Astro2020 Science White Paper

Imaging Entire Molecular Clouds in many Lines: Formation of Stars and Planets

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: 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 will substantially advance our picture of how dense substructure emerges in clouds, fuels star formation, and is dispersed by feedback. Such work requires spatially resolved imaging at ~ 0.1 pc resolution of species like HCN, CN, and N_2H^+ across entire molecular clouds of $\gtrsim$ 10 pc size. Single–dish telescopes with modest diameters $\gtrsim$ 10 m are needed to study relatively nearby clouds of large angular size, while large telescopes and ALMA are required to resolve fine detail and distant clouds.

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^+). Spatially resolved imaging of entire clouds of $\gtrsim$ 10 pc size at ∼ 0.1 pc resolution in rich sets of lines would allow to explore clouds much more comprehensively than possible today. Specifically, extensive mapping of molecular emission lines would substantially improve our understanding of the kinematics of dense gaseous filaments and associated star–forming cores and clumps in molecular clouds (André et al. 2014; see Sec. 2.1). Comprehensive measurements of molecular abundances would provide rich and new constraints on the timescales on which molecular clouds form, establish dense substructure, and get disrupted by feedback from star formation (see Sec. 2.2).

Such imaging would sample new and important segments of the observational discovery space. Specifically, while regions of $\gtrsim$ 0.5 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[1], given the mapping speed of current instrumentation. As a consequence, we lack comprehensive data sets from key species that would deliver

- information on the origin of the stellar initial mass function (IMF),
- insights into the mechanisms controlling the star formation rate in galaxies, and
- constraints on the processes shaping the astrochemical makeup of stars and planets.

Figure 1 presents a well–resolved map covering large sections of a molecular cloud. It is evident that different lines trace different parts of the cloud. Table 1 outlines the extent to which such emission lines can probe a variety of physical gas conditions. The table is based on Kauffmann (2019), an Astro2020 companion paper discussing how multi–species mapping of molecular clouds in the Milky Way can advance our understanding of cosmic star formation, galaxy evolution, and the structure of our own galaxy.

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 in Star Formation

2.1 Kinematics of Dense Gas in Filaments, Cores, and Clumps

The kinematics of dense gaseous filaments inside molecular clouds (with a width ∼ 0.1 pc, and a substantially larger length), of dense cores in these filaments (∼ 0.1 pc size), and of the dense

[1]Maps of size $\gtrsim$ 0.5 deg^2 that cover emission lines from a range of molecules near 100 GHz frequency have only been obtained for the Galactic Center (Jones et al. 2012), W51 (Watanabe et al. 2017), G333 (Lo et al. 2009), W3 (Nishimura et al. 2017), Rosette (Kauffmann et al., in prep.), and Orion (Kauffmann et al. 2017; Melnick et al. 2011; Pety et al. 2017). Many studies of larger complexes, such as mapping of W43 (e.g., Nguyen Luong et al. 2013 and Carlhoff et al. 2013) and Cygnus–X (e.g., Schneider et al. 2010), are limited in angular size (e.g., ∼ 10×10 arcmin^2), only cover few molecular species (e.g., Shimajiri et al. 2017, Fissel et al. 2018), or both. The MALT90 project observed 2,000 regions in a large number of lines, but only in relatively small maps of $3' \times 3'$ size at frequencies < 93.2 GHz that exclude many pivotal lines (such as CS, CH_3OH, CN, and HNCO; Jackson et al. 2013). Further patchy and inhomogeneous coverage at low sensitivity in selected lines is provided by CHaMP (Barnes et al. 2011).

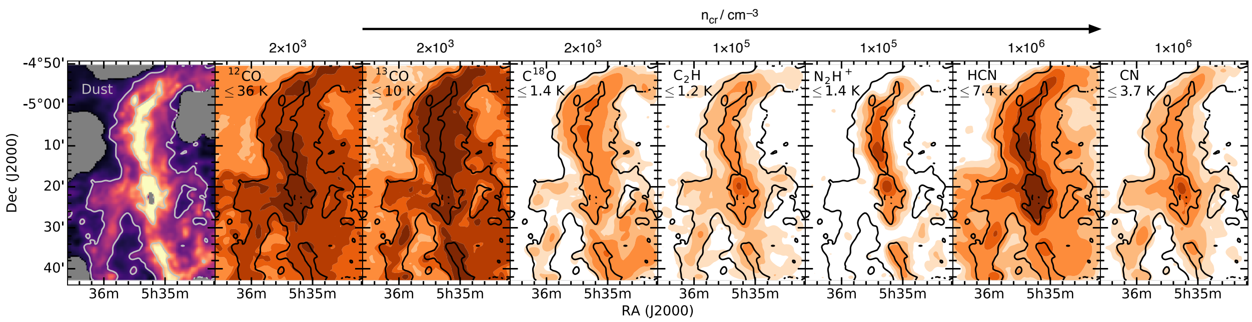

Figure 1: Orion A in emission lines near 100 GHz, taken from Kauffmann et al. (2017) and based on Melnick et al. (2011). The emission lines probe a variety of physical conditions (Table 1).

