Astro2020 Science White Paper

Imaging Entire Molecular Clouds in many Lines: From the Milky Way to Galaxies

Thematic Areas: ☐ Planetary Systems ☑ Star and Planet Formation
☐ Formation and Evolution of Compact Objects ☐ Cosmology and Fundamental Physics
☐ Stars and Stellar Evolution ☐ Resolved Stellar Populations and their Environments
☑ Galaxy Evolution ☐ Multi-Messenger Astronomy and Astrophysics

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Abstract (optional): Emission lines from molecules at frequencies $\gtrsim$ 70 GHz to $\gg$ 100 GHz provide astronomy with substantial diagnostic power to explore the kinematics, density structure, radiation field, and density–temperature history of the gas in molecular clouds. Studies of this line emission in the Milky Way will substantially refine tools that can then be used to advance our picture of how molecular cloud properties control star formation, and to what extent cloud properties vary inside galaxies, including the Milky Way. Such work requires imaging of entire molecular clouds of $\gtrsim$ 10 pc size in species like HCN, CN, and N_2H^+, sometimes down to resolutions $\sim$ 0.1 pc. Small and large single–dish telescopes, as well as ALMA, are needed to refine the use of molecular emission lines a tool to study cloud structure. Telescopes with modest diameters $\gtrsim$ 10 m are ideally suited to study changes in cloud structure in the Milky Way.

This text is likely to receive further community feedback. It is therefore encouraged to refer to the arXiv publication of the same name, which will be more up–to–date.

1 Introduction: Potential of Multi–Species Observations

The frequency band at $\gtrsim 70$ GHz is uniquely rich in bright transitions of molecules that allow to probe the kinematics, density structure, radiation field, and density–temperature history of the gas in molecular clouds (e.g., HCN, CN, N_2H^+). Such molecules are bright enough to be studied in galaxies (e.g., Watanabe et al. 2014), and observations of their emission lines can be combined to probe dense gas, radiation feedback from star formation, and shocks. Detailed investigations using these lines would thus allow to explore molecular clouds and star formation in other galaxies much more comprehensively than possible today (Sec. 2.1). A companion Astro2020 white paper discusses how related studies in the Milky Way would advance our detailed understanding of star formation on the scales of molecular clouds (Kauffmann et al. 2019).

Such work on extragalactic targets must, however, be complemented with comprehensive studies of molecular clouds in the Milky Way that refines our understanding of molecular emission lines. Specifically, while regions of $\gtrsim 0.5\ \mathrm{deg}^2$ are frequently studied in lines of ^{12}CO and ^{13}CO (e.g., Goldsmith et al. 2008), no other astrophysically relevant molecule has ever been mapped comprehensively on such cloud–like scales (see Kauffmann et al. 2019). This includes lines from key species like HCN, CN, CH_3OH, and N_2H^+. This text therefore considers imaging of entire clouds of $\gtrsim 10$ pc size at $\gtrsim 70$ GHz, in part down to the smallest physically relevant scales ~ 0.1 pc. Such research would allow to

- substantially refine tools for the characterization of gas properties in galaxies,
- investigate the processes controlling the rate at which stars form in galaxies, and
- reveal the extent to which molecular cloud properties vary in the Milky Way and are influenced by galactic structure in the form of galactic bars and spiral arms.

Table 1 outlines the value of some molecules in tracing physical conditions.

Ground–based observations at about 70 to 115 GHz are unique in that they can easily access numerous bright ground–state transitions. Studies at higher frequencies (e.g., $J = 3$–2 transition of HCN at 266 GHz, and of ^{12}CO at 346 GHz) remove uncertainties in radiative transfer. Observations at all frequencies are important, but they become increasingly difficult at high frequencies.

2 Scientific Questions

2.1 Selected Current Challenges in Extragalactic Star Formation Research

Star formation is the key process that converts baryonic matter into the stars that form the "backbone" of galacy structure. A detailed understanding of galaxy evolution thus requires an understanding of

- how molecular cloud properties control a cloud's star formation rate, and of
- how molecular cloud properties vary inside galaxies.

