CO", 1990, ApJ, 358, 459

Blitz, L., Bazell, D., & Desert, F. X., "Molecular clouds without detectable CO", 1990, ApJL, 352, L13

Bohlin, R. C., Savage, B. D., & Drake, J. F., "A survey of interstellar H I from L-alpha absorption measurements. II", 1978, ApJ, 224, 132

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

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., "The Milky Way in Molecular Clouds: A New Complete CO Survey", 2001, ApJ, 547, 792

Desert, F. X., Bazell, D., & Boulanger, F., "An all-sky search for molecular cirrus clouds", 1988, ApJ, 334, 815

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

Groppi, C., et al., "SuperCam: a 64-pixel heterodyne imaging array for the 870-micron atmospheric window", 2006, Proc. SPIE, 6275, 20

Heyer, M. H., Brunt, C., Snell, R. L., Howe, J. E., Schloerb, F. P., & Carpenter, J. M., "The Five College Radio Astronomy Observatory CO Survey of the Outer Galaxy", 1998, ApJS, 115, 241

Jackson, J. M., et al., "The Boston University-Five College Radio Astronomy Observatory Galactic Ring Survey", 2006, ApJS, 163, 145

Kulesa, C. A. & Black, J. H., "Abundances and Excitation of H2, H3+ & CO in Star-Forming Regions", 2002, Chemistry as a Diagnostic of Star Formation, 60

Kulesa, C. A. & Black, J. H., "Direct Measurement of Molecular Hydrogen and its Ions in Dark Interstellar Clouds and Star-Forming Regions", submitted to ApJ, 2006, estd. publication 3/2007

Kulkarni, S., & Heiles, C., "The Atomic Component", 1987, "Interstellar Processes", eds. Hollenbach & Thronson, Reidel Publishing: Dordrecht.

Lacy, J. H., Knacke, R., Geballe, T. R., & Tokunaga, A. T., "Detection of absorption by H2 in molecular clouds: A direct measurement of the H2:CO ratio", 1994, ApJL, 428, L69

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

Lee, J.-E., Kim, K.-T., & Koo, B.-C., "Infrared Excess and Molecular Gas in Galactic Supershells", 1999, Journal of Korean Astronomical Society, 32, 41

Lee, Y., Stark, A. A., Kim, H.-G., & Moon, D.-S., "The Bell Laboratories 13CO Survey: Longitude-Velocity Maps", 2001, ApJS, 136, 137

Low, F. J., et al., "Infrared cirrus - New components of the extended infrared emission", 1984, ApJL, 278, L19

McCarthy, D. W., Burge, J. H., Angel, J. R. P., Ge, J., Sarlot, R. J., Fitz-Patrick, B. C., & Hinz, J. L., "ARIES: Arizona infrared imager and echelle spectrograph", 1998, Proc. SPIE, 3354, 750

Meyerdierks, H., & Heithausen, A., "Diffuse molecular gas in the Polaris flare", 1996, A&A, 313, 929

Mitchell, G. F., Curry, C., Maillard, J.-P., & Allen, M., "The gas environment of the young stellar object GL 2591 studied by infrared spectroscopy", 1989, ApJ, 341, 1020

Onishi, T., Yoshikawa, N., Yamamoto, H., Kawamura, A., Mizuno, A., & Fukui, Y., "A Survey for High-Latitude Molecular Clouds toward Infrared-Excess Clouds with NANTEN", 2001, PASJ, 53, 1017

Reach, W. T., Koo, B.-C., & Heiles, C., "Atomic and molecular gas in interstellar cirrus clouds", 1994, ApJ, 429, 672

Reach, W. T., Wall, W. F., & Odegard, N., "Infrared Excess and Molecular Clouds: A Comparison of New Surveys of Far-Infrared and HI 21cm Emission at High Galactic Latitudes", 1998, ApJ, 507, 507

Rieke, G. H., & Lebofsky, M. J., "The interstellar extinction law from 1 to 13 microns" 1985, ApJ, 288, 618

Schlegel, D. J., Finkbeiner, D. P., & Davis, M., "Maps of Dust Infrared Emission for Use in Estimation of Reddening and Cosmic Microwave Background Radiation Foregrounds", 1998, ApJ, 500, 525

Scoville, N., Kleinmann, S. G., Hall, D. N. B., & Ridgway, S. T., "The circumstellar and nebular environment of the Becklin-Neugebauer object - 2-5 micron wavelength spectroscopy", 1983, ApJ, 275, 201

Skrutskie, M. F., et al., "The Two Micron All Sky Survey (2MASS)", 2006, AJ, 131, 1163

Wiklind, T., Rydbeck, G., Hjalmarson, A., & Bergman, P., "Arm and interarm molecular clouds in M 83", 1990, A&A, 232, L11