Star-forming Filaments and Cores on a Galactic Scale

James Di Francesco¹, Jared Keown², Rachel Friesen³, Tyler Bourke⁴, and Paola Caselli⁵
¹National Research Council of Canada, Victoria, BC, Canada; james.difrancesco@nrc-cnrc.gc.ca
²University of Victoria, Victoria, BC, Canada; jkeown@uvic.ca
³National Radio Astronomy Observatory, Charlottesville, VA, U.S.A.; rfriesen@nrao.edu
⁴Square Kilometre Array Organization, Macclesfield, UK; t.bourke@skatelescope.org
⁵Max Planck Institute for Extraterrestrial Physics, Garching, Germany; caselli@mpe.mpg.de

Abstract. 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. In this Chapter, we describe how an ngVLA can probe effectively the dynamics of filaments and cores in nearby star-forming molecular clouds using the NH₃ rotation-inversion transitions at 24 GHz. Such emission has been proven to trace well the high column density environments of star-forming cores and filaments but higher-resolution observations are needed to reveal important details of how dense gas is flowing within and onto these substructures. In particular, we describe how 150 × 18-m antennas with a maximum baseline of 1 km can be used to map sensitively NH₃ emission across high column density locations in clouds in roughly an order of magnitude less time than with the current Jansky VLA.

1. Introduction

Stars form out of molecular cloud gas, when dense pockets (i.e., “cores”) become gravitationally unstable and collapse (see Di Francesco et al. 2007 for a review). Recent far-infrared/submillimeter continuum observations (e.g., from Herschel or 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 ∼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 ~ 7 magnitudes (André et al. 2010, 2014). Indeed, the
resulting core mass function strikingly resembles the initial stellar mass function, suggesting the process that forms cores also ultimately determines stellar masses (Könyves et al. 2015). 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. For example, how does gas in clouds assemble into filaments and cores? Also, how will the gas in these substructures evolve? Is there further coherent substructure within filaments (e.g., “fibers”; Hacar et al. 2013, 2017). 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. More specifically, to understand the structure and dynamical evolution of molecular clouds in general, large-scale surveys of lines must be performed at sensitivities and resolutions not possible with currently available observatories.

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. NH$_3$ emission has been shown repeatedly to trace best the loca-
Figure 2. Integrated intensity map of the NH$_3$ (1,1) line for the Cygnus X North region, including DR21, obtained by the KEYSTONE survey (Keown et al. 2018). Colors range from -1 K km s$^{-1}$ (black) to 10 K km s$^{-1}$ (yellow). Contours are at 1.0, 3.5, and 10 K km s$^{-1}$. Circles show the locations of H$_2$O maser emission simultaneously detected during the NH$_3$ observations. The size of the circle indicates the relative brightness of the maser emission.
tions of significant column density revealed by continuum emission from dust (e.g., Benson & Myers 1989). 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 & Townes 1983). In addition, these NH$_3$ transitions have hyperfine structure that spreads out their overall optical depths over numerous components, enabling better probes of all dense gas along the line of sight (Crapsi et al. 2007). In contrast, other molecules have emission that is too optically thick to sample such environments (e.g., $^{12}$CO) or have been themselves too drastically depleted in cold dense gas to be effective probes (e.g., C$^{18}$O; see Di Francesco et al. 2007). Even other less-abundant "dense gas tracers" like HCN or CN emission may yet suffer from optical depth and depletion issues on the scales of cores and filaments. Furthermore, the hyperfine structure of the NH$_3$ transitions further allows, through simultaneous fitting, direct determinations of excitation temperature and opacity, and hence column density. Finally, these NH$_3$ transitions can directly provide the gas kinetic temperature along the line of sight via their ratios (Walmsley & Ungerechts 1983), unlike those of other nitrogen-based molecules (e.g., N$_2$H$^+$).

