The warm and dense Galaxy - tracing the formation of dense cloud structures out to the Galactic Center

Abstract: The past two decades have seen extensive surveys of the far-infrared to submillimeter continuum emission in the plane of our Galaxy. We line out prospects for the coming decade for corresponding molecular and atomic line surveys which are needed to fully understand the formation of the dense structures that give birth to clusters and stars out of the diffuse interstellar medium. We propose to work towards Galaxy wide surveys in mid-J CO lines to trace shocks from colliding clouds, Galaxy-wide surveys for atomic Carbon lines in order to get a detailed understanding of the relation of atomic and molecular gas in clouds, and to perform extensive surveys of the structure of the dense parts of molecular clouds to understand the importance of filaments/fibers over the full range of Galactic environments and to study how dense cloud cores are formed from the filaments. This work will require a large (50 m) Single Dish submillimeter telescope equipped with massively multipixel spectrometer arrays, such as envisaged by the AtLAST project.
1 Introduction

The last 10-15 years have seen the advent of comprehensive continuum surveys of the Galactic plane, covering large portions of the plane, at wavelengths ranging from the thermal infrared (Spitzer) over the far-infrared (Herschel) to the submillimeter and millimeter regime (e.g., GLIMPSE [1], MIPSGAL [2], HIGAL [3], ATLASGAL [4], Bolocam Galactic Plane survey [5]). The spatial resolution of these surveys ranges from a few arcseconds (Spitzer) to a few ten arcseconds (Bolocam, Herschel).

While spectral line observations can provide us with important physical gas properties (temperature, density, ionisation state, chemistry, kinematics), the coverage in lines is much more patchy, both in terms of area coverage and spectral coverage. Area covering surveys only exist for the lowest-J CO lines ($1\rightarrow0$ and $2\rightarrow1$) in $^{12}$CO, $^{13}$CO and C$^{18}$O at comparatively low angular resolution (Fig. 1; 20-30 arcseconds at the best, e.g., [6–9]), with the only truly Galaxy-wide survey of Dame et al. 2001 [10] providing a spatial resolution of only 8.5 arcminutes in CO($1\rightarrow0$). The advent of multipixel heterodyne receivers at (sub)millimeter wavelength telescopes is starting to change the situation (e.g., HARP/JCMT ([11, 12]), SuperCAM/APEX [13]; LASMA/APEX (as of 2019)), but still surveys remain limited to CO and its isotopologues.

Figure 1: Existing Galactic Plane CO surveys

| Survey          | Line                  | $|b|$ | Reference |
|-----------------|-----------------------|------|-----------|
| Mopra SGP [14]  | CO/$^{13}$O/$^{18}$O/$^{17}$O(1-0) | $|b|$ ≤ 0.5 |           |
| SEDIGISM [8]    | $^{13}$CO/$^{18}$O(2-1) | $|b|$ ≤ 0.5 |           |
| ThrUMMS [7]     | CO/$^{13}$CO/$^{18}$O/CN(1-0) | $|b|$ ≤ 1  |           |
| Forg. Qu. S. [15]| CO/$^{13}$CO(1-0)     | $|b|$ = 0.2 |           |
| FCRAO Out Gal [16]| CO(1-0)                  | $|b|$ = -3.5.4 |           |
| MassSB COGps [17]| CO(1-0)                  | $|b|$ ≤ 1  |           |
| MWISP [18]      | CO/$^{13}$CO/$^{18}$O(1-0) | $|b|$ ≤ 5.2 |           |
| COHRS [11]      | CO(3-2)                | $|b|$ ≤ 0.5 |           |
| GRS [6]         | $^{13}$CO(1-0)         | $|b|$ ≤ 1  |           |
| CHIMPS [12]     | $^{13}$CO/$^{18}$O(3-2) | $|b|$ ≤ 0.5 |           |
| FUGIN [9]       | CO/$^{13}$O/$^{18}$O(1-0) | $|b|$ ≤ 1  |           |
| COCA, CHaMP, OGHReS, CO FCRAO Ex.: in prep |

