Star-Forming Filaments and Cores in Molecular Clouds

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Primary Area: *Star and Planet formation*

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Executive Summary

Continuum observations of molecular clouds have revealed a surprising amount of substructure in the form of filaments of a few pc length and cores of ∼0.1 pc diameter. Understanding the evolution of these substructures towards star formation requires the kinematic and dynamical insights provided uniquely by sensitive line observations at high angular and spectral resolution. We describe the best probes of the dynamics of filaments and cores in nearby star-forming molecular clouds, and our recommendations for furthering our understanding of star formation physics through observations over the next decade.

1 Introduction

Stars form out of molecular cloud gas, when dense pockets (i.e., "cores") become gravitationally unstable and collapse (for a review, see Di Francesco et al., 2007). Recent far-infrared/submillimeter continuum observations (e.g., from *Herschel* and the JCMT) of Galactic clouds at distances < 3 kpc have revealed close connections between the detailed substructures of clouds and star formation. First, molecular clouds are suffused with filaments, parsecs-long substructures of $\sim$0.1 pc width, regardless of their star-forming activity (André et al., 2010; Ward-Thompson et al., 2010). Second, clouds can have hundreds of cores, many of which appear bound and hence likely to form stars in the future (Könyves et al., 2010). Third, core formation, and hence star formation, appears to be most efficient within supercritical filaments above a given column density threshold equivalent to $A_V \sim 7$ magnitudes (André et al., 2010, 2014). Finally, high-mass star and cluster formation occur most efficiently where supercritical filaments appear to intersect (Schneider et al., 2012). Understanding the relationships between filamentary substructures and star formation requires kinematic and dynamical insights. Some key questions that remain unanswered include [i] how does gas in clouds assemble into filaments and cores?; [ii] how will the gas in these substructures evolve?; [iii] is there further coherent substructure within filaments (e.g., "fibers"; Hacar et al., 2013, 2017); [iv] what fraction of starless cores are transient, and what fraction form stars?

The continuum observations that identified filaments in molecular clouds do not themselves have the ability to trace their kinematics and dynamics. Instead, observations of line emission are essential to determine how mass flows within filaments and cores and whether or not such substructures are stable. Large-scale surveys of lines are needed at sensitivities and resolutions not possible with currently available observatories.

2 Current Observations

Nitrogen-bearing molecules like NH_3 and N_2H^+ are commonly-used tracers of dense gas in cores and filaments, due to their preferential formation and excitation in cold, dense molecular environments, and their resistance to freeze-out onto dust grains that plague analyses of more abundant, carbon based molecules (i.e., CO and its isotopologues) in the dense ISM.

The NH_3 rotation-inversion transitions at 24 GHz (e.g., (1,1), (2,2), (3,3), etc.) can probe effectively the kinematics and dynamics of star-forming substructures in nearby molecular clouds. This behavior follows partly because the NH_3 transitions are excited in moderately dense gas; e.g., the critical densities of (1,1) and (2,2) at 10 K are 10^{3-4} cm^{-3} (Ho and Townes, 1983). The proximity of the transitions in frequency means that many telescopes are able to observe multiple transitions simultaneously, which provide directly the gas kinetic temperature along the line of sight via their ratios (Walmsley and Ungerechts, 1983). The hyperfine structure of the NH_3 transitions further allows, through simultaneous fitting, direct determinations of excitation temperature and opacity, and hence column density.

We have moved recently beyond detailed observations of small-scale regions through large-scale, Legacy-scale programs, which are only possible with the Green Bank Telescope