Given the utility of NH$_3$ emission, it is being widely observed to trace the kinematics and dynamics of moderately dense gas in molecular clouds, especially in filaments and cores. These programs are being largely run from the Green Bank Telescope (GBT) using its unique K-band Focal Plane Array (KFPA) instrument to map many square degrees of sky in nearby molecular clouds, Giant Molecular Clouds, and large swaths of the Galactic Plane. Figures 1 and 2 show examples of recent wide-field GBT KFPA observations of NH$_3$ (1,1) emission toward star-forming molecular clouds. 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 with the KFPA (Friesen et al. 2017), while Figure 1 (right) shows the H$_2$ column densities of the same region derived from continuum data obtained by Herschel (Singh et al. 2018). Figure 2 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 (KEYSTONE) survey (Keown et al. 2018). In both cases, widespread NH$_3$ emission indicative of dense, star-forming gas is seen, much of it in filaments.

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, Kirk et al. (2017) combined GAS and JCMT Gould Belt Legacy Survey data to estimate the virial states of dense cores within the Orion A molecular cloud. They found that none of the dense cores are sufficiently massive to be bound when considering only the balance between self-gravity and the thermal and non-thermal motions present in the dense gas, in contrast to analyses which include only thermal gas motions. Instead, most of the dense cores are pressure-confined by the additional pressure binding imposed by the weight of the ambient molecular cloud material and additional smaller pressure term. Over larger spatial scales, Keown et al. (2017) showed that NH$_3$-identified structures in Cepheus are gravitationally dominated, yet may be in or near a state of virial equilibrium. Filamentary structures in Cepheus have virial parameters $\ll 2$, such that they should be gravitationally unstable unless there is significant support by magnetic fields. This result is consistent with a similar analysis of the more massive, more actively star-forming Serpens South region (Friesen et al. 2016),
and hints that large-scale gravitational instability is a general property of the dense gas structure in star-forming environments.

Though wide-field observations such as those in Figures 1 and 2 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 relatively low 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, but cores and filaments each have characteristic widths of 0.1 pc (Di Francesco et al. 2007; Arzoumanian et al. 2011). Hence, the GBT observations do not resolve the gas kinematics and dynamics of such structures in clouds much more distant than Orion. Indeed, 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. Though the Jansky VLA can be currently used to observe NH$_3$ emission at 24 GHz, its limited point-source sensitivity to line emission, its relatively small field-of-view, and its insensitivity to moderate spatial scales, qualities effectively hardwired since the beginning of the VLA’s operations in 1980, make it challenging to map the internal details of multi-pc long filaments and numerous cores. Instead, a next generation Very Large Array (ngVLA) 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 an flexible ngVLA, targets could include large samples of targeted individual pre-/protostellar cores and their host filaments or wide-field mapping across star-forming molecular clouds.

2. NH$_3$ observing with ngVLA

This science is uniquely addressed with sensitive observations of low surface brightness emission at high spectral and spatial resolution in K-band. The current ngVLA design will enable acquisition of such data through two important features: i) a large amount of surface area over relatively small baselines to obtain high sensitivity to compact sources, and ii) a Short Baseline Array (SBA) of antennas in a compact fixed configuration that provides high sensitivity to extended sources. As stated above, the Jansky VLA does not have the sensitivities or field-of-view in K-band for wide-field imaging of NH$_3$ emission (see also below). The GBT is useful for locating NH$_3$ emission but it does not have the intrinsic angular resolution to resolve cores and filaments beyond Orion, e.g., in several key Giant Molecular Clouds like Cygnus X (see Figure 2). At present, no other single-dish radio telescope on the planet is as optimally equipped for wide-field K-band observing than the GBT. The SKA’s current specifications on sensitivity only go up to 15 GHz. While there is a specification for aperture efficiency at 20 GHz, the SKA antennas are not being optimized for performance above 15 GHz. (We note that design work indicates that performance of the SKA antennas will be good at 25 GHz but their actual performance remains to be determined.) ALMA can observe emission from N$_2$H$^+$, a nitrogen-based molecule chemically similar to NH$_3$ that can also trace dense gas, but the critical density of its lowest rotational transition is 1-2 orders of magnitude higher than those of the lower NH$_3$ transitions, suggesting it is less able to map typically lower density filaments or the transition regions between dense cores and the filaments within which they are embedded. Moreover, N$_2$H$^+$ cannot be used to determine kinetic gas temperatures directly as NH$_3$ can. (Note that an ngVLA with frequency coverage up to 115 GHz will be able to detect N$_2$H$^+$ 1-0 emission at 93
GHz at higher sensitivity than ALMA, allowing sensitive probes of compact dense gas in cores.)