The interstellar medium (ISM) is highly structured. Molecular gas is found in clouds spanning a wide range in mass (few $M_\odot$ to few $10^6 M_\odot$) and size (few to few 10 pc). Filamentary structures are a common feature of the structure of molecular clouds and thought to play an important role in the formation of the dense structures from which stars and clusters form. Molecular "clumps", with sizes on the order of 1 pc and densities on the order of $10^3$ to $10^4$ cm$^{-3}$, may give birth to stellar clusters. Dense cloud "cores", with sizes on the order of 0.1 pc and densities on the order of $10^5$ to $10^6$ cm$^{-3}$, give birth to individual stars or small-n multiple systems.

A proper understanding of the star formation process implies an understanding of how these structures form, how they evolve, and how varying ambient conditions influence their properties and evolution. The location of a molecular cloud within the Galaxy has an impact on the conditions under which dense structures form: close to the Galactic Center clouds are highly turbulent and have higher temperature (60-100 K, e.g., [19]), while towards the outer Galaxy they are much more quiescent and colder; reduced metallicity may further influence their structure and chemistry. HII regions or supernova remnants will also impact the evolution of the cloud and its internal structures.
Following the formation and evolution of dense structures, on scales of 0.1-0.2 pc, over the full range of Galactic environments, i.e., out to distances on the order of 8 kpc, will require a spatial resolution of the order of a few (2.5-5) arcseconds. Wide-field surveys (Galaxy-wide for the more abundant tracers, deeper and more restricted for less abundant tracers or high-density tracers) are needed but will require significant improvements in observing capabilities, in particular large format Heterodyne receiver arrays and a large Single Dish submillimeter telescope such as AtLAST.

2 Survey projects for the coming Decade

2.1 A Galaxy-wide survey for warm molecular gas and shocks

The temperature and density structure of molecular clouds is determined by their formation process. Of relevance here may be the picture of dense structure formation out of “colliding flows” in the interstellar medium (ISM). The turbulent nature of the ISM will unavoidably result in regions where large scale, moving gas parcels meet and collide. At the collision front a sheet of denser gas will form, which is highly unstable to fragmentation, first into filamentary structures, which then fragment to form clumpy structures within them (e.g., [20–22]). The zones where the incoming flows collide with the dense sheet can be expected to show up as warm, shocked regions, featuring emission from warm molecular gas (CO) and/or shock tracers (e.g., [23–26]).

CO is the most commonly observed tracer of molecular gas, being abundant and bright, tracing mostly moderately dense gas ($10^{3}$ cm$^{-3}$). It is a good tracer of the bulk of a molecular cloud, although a significant fraction of molecular gas might be “CO-dark” (e.g., [27]). With the main isotopologue becoming optically thick rapidly, a full account of molecular gas requires covering rarer isotopologues ($^{13}$CO, C$^{18}$O), and higher energy transitions. The spectral-line energy distribution (SLED) of CO lines from different rotational levels holds important clues about the temperature and excitation mechanisms of the CO molecular gas. Covering intermediate- to high-J CO lines will allow us to trace warm gas, and comparing line strengths with low-J lines will enable us to discriminate between emission from Photon Dominated Regions (PDRs) and low velocity shocks, e.g., from converging flows forming dense structures [25]. Area covering surveys of submillimeter CO lines, at least up to the J=7→6 transition, will be crucial in identifying converging flows and in quantifying their importance for the formation of clouds and substructures within them.

2.2 Cloud formation from the atomic to the molecular phase

There is still significant debate regarding the transition from the atomic to the molecular ISM phases. Are quasi-static contraction processes associated with ever increasing densities and related conversion of atomic to molecular gas dominating (e.g., [28]), or is the process more dynamic where converging gas flows create over-densities and within them the gas converts the atomic into the molecular phase (e.g., [29, 30])?