clumps enveloping clusters of cores ($\sim$ 1 pc size) can be probed via spectroscopy with $\lesssim 0.1$ km s^{-1} resolution. Wideband instrumentation enables imaging of these structures in multiple lines.

The detailed characterization of dense gaseous filaments in dust continuum emission is considered to be one of the key achievements of the Herschel Space Telescope. This research, done almost a decade ago, indicates that density enhancements in filaments morph into cores and then stars (André et al. 2014). However, given limited mapping speeds, few actual measurements of the gas kinematics in filaments via molecular emission lines exist (Arzoumanian et al. 2019), and the actual role of filaments in the star formation process remains unclear. The GAS survey of clouds near 23 GHz will greatly improve this situation for nearby ($d \lesssim 500$ pc) northern regions (Friesen et al. 2017). But GAS primarily targets NH_3, and this focus on a single species results in biases.

Hacar et al. (2013) demonstrate the value of imaging filaments in lines at $\gtrsim 70$ GHz, which probe a variety of environmental conditions. Combined exploration of lines tracing gas at low (i.e., $C^{18}O$) and high density (i.e., N_2H^+) in Taurus revealed complexity that has fundamentally altered our views of dense gaseous filaments. More such work at $\gtrsim 70$ GHz is needed.

Such studies of filaments will at the same time provide rich and influential information on the cores and clumps in and along filaments. The smart combination of emission lines probing separate regions in clouds (e.g., low and high density) allows to characterize gas flows assembling filaments (Shimajiri et al. 2018) and cores (Lee et al. 2001), as well as collapse motions during star formation in dense cores (e.g., Keto et al. 2015) and clumps (e.g., Kirk et al. 2013, Peretto et al. 2014). Even very fundamental properties, like the gravitational binding of dense cores, have to date only been studied in limited samples that deliver no clear picture for the general population of clouds (e.g., Lada et al. 2008 vs. Kauffmann et al. 2013). This is problematic, because the binding and collapse motions control the stellar properties resulting from star formation, such as the IMF.

The Herschel Space Telescope showed that even entire clouds are elongated (Molinari & et al. 2010). Research into filamentary cloud kinematics is just starting now (Mattern et al. 2018).

Observations of gas kinematics also enable research into the nature and generation of “turbulence” in clouds (e.g., Koch et al. 2017). Access to a range of molecular emission lines that selectively probe specific domains of a cloud’s gas content would make such work more potent.

2.2 State, Formation, and Dispersal of Molecular Cloud Structure

The modeling of observed molecular abundances can provide us with rich constraints on the evolution of cloud structure, in particular if several molecular species are investigated at the same

Table 1: Outline of molecules as tracers of gas conditions (from Kauffmann 2019).

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
DCO^+, DCN, DNC, N_2D^+	cold and dense gas

time. Such assessments are possible because the formation and destruction rates of molecules depend on the environmental conditions, and they differ between species. Barnes et al. (2016) use observations of N_2D^+ in some high–mass clouds to show that the gas in these regions must have been cold and dense (i.e., ≈ 15 K at $\approx 10^4$ cm^{-3}) over substantial periods ~ 3 Myr. Closer to Sun (i.e., $d \lesssim 500$ pc), the study of dust emission from clouds indicates that cold dense cores have a lifetime ~ 0.5 Myr (Evans et al. 2009). Confirmation of these indirect statistical estimates via line observations would be extremely valuable, since the star formation rate of a galaxy depends in part on the collapse timescale of cores. Such work would require comprehensive line observations towards unbiased samples of dense cores that do currently not exist.