No other facilities are planned to sample K-band frequencies with the sensitivities and resolutions of the ngVLA. Synergies may exist with future far-infrared or submillimeter space missions like SPICA and OST, if such facilities have wide-field continuum imaging capabilities. In particular, the potential addition of polarizers on these telescopes would provide high-resolution information on magnetic field morphologies, from which ngVLA line data could allow magnetic field strengths to be determined using the Davis-Chandrasekhar-Fermi method. Though cores and filaments emit largely at far-infrared and submillimeter wavelengths, maps of their internal structures at resolutions higher than Herschel or the JCMT, i.e., 1-3”, could arise from extinction mapping of molecular cloud material using deep wide-field near-infrared observations from next-generation facilities such as TMT/E-ELT or LSST. Complementarity with kinematic information on such scales is therefore vital.

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), so there are several targets available from any potential ngVLA site. The targets, however, are generally within 30 degrees of the Galactic Plane. Dense gas is found within molecular clouds in relatively isolated locations, a small percentage of total cloud surface areas. Nominally, such locations exhibit extended NH$_3$ emission over ∼10’ × 10’ scales in single-dish maps. The typical peak brightnesses of NH$_3$ (1,1) emission are 1-3 K (T$_{mb}$) in a 33” beam. Assuming no beam dilution, those brightnesses translate to 7.5-25 mJy beam$^{-1}$ for a “standard resolution” ∼4” beam (see below). Detection of such emission at an SNR of ∼5, the minimum needed for high-quality line fitting, requires per channel sensitivities of ∼5 mJy beam$^{-1}$.

3. Example ngVLA Mosaic Observations

To determine examples of reasonable observations for an ngVLA, we first assume a standard target resolution of 4” FWHM, similar to that provided by the D configuration of the Jansky VLA. Going to higher resolution has a profound impact on surface brightness sensitivity, so there are tradeoffs expected between sensitivity and field-of-view. Of course, more distant clouds for which higher resolution may be most beneficial will be intrinsically more compact and require fewer pointings per mosaic. Single-dish data show NH$_3$ emission in dense gas regions of nearby molecular clouds to be extended over ∼10’ × 10’ fields, leading to a mapped image size of ∼100 sq. arcmin. In addition, the target maximum angular scale is ∼30”. The important addition of an SBA to the ngVLA will enable low surface brightness emission to be detected over larger scales. Here, however, we focus on ngVLA observations without an SBA, to provide a more straightforward comparison with the current Jansky VLA.

We expect that a target sensitivity of ∼0.5 K in channels 0.05 km s$^{-1}$ wide over a mosaic of 10’ × 10’ provides a reasonable minimum goal for ngVLA observations of dense gas in star-forming regions. Such high spectral resolution is necessary to resolve NH$_3$ lines at low temperatures, e.g., the thermal line width of NH$_3$ at 10 K is 0.07 km s$^{-1}$. According to the VLA Exposure Calculator$^1$, 24 GHz can be observed

