C Project Description

1 Results from Prior Support

AST/RO [Stark *et al.* 2001]

2 Research Activities

2.1 Overview

The internal evolution of galaxies, from the Milky Way to the earliest protogalaxies, is defined by three principal ingredients that closely relate to their interstellar contents:

1. the transformation of neutral, molecular gas clouds into stars and star clusters (star formation).
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 (the stellar population 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 the nascent stars they spawn.

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 at 1420 MHz, but because the emission line is insensitive to gas density, cold (T$\sim$70K) atomic clouds are not distinguishable from the warm (T$\sim$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.

In general, however, only global properties can be gleaned from the coarse spatial resolution offered by studies of external galaxies. Therefore detailed interstellar studies of the widely varying conditions in our own Milky Way Galaxy serve as a crucial diagnostic template or "Rosetta Stone" that can be used to translate the global properties of distant galaxies into reliable estimators of star formation rate and state of the ISM. These studies are very incomplete, however. 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 has become acute. The National Research Council's most recent Decadal Survey, under the the advisory of a distinguished committee, 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.

New, comprehensive surveys of Galactic clouds must address the following questions to make significant progress toward a complete and comprehensive view of Galactic star formation:

- How do molecular clouds form, evolve, and get disrupted? How do typical atoms and grains cycle through the ISM?
- How and under what conditions do molecular clouds form stars?
- How do the energetic byproducts of stellar birth, UV radiation fields and (bipolar) mass outflows regulate further star formation in molecular clouds?

- How does the Galactic environment impact the formation of clouds and stars? What are the specific roles of spiral arms, central bars, and infall and other influences from outside the Galaxy?

To these questions the AST/RO facility brings crucial and unique capabilities. It provides an established suite of leading-edge single- and multi-beam receivers from 200 to 1300 μm, an optimized and reliable antenna with high aperture efficiency, and the most stable and transparent submillimeter sky of any established observing site on Earth. Here, we present two Key Projects for the duration of this proposal that maximize AST/RO's impact upon contemporary datasets from the ground and space.

2.2 Key Project 1: Comprehensive Mapping of Southern Clouds in the "C2D" Spitzer Legacy Survey

The Spitzer Space Telescope (SST) supports six "Legacy" programs that will provide public datasets of wide astronomical interest within the first 18 months of operation. One of these programs, entitled "From Molecular Cores to Planet-Forming Disks" (C2D) and headed by Neal Evans will explore five diverse molecular clouds in detail, with the aim of probing crucial steps in the formation of stars and planets. Broadband far-infrared imaging will probe the dust structure of the clouds themselves, and near infrared imaging will provide a census of of the star forming activity in these clouds.

While the Spitzer approach adds crucial new observations of star-forming clouds, ground-based supporting observations will greatly enhance their interpretation. This point is perhaps no better made than by the "COordinated Molecular Probe Line Extinction and Thermal Emission" (COMPLETE) survey initiated by Alyssa Goodman. COMPLETE aims to fill crucial gaps in the C2D dataset: (1) the Spitzer continuum studies probe optically thick dust and saturates the MIPS 160 μm detector. COMPLETE provides optically thin tracers of interstellar dust at submillimeter wavelengths, constraining the spectral energy distribution (SED) and providing a more reliable estimate of the dust column density. (2) Spitzer provides no systematic tracer of the dominant gas component in these clouds. COMPLETE molecular line observations in the J=1→0 transition of CO and ^{13}CO are used to determine how well the gas and dust track each other, and provide kinematic information about the clouds, which are unconstrained by the Spitzer observations of the infrared dust continuum. These studies will measure the kinematic structure of clouds and star forming regions, measure the interface and relationship between interstellar turbulence, (coherent) protostellar infall and (disruptive) outflow.

The combination and coherency of these observations, and their importance to the proper derivation of the properties of star formation, cannot be overestimated. Indeed, the C2D Legacy Survey which COMPLETE was designed to complement was proposed on the grounds that "our understanding of star formation is hampered by the lack of complete databases for systematic studies" (Evans, private communication). The coordination of line, continuum and extinction surveys is pivotal to significant new progress to the questions posed in Section 2.1.

While COMPLETE provides important new insight into the Spitzer observations, it will only examine the northern clouds observable from FCRAO and Mauna Kea; limited observations of the ρ Ophiuchi cloud will be performed, and no observations of Lupus and Chameleon are possible. **AST/RO is not only ideally placed to observe these Southern clouds, but provides access to much more incisive spectral line diagnostics than those adopted by the COMPLETE survey, extending it in important ways. We propose to have AST/RO perform and extend the COMPLETE Survey to the remaining Spitzer Legacy Southern clouds during this proposal period.**

What will we measure and why?