On larger spatial scales, the study of molecular abundances can constrain scenarios for the formation and dispersal of molecular clouds. Harada et al. (2019) use line observations of the W51 and W3(OH) complexes (studied by Watanabe et al. 2017 and Nishimura et al. 2017) to suggests that most of the mass was accreted into the clouds just about 10^5 yr ago, or is regularly chemically "reset" by star formation on these timescales. Application of the Harada et al. modeling in a spatially resolved fashion to clouds less disturbed by star formation could thus reveal "age gradients" in clouds. Recent studies of limited cloud samples have indeed found evidence for the growth of clouds in the form of emission from SiO, HNCO, and CH_3OH that might trace weak accretion shocks (Cosentino et al. 2017; Jiménez-Serra et al. 2010; Yu et al. 2018). Clarification is needed because cloud formation controls star formation rates in galaxies.

Similarly, the dispersal of molecular clouds controls the period over which a cloud can form stars. Work in this field would benefit from better information on shocks (e.g., from SiO, HNCO, and CH_3OH) and the extent to which gas is exposed to star formation feedback (Harada et al. 2019).

2.3 Astrochemistry of Star and Planet Formation

Aspects of the composition of Earth's oceans (i.e., the deuterium abundance) are probably inherited from the Sun's natal dense core (Caselli & Ceccarelli 2012). This must be explored further.

First, the chemistry of the material in dense cores that is available at the onset of collapse must be studied. This holds in particular for numerous deuterium–bearing molecules accessible at 70 to 80 GHz, which primarily exist in the coldest and densest gas that gets accreted most efficiently. Detailed observational and theoretical studies are needed to resolve stark conflicts between measured and expected astrochemical compositions in cores (e.g., Bacmann et al. 2012).

Second, unbiased surveys of the astrochemical diversity among dense cores are needed. Such data are required to constrain the initial astrochemical conditions for the subsequent dense core evolution ahead of gravitational collapse. Cores vary in their mass, density, and evolutionary state. They are enveloped by filaments and clumps that also affect dense core evolution. Complete surveys

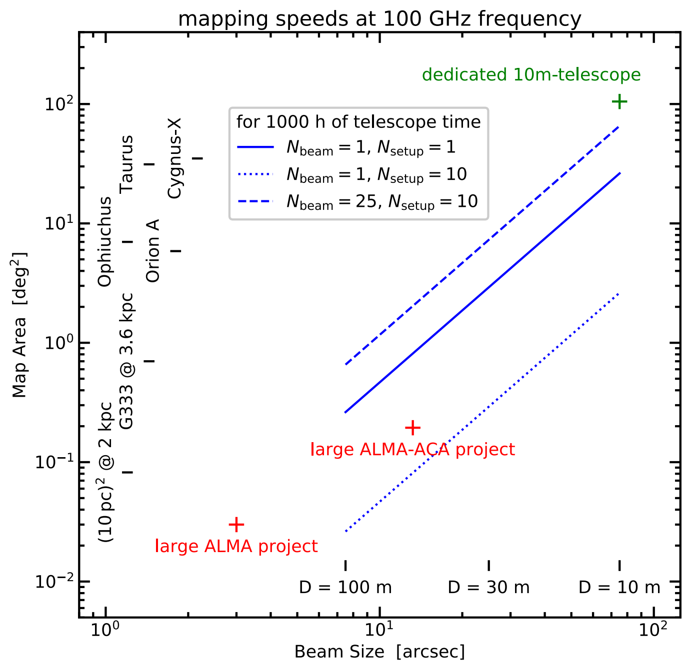

Figure 2: Comparison between target sizes (indicated along vertical axis) and observational capabilities. For ALMA we assume observations of one setup in a large project of 50 h, respectively observations with the ALMA–ACA for 100 h. The blue lines assume observations for 1,000 h on telescopes of various sizes, including overheads. The green cross holds for a dedicated 10m–telescope observing with $N_{setup} = N_{beam} = 1$ for 4,000 h.

of all cores, filaments, and clumps in clouds would thus be desirable for such work.

3 Outline of Observations beyond 2020

3.1 Technical Considerations

For fixed noise level and velocity resolution, the achievable map area Ω_{map} scales as

$$\Omega_{map} \propto \frac{N_{beam}}{N_{setup}} \cdot T_{sys}^{-2} \cdot \vartheta_{beam}^2 \cdot t_{map} \,, \tag{1}$$

where the map duration t_{map} includes overheads, $\vartheta_{beam} \propto D^{-1}$ is the beam size of a telescope of diameter D, and T_{sys} is the noise temperature of the system. Instruments with limited spectral bandwidth will need to cycle through N_{setup} receiver setups. Multi–feed cameras allow to simultaneously observe with $N_{beam} > 1$ independent beams on the sky. We evaluate Eq. (1) in Fig. 2 after scaling to $T_{sys} = 200$ K, 100 GHz frequency, and a target noise level of 0.1 K in channels of 0.5 km s^{-1} width. We also include estimates from the ALMA Observing Tool for a single setup observed with channels of 0.4 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).