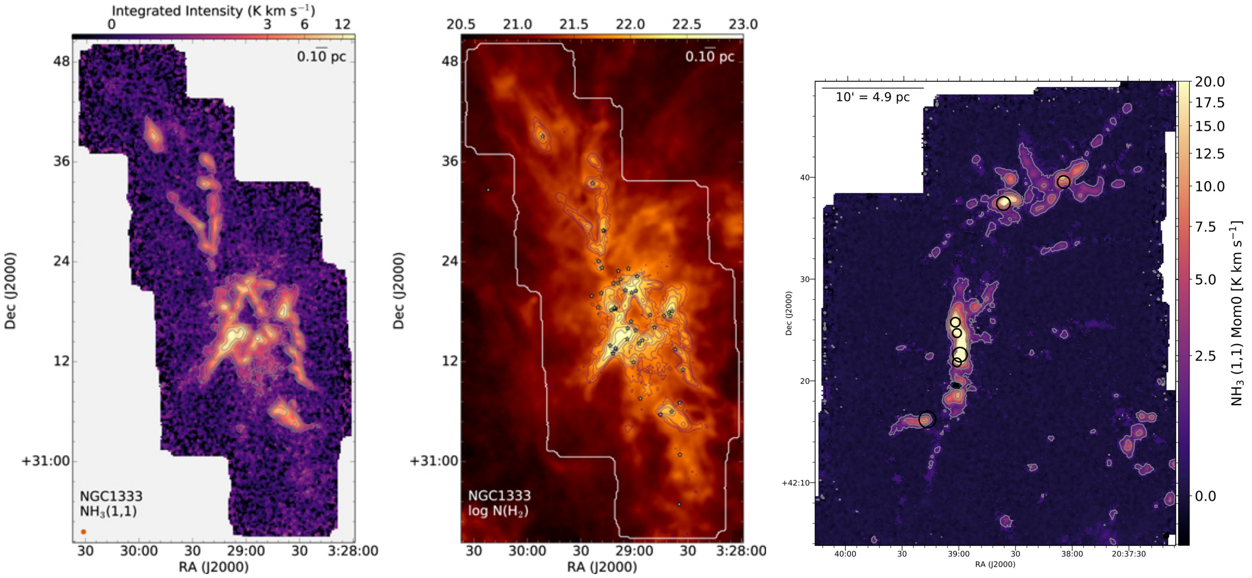

Figure 1: Left: Integrated intensity of NH_3 (1, 1) toward NGC 1333 obtained by the Green Bank Ammonia Survey (GAS; Friesen et al., 2017). Contours are drawn at [3, 6, 12, 24, ...]-σ. Middle: the H_2 column density, $\log_{10}$ [$N(H_2)$ cm^{-2}], derived from SED fitting of Herschel submillimeter dust continuum data (A. Singh et al., in preparation). Contours show the NH_3 (1,1) integrated intensity, as in the left panel. White contours show the GAS map extent. Stars show the locations of Class 0/I and flat-spectrum protostars (Dunham et al., 2015). Right: Integrated intensity of NH_3 (1,1) toward the Cygnus X North region, including DR21 (KEYSTONE; Keown et al., in preparation). Contours are at 1.0, 3.5, and 10 K km s^{-1}. Circles show the locations of H_2O maser emission simultaneously detected during the NH_3 observations. The size of the circle indicates the relative brightness of the maser emission.

(GBT) using its unique, 7-pixel K-band Focal Plane Array (KFPA) instrument. (The only telescope other than the GBT equipped with a K-band array is the 64m diameter Sardinia Radio Telescope, which has a 7-pixel array covering 18 to 26.5 GHz.) These Large Programs are mapping many square degrees of sky in nearby molecular clouds, Giant Molecular Clouds, and large swaths of the Galactic Plane. Figure 1 (left) shows the integrated intensities of NH_3 (1,1) emission toward the NGC 1333 star-forming region of the Perseus molecular cloud from the Green Bank Ammonia Survey (GAS; Friesen et al., 2017), compared with the H_2 column densities of the same region derived from continuum data obtained by *Herschel* (middle; A. Singh et al., in preparation). Figure 1 (right) shows the integrated intensity of NH_3 (1,1) emission toward the Cygnus X North region, including DR21, from the K-band Examinations of Young STellar Object Natal Environments survey (KEYSTONE; Keown et al., in preparation). In both cases, NH_3 emission indicative of dense, star-forming gas is widely detected, much of it in filaments. At lower sensitivities but over a much larger area, the RAMPS project is mapping NH_3 emission across the GBT-visible Galactic Plane (Hogge et al., 2018).