Section 2.2 discusses the specific extent to which molecular emission lines can probe the gas conditions that need to be investigated to tackle these questions. As described there, a galaxy's luminosity in HCN lines contains information on the mass of gas exceeding some density threshold, CN line luminosities constrain the extent to which a galaxy's molecular clouds are exposed to radiative feedback from star formation, and the luminosity in lines of CH_3OH delivers knowledge about violent gas motions in galaxies. Today, more than a dozen emission lines at $\gtrsim 115$ GHz are bright enough to be studied in other galaxies to facilitate such work (e.g., Watanabe et al. 2014),

Table 1: Outline of molecules as tracers of physical gas conditions, as described in the text.

Species	Associated Physical Conditions
^{12}CO, ^{13}CO	lower–density gas
HCN, N_2H^+	dense gas
C_2H, CN	UV–irradiated gas
SiO, HNCO, CH_3OH	shocked gas

and future instruments are bound to further increase this range.

The relation found by Gao & Solomon (2004) arguably constitutes the best–known example for a "star formation law" that was derived in such studies. Gao & Solomon found that a galaxy's luminosity in the HCN (1–0) line — which is a probe of a galaxy's mass of gas at high density — correlates with the infrared luminosity — which is a measure of a galaxy's star formation rate. The strict correlation $L_{IR} = C_{GS} \cdot L_{HCN}$ with C_{GS} = const. initially found by Gao & Solomon (2004) suggests that gas exceeding some density threshold forms stars at a constant rate per unit mass. However, recent work shows that C_{GS} does actually vary substantially inside and between galaxies (e.g., Usero et al. 2015, Bigiel et al. 2016). It is most likely that these variations in star formation properties result from variations in the cloud properties controlling the star formation process.

Many current studies use molecular emission lines to investigate such variations in cloud properties. The luminosity of CO lines provides information on the total mass of molecular gas. The observed variations in the HCN–to–CO line ratio thus indicate that the mass fraction of dense gas varies substantially inside and between galaxies (e.g., Usero et al. 2015, Bigiel et al. 2016). Separate work shows that also the CN–to–CO line ratio depends on the galaxy and the location in it (Wilson 2018). As described above, this delivers information about the extent to which feedback from star formation varies inside galaxies. Beyond this, we know that line ratios between HCN, HCO^+, CS, ^{13}CO, and $C^{18}O$ vary inside galaxies (Gallagher et al. 2018). Data from Watanabe et al. (2017) and Nishimura et al. (2017) further show that also star–forming complexes in the Milky Way differ in line ratios averaged over the entire cloud.

Extragalactic multi–tracer molecular line studies of galaxies are therefore now commonplace at all major observatories. This includes the PHANGS project that uses ALMA to image $\sim$ 60 spiral galaxies (e.g., Sun et al. 2018), the EMPIRE survey of 9 nearby galaxies on the IRAM 30m–telescope (e.g., Bigiel et al. 2016; $\sim$ 450 h of observing time), and the DEGAS study of 36 galaxy centers on the GBT (A. Kepley et al.; $\sim$ 500 h).

However this important research depends on our ability to use molecular emission lines as probes of gas properties. These tools require substantial refinement, as discussed in Sec. 2.2. Further, the application of these tools to data on the Milky Way can deliver rich new information on our own galaxy (Sec. 2.3), and it can test the methods that we use to study distant galaxies.

2.2 Refining Molecular Emission Lines as Probes for Gas Properties

The formation and destruction rates of molecules, as well as their excitation, depend on the environmental conditions, and they differ between species. As a consequence, the absolute intensities of molecular emission lines, as well as line ratios between species, deliver rich information on the conditions in the gas containing the molecules.