Here we focus on the range $\lesssim 115$ GHz (but see Sec. 3.4). Pety et al. (2017) show that ~ 20 valuable emission lines can be imaged at frequencies of 85 to 115 GHz. The science discussed here requires to match or exceed this coverage. A few current systems can achieve $N_{setup} \sim 1$, but typical spectrometer bandwidths ~ 1.5 GHz rather imply $N_{setup} = 10$. Some planned multi–feed cameras achieve $N_{beam} \approx 25$, but for relatively low bandwidths (e.g., ARGUS on GBT, Sieth et al. 2014), so that $N_{setup} \approx 10$. Consistent with current experience, Fig. 2 assumes that large programs on single–dish telescopes receive allocations of up to 1,000 h, including overheads. Figure 2 also considers the case of a dedicated 10m–telescope with $N_{setup} = N_{beam} = 1$ operated for $\gtrsim 4,000$ h.

3.2 Studies of Nearby Clouds

It is important to study very nearby clouds within $\sim$ 500 pc from Sun, given the rich complementary information we possess on these regions. However, as we see in Fig. 2, regions like the Taurus, Ophiuchus, and Orion A clouds are very large on the sky (e.g., Goldsmith et al. 2008, Evans et al. 2009, Megeath et al. 2012).

Figure 2 shows that regions like the entire Orion A cloud 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. ALMA, as well as telescopes with $D \sim 100$ m, are not suited for this work, even if ALMA evolves as envisioned (Carpenter et al. 2019). Small telescopes achieve a spatial resolution $\ell_{\rm beam} = 0.18~{\rm pc} \cdot (d/500~{\rm pc}) \cdot (\nu/100~{\rm GHz})^{-1} \cdot (D/10~{\rm m})^{-1}$. Facilities with $D \approx 10$ m might not entirely resolve all structure inside clouds.

3.3 Clouds in the Galactic Disk

A larger range of facilities becomes relevant for full–scale mapping of molecular clouds if we consider regions at $d \lesssim 4$ kpc. Provided $N_{\rm setup} \sim 1$ or $N_{\rm beam} \gtrsim 10$, telescopes with $D = 100$ m can deliver valuable studies of clouds of $(10~{\rm pc})^2$ size (Fig. 2). They can also image larger regions, such as the G333 complex (Lo et al. 2009), at decent spatial resolutions $\ell_{\rm beam} = 0.15~{\rm pc} \cdot (d/4~{\rm kpc}) \cdot (\nu/100~{\rm GHz})^{-1} \cdot (D/100~{\rm m})^{-1}$. But the Galactic Disk also contains much larger regions of interest, such as Cygnus–X (Schneider et al. 2011). Such complexes, or sections within them, can only be studied with smaller telescopes. But such facilities, with beams $\ell_{\rm beam} = 1.5~{\rm pc} \cdot (d/4~{\rm kpc}) \cdot (\nu/100~{\rm GHz})^{-1} \cdot (D/10~{\rm m})^{-1}$, will only reveal structure on the scale of clumps. ALMA, by comparison, can only investigate small regions within clouds. But this can be done at an excellent spatial resolution $\ell_{\rm beam} = 0.02~{\rm pc} \cdot (\vartheta_{\rm beam}/1'') \cdot (d/4~{\rm kpc})$ that is required for the study of fine cloud substructure.

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 detail at large distances. 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

Ambitious current studies begin to image entire molecular clouds in rich sets of molecular emission lines. This simultaneous access to many emission lines allows to refine our understanding of the gas kinematics that control star formation, and thus shape stellar properties like the IMF (Sec. 2.1). Rich data on molecular lines also allow to constrain the evolutionary timeline of molecular clouds, which impacts the star formation efficiency of galaxies (Sec. 2.2). Emission from molecules further probes the processes shaping the astrochemical composition of stars and planets (Sec. 2.3).

Large telescopes and ALMA are needed to resolve detail in distant clouds. But numerous relevant targets have a large angular size, requiring observations with telescopes as small as $D \approx 10$ m. 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. 2 and Sec. 3).

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