To investigate these different possibilities, studying the different gas phases in the molecular as well as atomic environment is important. While there exist several surveys of the Milky Way in the molecular phase (Fig. 1) as well as in the neutral atomic hydrogen (e.g., [31–33]), large-scale maps of a good tracer of the transition phase are still rare and very limited in area coverage (e.g.,
[34]: [CI] in the Galactic Center; [35]: [CI] in Orion A). One of the best transition phase tracer may be the fine structure lines of carbon [CI] (e.g., [36]), but currently the picture is very unclear. [CI] emission at times is found to extend to more diffuse, CO-dark regions, and thus out to larger size scales, potentially even the scales at which turbulence may be driven (e.g., [37]). Often, [CI] is also found to be similar in extent to dense material traced, e.g., in $^{18}\text{O}$ (e.g., [38]; see also [39]), with small, but significant differences in exact location and extent seen in some cases (e.g., [40]).

A large (50 m) Single Dish submillimeter telescope such as AtLAST would allow the first high-spatial-resolution Galactic plane survey in both atomic carbon transitions at 492 GHz ([CI]$^3\text{P}_1 - ^3\text{P}_0$, $E_u/k = 23.6$ K) and 809 GHz ([CI]$^3\text{P}_2 - ^3\text{P}_1$, $E_u/k = 62.5$ K). With a dish size of 50 m, angular resolution elements at the two transitions of $\sim 3''$ and $\sim 1.8''$ will be achieved. At typical molecular cloud distances in the Milky Way of several kpc, that corresponds to linear resolution elements typically significantly below 0.1 pc; a careful comparison of these atomic Carbon data with comparable datasets then available for atomic hydrogen from the SKA, and molecular data from AtLAST as well as ALMA will allow us to study the atomic to molecular gas conversion processes as well as cloud formation and destruction mechanisms in great detail.

### 2.3 Intermediate scales/Filaments

Filaments have since long been known to permeate molecular clouds (e.g., [41]). Herschel far-IR surveys in particular have revealed extensive networks of filaments in nearby molecular clouds, intimately related to the location of cloud cores (e.g., [42]). Typically, these filaments have a width on the order of 0.1-0.2 pc. More distant filaments (few kpc) such as identified by [43] from the ATLASGAL survey are found to cover a much larger range in widths (0.1-2.5 pc). Cluster forming massive clumps are often seen to be located on massive filaments (termed ”ridges”) and/or at the intersection of filaments.

In addition to the continuum, molecular line observations allow to study the internal mass distribution and dynamical properties of filaments. The analysis of different density selective tracers (i.e., $^{18}\text{O}$ and $\text{N}_2\text{H}^+$) in clouds such as Taurus and Orion demonstrates that different nearby filaments are actually collections of the so-called fibers, namely, smaller-scale sub-filaments twisted in space forming a bundle [44, 45]. Similar fiber-like arrangements have been also reported in other nearby regions (e.g., [46]) as well as in more distant Infrared Dark Clouds (IRDCs, e.g., [47]). It remains to be investigated to which extent more massive filaments identified across the Galaxy are indeed monolithic structures, typically unresolved by current single-dish observations, or if they rather separate into sub-filaments when observed at higher spatial resolution. Molecular line studies indicate a widespread detection of multi-scale velocity oscillations and excursions along filaments across their entire mass spectrum (e.g., [48]). Also, and at sub-parsec scales, sinusoidal velocity fields may indicate gas flows towards the densest portions of fibers, leading to core formation, but have only tentatively been detected (L1517, [49]). Investigating the nature and magnitude of these motions, only accessible using multi-line surveys, could provide fundamental insights about the formation mechanism of filaments, their fragmentation process, and the origin of stars in them.

Recent molecular maps reported the first evidence of ordered velocity gradients in both clusters [50] and IRDCs [51] detected in species like NH$_3$ and N$_2$H$^+$. Converging velocity patters are found along filaments forming hub-like structures, likely funneling material towards the most massive clumps located at the centre of these filamentary associations (e.g., [52]). Global infall
velocity patterns detected at parsec scales indicate that young clusters such as the Orion Nebula Cluster continue accreting material after several Myrs [53]. Resolving these motions at high spatial resolutions result key to understand how clusters assemble their masses over time as well as the formation of massive stars within these regions. The study of these motions requires the simultaneous characterization of dense (e.g., low-J lines from density selective species such as N$_2$H$^+$ or HCN) and diffuse tracers (e.g., high-J CO lines) in order to disentangle the strong feedback effects present in these regions. The expected multi-scale, high-dynamic range mapping capabilities of AtLAST offer the first opportunity to systematically study these processes in detail across the Milky Way.