The relationships between molecular emission lines and gas properties can be established observationally. Pety et al. (2017) image parts of the Orion B cloud in $\sim$ 20 emission lines accessible at frequencies of 85 to 115 GHz. Gratier et al. (2017) study how these emission lines correlate with independent estimates of the gas column density, the volume density, and the UV radiation field (also see Lo et al. 2009 and Bron et al. 2017). This research suggests to use N_2H^+ to probe the dense gas in molecular clouds, and to use C_2H and CN to constrain the UV radiation field in clouds. Using other methodologies, Pety et al. (2017) and Kauffmann et al. (2017) use maps of Orion to show that the HCN (1–0) line is emitted at a typical density of $\sim 10^3$ cm^{-3}.

The latter is an important example for the impact of observational work. Previous studies used theoretical arguments (e.g., Gao & Solomon 2004), or combinations of theoretical considerations and observational data (e.g., Jimenez-Donaire et al. 2017), to argue that the HCN (1–0) transition selectively samples gas at densities $\gtrsim 6 \times 10^4$ cm^{-3}. Observational refinements are thus essential. This holds in particular for advanced techniques, that are motivated by theoretical work: Leroy et al. (2017) suggest to use line ratios to constrain the probability density function (PDF) of gas density in clouds, while Harada et al. (2019) argue that line ratios are probes of the timeline over which molecules are accreted into clouds and then processed by star formation feedback.

One important aspect of the work above is that it constrains the relation between line and gas properties only broadly. Research by Shimajiri et al. (2017) suggest that the coupling between HCN emission and dense gas depends on the radiation field to which the dense gas is exposed. Jiménez-Serra et al. (2010), Cosentino et al. (2017), and Yu et al. (2018) study the molecules SiO, HNCO, and CH_3OH, which are well–known shock tracers, and they find that a substantial fraction of the emission in these lines comes from cloud sections not affected by shocks. Such details must be modeled thoroughly, if one wishes to use molecular emission lines as probes of gas properties.

The observational establishment of detailed relationships between specific emission lines and gas properties thus requires studies of substantial cloud samples that are diverse in characteristics like their star formation activity, dense gas content, and metallicity. One challenge for this work is that it must sample molecular clouds of size $\gtrsim$ 10 pc in their entirety. This is necessary because extragalactic observations, with limited physical resolution, typically measure line intensities that represent a spatial average over several molecular clouds. Further, at least some observations of this type must resolve clouds down to the spatial scale of dense cores and filaments ($\sim$ 0.1 pc), which are the smallest spatial scales on which substantial variations in line emission properties are seen (such as molecules primarily associated with dense cores, like N_2H^+). The Astro2020 paper by Kauffmann et al. (2019) describes that very few such data currently exist.

2.3 Exploring the Milky Way as a Galaxy

A fundamental prerequisite for the work described in Sec. 2.2 is the ability to observe large areas in the sky in many molecular emission lines. This ability would also enable us to explore how the properties of molecular clouds vary in the Milky Way, and how such variations would correlate with galactic structure in the form of spiral arms, galactic bars, and galactocentric distance. Such work would be inspired by the trends seen in other galaxies (Sec. 2.1).

It would be very interesting to explore whether the HCN–to–CO line ratio increases towards the center of the Milky Way. Observations of such trends in other galaxies are taken as evidence for an increase in the average density of molecular clouds towards galaxy centers (Bigiel et al. 2016; Usero et al. 2015). Likewise it is possible to examine properties like the CN–to–CO ratio, that varies inside galaxies (e.g., Wilson 2018) and is connected to the feedback of star formation on molecular clouds (Sec. 2.2).