Such wide-field NH_3 mapping surveys are already changing our understanding of the stability of dense cores and hierarchical structures - and hence, their ability to collapse and form stars, disperse without collapse, fragment, and accrete additional mass. For example, comparisons of core masses with their estimated virial states suggest that many cores are not gravitationally bound, but are instead confined by external pressure (Seo et al., 2015; Kirk et al., 2017; Kerr et al., 2019). Over larger spatial scales, however, NH_3-identified structures appear gravitationally dominated, such that they should be gravitationally unstable unless there is significant support by magnetic fields (Friesen et al., 2016; Keown et al., 2017). These surveys have also driven significant effort into public data reduction, calibration, and analysis pipelines to fully realize the scientific potential of these large data products.

N_2H^+ ($n \gtrsim 10^5$ cm^{-3}) traces higher density material than NH_3, and its rotational lines at mm to sub-mm wavelengths also contain hyperfine structure. Wide-field N_2H^+ observations remain challenging due to limitations in sensitivity from smaller single-dish telescopes, small numbers of pixels, and the limited field of view provided by current and past (sub)mm interferometers. Toward selected star-forming regions, N_2H^+ observations identify the high density spines of star-forming filaments (Fernández-López et al., 2014; Storm et al., 2014; Lee et al., 2014), revealing accretion flows toward young stellar clusters (Kirk et al., 2013) and infall in gravitationally unstable filaments and cores (e.g., Peretto et al., 2014), and probe the density structure of highly-evolved starless cores. The 16-pixel Argus focal plane array on the GBT, combined with new and future dish surface upgrades, now allows much broader mapping of the N_2H^+ 1-0 line at 93 GHz, along with other mm lines (including those from deuterated species, see below); large (greater than a few arcmin) maps with both high sensitivity and narrow velocity resolution, however, are still time-prohibitive.

Finally, at the high densities and low temperatures typical of starless and protostellar cores, the relative abundance of deuterated species to their non-deuterated counterparts can become orders of magnitude greater than in the local interstellar medium. Sensitive, high resolution observations of deuterated molecules trace both the dense gas structure and kinematics on the compact physical scales required to track the gravitational collapse of star-forming cores and the subsequent formation of young protostars and circumstellar accretion regions. Simultaneously, such observations play a critical role in tracing the chemical history throughout the various phases of star and planet formation. In addition, many of these species are also predicted to distinguish well between disks and pseudodisks in magnetised models of core collapse (Hincelin et al., 2016), and are thus critical to distinguish rotationally-supported disks from collapsing pseudodisks, and to measure infall. Many low$-J$ transitions of key deuterated species, along with their undeuterated counterparts, lie within the 60-110 GHz frequency window, the lower end of which is largely unavailable with current facilities and instrumentation (the IRAM 30 m Telescope and NOEMA interferometer can now observe at frequencies as low as 71 GHz, but with limited resolution and sensitivity).

3 Observational Goals

3.1 Wide-field spectral line mapping from cm to mm wavelengths

There are hundreds of known molecular clouds, from those situated relatively near the Sun (0.1-0.5 kpc distance) to those largely confined to the Galactic Plane (∼10 kpc distance). Dense gas is found within molecular clouds in relatively isolated locations, a small percentage of total cloud surface areas, but nevertheless requiring mapping across relatively wide fields to fully capture the extent of the actively star-forming material.

Many other lines of interest are available at cm through mm wavelengths that complement the dense gas tracers and trace different components of the cloud. For example, the NH_3 surveys discussed here all observe simultaneously, within the limits of the current GBT spectrometer, a subset of emission lines around 24 GHz that are expected to trace different environments in the star-forming region. The presence of carbon-chains (e.g., C_2S, HC_5N) is strongly dependent on the physical and chemical history of the region. Significant carbon-chain emission is seen in a subset of GAS clouds, but it is not clear whether these lines reveal cloud collisions (Nakamura et al., 2014), accretion onto filaments (Friesen et al., 2013), or are solely due to differences in the initial chemistry of the cloud (Seo et al., 2019). In the KEYSTONE and RAMPS surveys, simultaneous observations of H_2O maser emission pinpoint locations of high mass star formation. These complementary data are needed to understand the physics of filament formation and evolution, but the surveys are limited in additional line selection by the available spectral capabilities at the telescope, and by the map depth available in a reasonable time with only seven pixels.