$^1$https://obs.vla.nrao.edu/ect/
Figure 3. Hours of integration required to reach a 1 $\sigma$ rms = 0.5 K at 24 GHz in a 0.05 km s$^{-1}$ channel over a 10' $\times$ 10' mosaic at 4'' FWHM resolution given the number of antennas in an array. Note that this resolution requirement means the number of antennas within about ~1 km maximum baseline. The number of hours is obtained using the current Jansky VLA Exposure Calculator and scaling the integration time by the $D^2N^4$ scaling relation for mapping speed. ($D$ is the antenna diameter and $N$ is the number of antennas.) The solid red line shows the number of 25-m antennas within 1 km needed to reach this target sensitivity in New Mexico (i.e., assuming Jansky VLA site conditions). The black triangle indicates the current Jansky VLA of 27 antennas. The solid green line shows the number of 12-m diameter antennas within 1 km needed in New Mexico, while the dashed green line shows the number of 12-m ALMA-like antennas required at the Llano de Chajnantor in Chile which has superior site conditions. For reference, the black square indicates the 50 $\times$ 12-m antennas of ALMA, though ALMA has no plans for K-band receivers for the foreseeable future. The solid blue line shows the number of 18-m antennas within 1 km needed to reach the target sensitivity in New Mexico, with a star indicating the reasonable number (150) needed in a compact distribution of ngVLA antennas.
in a single pointing to 0.5 K sensitivity in 0.05 km s\(^{-1}\) channels with 25 antennas in D configuration (i.e., ñ3-4" FWHM resolution) in ñ1.2 hours of winter time on source or ñ2.3 hours with overheads. (Baselines of up to 4 km are needed to reach 1" resolution.) A ñ10' Ê 10' field of dense gas, however, requires ñ126 pointings for Nyquist sampling in a mosaic. Indeed, a mosaic may benefit from a \(\sqrt{2}\) increase in sensitivity from overlapping pointings, equivalent to a savings of time by a factor of 2. Accordingly, the Jansky VLA can reach the target sensitivity over a 10' Ê 10' mosaic in approximately 78 hours. Though tractable for a small cloud of 100 sq. arcmin. size or less, mapping the NH\(_3\) emission of larger clouds with the Jansky VLA would take numerous such mosaics to cover their entirety, and hence would require a prohibitively large amount of observing time. For example, the mapped region of Cygnus X shown in Figure 2 consists of eleven such 10' Ê 10' fields.

Figure 3 shows the number of hours needed to reach the target sensitivity of 0.5 K in 0.05 km s\(^{-1}\) channels over a 10' Ê 10' mosaic for various numbers of antennas of different size. The trends follow the well-known \(D^2N^4\) scaling relation for mapping speed, where \(D\) and \(N\) are the diameter and number of the antennas, respectively. The hours needed for the Jansky VLA of 27 antennas of 25-m diameter is indicated, as is the impact on observing time given a lesser or greater number of such antennas. Also shown in Figure 3 are curves indicating the observing times needed to reach the target sensitivity for 18-m and 12-m diameter antennas in New Mexico, again following the \(D^2N^4\) scaling relation. For further comparison, a curve is also shown in Figure 3 for ALMA-like 12-m antennas on the Llano de Chajnantor in Chile, which has site conditions superior to those in New Mexico (e.g., a 50% better atmospheric opacity at 24 GHz is assumed). ALMA has 50 Ê 12-m antennas and the specific hours of integration needed for it to reach the target sensitivity is indicated in Figure 3. Note, however, that there are no plans to install K-band receivers on ALMA for the foreseeable future. Also, the sensitivity performance of ALMA equipped with K-band receivers would be merely comparable to that of the Jansky VLA.

Figure 3 indicates that ñ150 Æ 18-m antennas within 1 km distance would be sufficient to improve the observing speed of observing such a mosaic to the target sensitivity by roughly an order of magnitude, i.e., 9.4 hours. In contrast, hundreds of 12-m antennas in New Mexico would be needed to reach a similar performance improvement. Note that for the ngVLA curves in Figure 3 we assumed current Jansky VLA receiver and antenna performances and did not include further sensitivity improvements from receiver upgrades or better dish surfaces.

We conclude that 150 antennas with a maximum baseline of ñ1 km are required to fulfill this science case. Such antenna numbers are needed as an absolute minimum to enable roughly an order of magnitude improvement over the current Jansky VLA. Compact placement of ngVLA antennas is critical for the ability to image low surface brightness emission from dense gas. For context, a circular area of 1-km diameter has the same surface area as ñ3100 antennas of 18-m diameter, so the required configuration will be tight but doable. At present, however, the ngVLA concept includes ñ220 Æ 18-m antennas of which only ñ40% (i.e., 88) would be located within 2 km and another ñ40% located within 50 km. Hence, it may be worthwhile for the inner ngVLA antennas to have some limited reconfigurability for low surface brightness imaging. Note that the inclusion of an SBA in the ngVLA concept will provide complementary sensitivity to low surface brightness emission on large scales. Indeed, a subset of a few SBA antennas equipped with K-band focal plane arrays to obtain total power observations
efficiently would be very beneficial for this science. Detailed simulations of ngVLA observations of dense gas structures, including inputs from various SBA designs, are urgently needed.

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