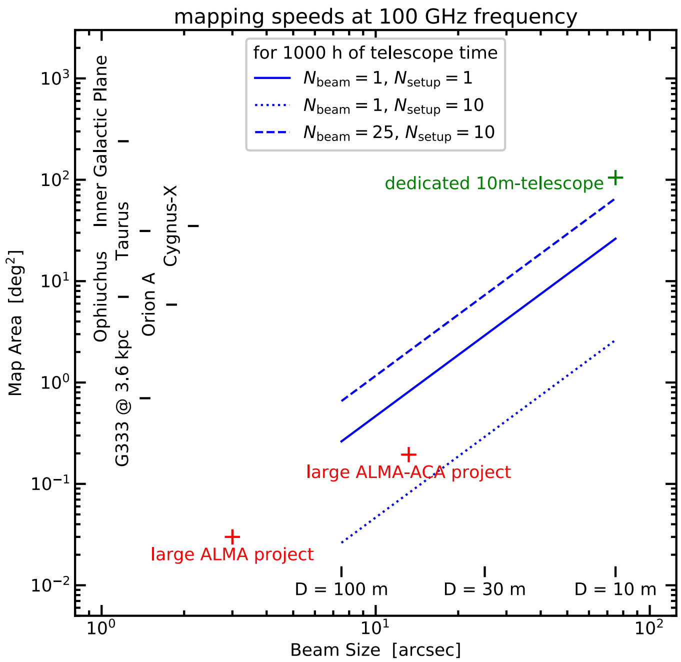

Figure 1: Comparison between target sizes (indicated along vertical axis) and observational capabilities. For ALMA we assume observations of one setup in a large project of 50 h, respectively observations with the ALMA–ACA for 100 h. The blue lines assume observations for 1,000 h on telescopes of various sizes, including overheads. The green cross holds for a dedicated 10m–telescope observing with $N_{setup} = N_{beam} = 1$ for 4,000 h. "Inner Galactic Plane" refers to $|\ell| \leq 60°$, $|b| \leq 1°$.

More generally, it is of high interest to see whether line ratios in the Milky Way vary as strongly and systematically as observed in other galaxies (e.g., Gallagher et al. 2018). Such work would help to distinguish between conflicting views of cloud properties in the Milky Way, i.e., that cloud properties do (e.g., Roman-Duval et al. 2016 and Zetterlund et al. 2018) or do not (e.g., Eden et al. 2013 and Battisti & Heyer 2014) vary systematically within the Milky Way.

Studies of SiO, HNCO, and CH_3OH would help to clarify our picture of spiral arm formation. Watanabe et al. (2014) observe bright lines of HNCO and CH_3OH towards a spiral arm in M51. They point out that these species are known tracers of shocks, and they speculate that the presence of these molecules might indicate that spiral arms form in strong shocks. The existence of such shocks would be very interesting, because they do not exist in current numerical simulations of spiral arms (Dobbs et al. 2014). However, Watanabe et al. also caution that HNCO and CH_3OH might also exist in clouds not subjected to shocks, and this has indeed been observed since (Cosentino et al. 2017; Jiménez-Serra et al. 2010; Yu et al. 2018). Mapping of the HNCO–to–CO and other line ratios against the Milky Way's structure would help to resolve this issue..

3 Outline of Observations beyond 2020

3.1 Technical Considerations

The Astro2020 companion paper by Kauffmann et al. (2019) presents a framework for the estimation of telescope mapping speeds. That publication should be consulted for details about the following considerations. Figure 1 assumes a system temperature T_{sys} = 200 K, 100 GHz frequency, and a target noise level of 0.1 K in channels of 0.5 $\mathrm{km\,s^{-1}}$ width. A range of telescope diameters, D, are assumed. The estimates include calculations for telescopes equipped with multi–feed cameras acquiring $N_{beam} > 1$ beams in parallel, and instruments with small receiver bandwidth that need to cycle through N_{setup} receiver setups. The calculations also include estimates from the ALMA Observing Tool for a single setup observed with channels of 0.4 $\mathrm{km\,s^{-1}}$ and 0.1 K depth at 100 GHz frequency. We consider a large program of 50 h with full ALMA ($3''$ resolution), and an ACA–only program of 100 h ($13''$ resolution). Consistent with current experience, Fig. 1 assumes that large programs on single–dish telescopes receive allocations of up to 1,000 h, including overheads. Figure 1 also considers the case of a dedicated 10m–telescope with $N_{\rm setup} = N_{\rm beam} = 1$ operated for $\gtrsim 4,000$ h. See Kauffmann et al. (2019) for the chosen combinations of $N_{\rm beam}$ and $N_{\rm setup}$.