2.4 Cores

Moving on to the cloud cores themselves, our current understanding is still largely based on detailed studies of individual objects or limited studies (in terms of available tracers) of moderate sized samples of cores. A full understanding of the physics of core formation and evolution towards and into star formation will require comprehensive studies of large core samples (comprising the full range of possible environments) for their physical properties (mass, density and temperature structure, chemical structure, etc.). E.g., mid-$J$ ($J = 7 \rightarrow 6$ to $J = 10 \rightarrow 9$) HCN and HCO$^+$ lines available at ALMA Band 9 and 10 (600-950 GHz) trace very dense ($n$(H$_2$)$_{cr} > 10^6$ cm$^{-3}$ at $T_K = 100$ K) and warm ($E_u/k > 150$ K) gas and will allow to identify and study the cores where stars are actually forming (or are about to form; e.g., [54]).

In the dense cores we shall also see the effects of ambipolar diffusion, expected to be observed in infalling gas in the presence of strong magnetic fields as a small difference in the velocity fields between ionized and neutral species (e.g., [55–57]). Doing this on large samples, covering scales from cluster forming, parsec-sized clumps down to individual star forming cores in one go, will help to understand better the role of magnetic fields as the star formation process proceeds. This type of observations requires a combination of decent area coverage (on the order of 10×10 arcmin), spatial resolution on the order of a few arcseconds, high sensitivity at high spectral reso-
olution, and spectral coverage (multi-line analysis to rule out optical depth and chemical effects on the line shapes).

3 The case for a large sub-mm single dish telescope

To summarize the above, following the formation and evolution of molecular clouds and their structure from Giant Molecular cloud scales down to cloud cores forming individual stars in a comprehensive manner requires:

- Galaxy-wide surveys of tracers of molecular gas (to first order CO isotopologs) and the precursor atomic gas ([CI]);
- multiline observations in CO, up to at least mid-J transitions, (and other shock tracers) to identify large scale shocks from cloud collisions;
- deep surveys of high density tracers (e.g., HCO$^+$, HCN; covering areas of hundreds of square arcminutes to tens of square degrees) to follow the formation of dense structures such as filaments and cores, with angular resolution up to 2-3 arcsec (cloud core size at the distance of the Galactic Center)

These requirements can be met by a 50 m single-dish telescope operating at submillimeter wavelengths (1 mm - 250 $\mu$m), equipped with massively multipixel ($\sim$1000) spectrometers providing wide spectral coverage and high spectral resolution (better than 100 m/s), as envisaged by the AtLAST project.

3.1 50 m Single Dish (AtLAST) vs. ALMA:

ALMA easily provides the required angular resolution, but will not be competitive in mapping speed (50 12 m diameter antennas with single-pixel receivers vs. one 50 m antenna with $\sim$1000-pixel receiver array). In addition, molecular clouds show complex, multiscale emission, which will be subject to spatial filtering with ALMA; it becomes more and more evident that even multi-configuration interferometric observation including total power observations give a skewed representation of the actual intensity distribution (e.g., [58]). Single dish observations, covering the required range of angular scales from very large down to the resolution limit are crucial for a proper recovery of the true source emission structure particularly in regions having a complex spatial and velocity structure (Hacar et al, in prep). On the other hand, a 50 m ATLAST will readily provide data that can be used to complement ALMA interferometric data as zero-spacings, with a very good overlap in uv-space with ALMA (shortest ACA 7 m baselines 10-15 m); this is also in contrast with CCAT-prime, which (with only 6 m diameter) does not overlap with the ALMA interferometric uv-space.
References