- **High-J CO Mapping:** The COMPLETE survey traces only the $J = 1-0$ lines of CO and ^{13}CO, which are less sensitive to warm, low-opacity, high velocity gas such as produced by outflows, photodissociation regions (PDRs), and shocks. This point is illustrated in Figure 1, with images of a synthetic model cloud constructed in the integrated light of different spectral lines of CO. The model cloud is

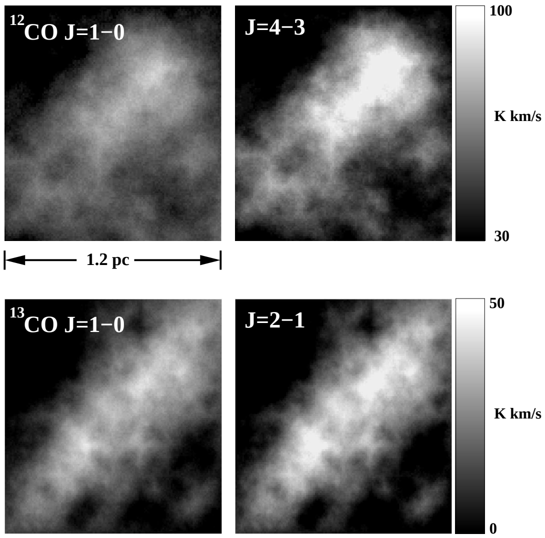

Figure 1: **The need for a submillimeter survey**: Simulated image of a fractal molecular cloud in several CO transitions. The energetic gas that interacts with stars is far better probed by the $4-3$ line; both low- and high-J lines are needed to extract a comprehensive understanding of cloud properties, dynamics & evolution.

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=4→3 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 the higher-J lines recovers over 90% of the H_2 mass. AST/RO will focus on unbiased ^{13}CO J=2→1 and CO J=4→3 large-scale mapping with sub-arcminute sampling, with supplementary $C^{18}O$ J=2→1 observations in regions where ^{13}CO becomes optically thick. Monitoring of the receiver total power, coupled with the superlative sky stability at the South Pole, will allow accurate measurement of the dust continuum at 1300 and 650 μm near column density peaks.

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 molecular outflows, 2) senses radiation fields at the photodissociated surfaces of clouds, and 3) is warmed by star-formation in cloud cores. Higher-J lines are also needed to properly interpret even basic properties of clouds derived from existing CO 1→0 observations.

- **Atomic Carbon Line Emission as a Thermometer & Chronometer:** The fine structure lines of neutral carbon (C^0) at 609 and 370 μm provide unique insight into the physical structure and chemistry of star-forming clouds. The low critical density of these transitions ($n_H \sim 5\times10^2$ & 3×10^3 cm^{-3}) allow them to be readily thermalized at the densities prevalent in molecular clouds. Coupled with their low opacity, the derived excitation temperature constitutes an excellent interstellar thermometer over the full contents of molecular clouds, not just their molecular surfaces as probed by optically thick ^{12}CO line emission. The stratification of the photodissociated surfaces of molecular clouds (Figure 2) demonstrates that carbon line emission is found in precedence of CO. This stratification is identical to the time evolution of carbon-ionized clouds when the UV field is attenuated – thus atomic carbon emission has the capability of probing regions where molecular material has just formed and where carbon has not had time to become fully molecular ($t < 10^6$ yr). While carbon emission generally appears very similar to ^{13}CO J=2→1 emission in studies where both species have been probed, large scale systematic surveys have not tested this correlation. Even small deviations can elucidate the presence of newly-formed molecular clouds, as the building blocks of molecular clouds, cold atomic clouds of hydrogen, have small column densities of a few times 10^{21} cm^{-2}.

AST/RO will map the J=1→0 transition of atomic carbon at 609 μm in concert with CO and ^{13}CO as described above, will provide the best measures of physical conditions in the regions of star formation, and provide clues to the formation of molecular material in nearby clouds, putting star formation in context with cloud formation. Followup observations at 370 μm with the 4-beam PoleSTAR array will allow the excitation of carbon to be measured directly.

- **Synergistic Activities:** We will work closely with the COMPLETE team to construct infrared extinction maps of the Lupus and Chameleon clouds using photometry from the 2MASS survey. Interpretation of the continuum maps provided by AST/RO will be performed in accordance with those obtained by COMPLETE for northern sources. Overlap of the two surveys for the ρ Ophiuchi cloud will allow testing of these techniques. All of these data products will be made available to the greater astronomical community via a Web interface.

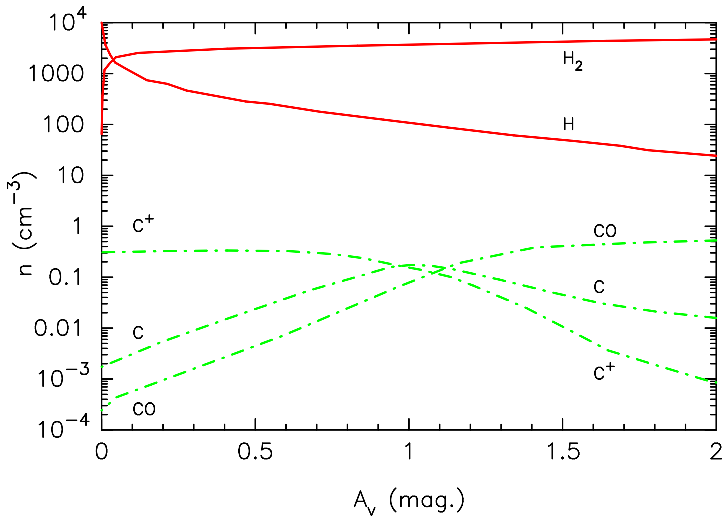

Figure 2: **Stratification of the Surfaces of Molecular Clouds**: One-dimensional models of the structure of molecular clouds show the transformation of hydrogen and carbon from atomic and ionized forms to molecules. This interface region represents the region where all stellar/interstellar feedback occurs, and is crucial to all models of galaxy evolution.

2.3 Key Project 2: A Southern Galactic Plane CO and [C I] Survey in Support of Spitzer's GLIMPSE Legacy Program

[in development; to be uploaded soon]