3.2 Refinement of Observational Tools

The science described in Sec. 2.2 requires imaging of entire clouds. Figure 1 shows that nearby clouds like Orion A ($d \approx 400$ pc; Megeath et al. 2012) can only be studied with instruments achieving $N_{\rm setup} \sim 1$ or $N_{\rm beam} \gtrsim 10$ on telescopes with $D \lesssim 30$ m. The situation is better for some more distant clouds. The G333 region, for example, is small enough to be studied efficiently with telescopes of size $D \sim 100$ m achieving $N_{\rm setup} \sim 1$ or $N_{\rm beam} \gtrsim 10$ (Lo et al. 2009). However, other distant targets, such as the Cygnus–X complex, have an extent that can only be covered efficiently with the smallest available telescopes (Schneider et al. 2011).

Section 2.2 explains that some of this research must be conducted at ~ 0.1 pc spatial resolution, in order to resolve the smallest spatial scales on which line emission properties change substantially. Such work can be done with relatively small telescopes in nearby clouds, where the spatial resolution is $\ell_{\rm beam} = 0.18~{\rm pc} \cdot (d/500~{\rm pc}) \cdot (\nu/100~{\rm GHz})^{-1} \cdot (D/10~{\rm m})^{-1}$. Telescopes of intermediate size can be useful for the exploration of somewhat more distant clouds, where $\ell_{\rm beam} = 0.24~{\rm pc} \cdot (d/2~{\rm kpc}) \cdot (\nu/100~{\rm GHz})^{-1} \cdot (D/30~{\rm m})^{-1}$. But large telescopes, and ALMA, are needed to resolve fine detail down to $\ell_{\rm beam} = 0.07~{\rm pc} \cdot (d/2~{\rm kpc}) \cdot (\nu/100~{\rm GHz})^{-1} \cdot (D/100~{\rm m})^{-1}$.

3.3 Studies of the Milky Way

The science described in Sec. 2.3 requires imaging of entire clouds throughout the disk of the Milky Way. This research requires no particular spatial resolution, and it is thus most efficiently conducted with small telescopes. Mapping of the Galactic Plane would constitute a very ambitious extension of such work. The area at $|\ell| \leq 60^\circ$ and $|b| \leq 1^\circ$ is indicated in Fig. 1. This area can only be mapped using substantial time allocations on small telescopes.

3.4 Need for Diversity in Dish Sizes & Frequency Coverage

The discussion above shows that some structures can only be imaged in their entirety with relatively small telescopes, while relatively large telescopes and ALMA are needed to resolve fine in some targets. Both small and large telescopes sample important parts of discovery space.

Imaging at $\gg 100$ GHz is technically more challenging, and emission lines are fainter. However, combination of such work with mapping at $\lesssim 115$ GHz generates new and highly desirable data (Sec. 1). Instruments at $\gg 100$ GHz are thus needed to map at least selected parts of clouds.

4 Summary

The study of emission lines from galaxies can substantially advance our understanding of extra-galactic star formation. Such research must, however, be complemented with studies of molecular clouds in the Milky Way, that allow to refine tools for the study of other galaxies. Such data on the Milky Way would also allow to understand how molecular cloud structure varies within the Milky Way. This work requires access to small telescopes that can efficiently map large sections of the sky. This research requires investments in multi–feed cameras and systems with large instantaneous bandwidth, i.e., that maximize $N_{\rm beam}$ and minimize $N_{\rm setup}$ (Fig. 1 and Sec. 3).

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