Deuterated species are abundant in cold, dense, star-forming filaments and cores. In these environments, the ground-level rotational transitions of these species are the most sensitive probe of molecular abundances, but observations are needed to test and refine astrochemical models. The rest frequencies of these transitions for many key deuterated species lie below 80 GHz, however, and are not accessible by most current single-dish telescopes or interferometers. In this wavelength regime, observations from the ground are limited by the water line at $50 - 70$ GHz. The greatest limitation is therefore not the receiver technology, but how close to the water line you can observe (i.e., site and weather). For many of these species, their non-deuterated counterparts also have observable transitions in this window, enabling direct measurements of the deuterium fractionation as a function of species. This band contains the low excitation lines of multiple deuterated species of interest in both starless cores and their more evolved, protostellar counterparts.

3.2 High resolution, low surface brightness mapping from cm to mm wavelengths

Though wide-field observations such as those in Figure 1 are enabling significant advances to be made about understanding star formation, it remains challenging to recover from such data important details of the kinematics and dynamics of the dense gas. For context, the GBT's angular resolution, i.e., $33''$ at 24 GHz, is equivalent to 0.07 pc at the 420 pc distance of the Orion molecular cloud complex, while cores and filaments each have characteristic widths of 0.1 pc (Di Francesco et al., 2007; Arzoumanian et al., 2011). Hence, the GBT ammonia observations do not resolve the gas kinematics and dynamics of such structures in clouds much more distant that Orion. ^{13}CO observations with the GBT using the Argus 16-pixel and with the LMT and the Sequoia array do give significantly higher resolution, but mapping speed is limited. Higher-resolution observations are critical for such targets, to probe for further substructure and allow details of mass flow and dynamical stability to be recovered. High mass star-forming regions are generally assumed to be dominated by supersonic motions. With the higher spatial resolution afforded by the Jansky VLA, however, extremely narrow, velocity coherent filaments were identified in NH_3 emission in Orion (Monsch et al., 2018). Sokolov et al. (2018) further suggest that instrumental limitations on spectral resolution may have biased our understanding of the turbulent nature of dense gas in these regions. The Jansky VLA is limited at 24 GHz by its point-source sensitivity to line emission, its relatively small field-of-view, and its insensitivity to moderate spatial scales, qualities determined by the sizes and configurations of the VLA dishes. It is thus challenging to map the internal details of multi-pc long filaments and numerous cores. This science is uniquely addressed with sensitive observations of low surface brightness emission at high spectral and spatial resolution in K-band. A next generation radio array (operating at least up to 24 GHz) with improved sensitivities and wider fields-of-view will enable acquisition of the data needed to probe best the kinematics and dynamics of dense star-forming gas. With a flexible array, targets could include large samples of targeted individual pre-/protostellar cores and their host filaments or wide-field mapping across star-forming molecular clouds.

4 Recommendations

To achieve the science and observational goals described above, we highlight several recommendations that will advance our understanding of star formation in filaments and cores over the next decade and beyond. We believe that significant investment in instrumentation and facilities focusing on cm-mm observations, particularly those that are able to detect faint emission, over large scales, and at high resolution, are sorely needed. The science enabled by these recommendations will also complement well already planned or potential future observatories in the submm and FIR regimes.

1. Development of flexible receivers that can simultaneously observe multiple spectral lines at cm - mm wavelengths for both single-dish and interferometer facilities. Surveys of dense filaments and cores require high spectral resolution to resolve the velocity dispersion of dense, quiescent gas ($\lesssim 0.1$ km s^{-1}), as well as the flexibility to observe simultaneously lines that trace different conditions and chemical histories to understand the past and future evolution of such structures - and hence the physics that drive star formation in our Galaxy.

2. Large, single-dish telescopes (such as the GBT and LMT) equipped with large–format ($N \geq 100$) focal plane arrays at cm through mm wavelengths to map extended molecular line emission over a wide range of Galactic environments, to probe the relatively unexplored link between star formation activity and environment, and to exploit the high sensitivity to low surface brightness emission single-dish telescopes provide.

3. Development of a next-generation interferometer array at cm through mm wavelengths, like the proposed ngVLA, that will enable multi-line observations of the tracers described above at high spatial resolution, while retaining sensitivity to low surface brightness emission.

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