Exploring Protostellar Disk Formation with the ngVLA

John J. Tobin  
*University of Oklahoma, jjtobin@ou.edu*

Patrick Sheehan  
*University of Oklahoma*

Doug Johnstone  
*NRC-Herzberg*

Rajeeb Sharma  
*University of Oklahoma*

**Abstract.** The formation and evolution of disks early in the protostellar phase is an area of study in which the ngVLA is poised to make significant breakthroughs. The high-sensitivity and resolution at wavelengths of 3 mm and longer will enable forming disks to be examined with unprecedented detail. The need to observe dust emission at wavelengths of 3 mm and longer is motivated by the fact that dust emission at these wavelengths is more likely to be optically thin, which is essential to understanding the structure of these disks. We explore the feasibility of detecting and resolving protostellar disks with a variety of radii, masses, and distances, out to distances as large as 1.5 kpc using radiative transfer models and simulations with the proposed ngVLA configuration. We also examine the potential for the ngVLA to enable studies of grain growth and radial migration of dust particles early in the protostellar phase with the broad multi-wavelength coverage. Studies of grain growth will require wavelength coverage extending at least to $\sim 4$ cm to characterize and quantify the location and intensity of free-free emission, which is expected to be generated at $< 10$ AU scales.

1. Introduction

The formation of disks occurs as a natural consequence of angular momentum conservation during the star formation process. As such, proto-planetary disks are found nearly ubiquitously toward pre-main sequence stars, with higher fractions of disks found toward members of clusters/associations having younger collective ages (Hernández et al. 2008). The origins of proto-planetary disks can be traced to the disks that form during the early phase of the star formation process, around Class 0 protostars. Class 0 protostars are characterized by a dense envelope of infalling material that feeds the protostellar disk. As the envelope dissipates due to continued accretion and erosion of the envelope by protostellar outflows (e.g., Frank et al. 2014), it becomes a Class I protostar. The Class 0 phase is expected to last $\sim 150$ kyr, while the combined Class 0 and
Class I phases are expected to last \( \sim 0.5 \) Myr (Dunham et al. 2014); these ages estimates are based on the assumption that pre-main sequence stars hosting proto-planetary disks (objects in the Class II phase) have an average age of \( \sim 2 \) Myr. These young, embedded disks are often collectively referred to as protostellar disks.

Protostellar disks are important for the formation and mass assembly of the star, as well as the planet formation process. Most of the mass that is accreted onto a star must pass through the disk, and these protostellar disks are the initial conditions for disk evolution into a proto-planetary disk. The radius and mass of the forming disk can be regulated by the angular momentum of the infalling material, and magnetic fields can remove angular momentum efficiently in the absence of dissipative processes (e.g., Li et al. 2014). As such, the structure of these protostellar disks is expected to be connected to their formation conditions, and clear detections of rotationally supported disks have been found toward Class 0 and I protostars (Tobin et al. 2012; Harsono et al. 2014). The disks may also increase in radius later via viscous evolution and the outward transport of angular momentum (e.g., Manara et al. 2016). Furthermore, if gravitational instability in disks is a viable mechanism for angular momentum transport, the formation of multiple star systems, and possibly giant planet formation, the disks in the protostellar phase are those most likely to have the requisite conditions (Kratter et al. 2010; Tobin et al. 2016). Finally, the growth of solid material can begin during the protostellar phase and this may catalyze the later formation of planets via the core accretion process if the protostellar disk is able to efficiently grow dust grains to pebble/rock sizes in order to promote planetesimal growth.

Typical proto-planetary disks have masses of \( \sim 0.005 \) \( \text{M}_\odot \), radii of \( \sim 50 \) AU, and surface density profiles \( \propto R^{-1} \), meaning that most of the disk mass is at large radii (Andrews et al. 2013; Ansdell et al. 2016). Proto-planetary disks tend to be significantly lower in mass than the protostellar disks, which can have masses \( > 0.1 \) \( \text{M}_\odot \) (Tobin et al. 2015; Jørgensen et al. 2009; Tychoniec et al. 2018). The typical masses, radii, and/or surface density profiles for protostellar disks are still poorly constrained, and the ngVLA has significant potential to unlock some of these characteristics.

### 2. Resolving and Characterizing Youngest Disks

Observational studies of young disks have only just begun to reach samples larger than 10-20 systems (Tobin et al. 2015; Segura-Cox et al. 2016), and young protostar systems (Class 0 and Class I phases) are inherently more rare than pre-main sequence stars hosting proto-planetary disks. This is because the lifetime of the protostar phase is expected to be at least \( \sim 4 \times \) shorter than the lifetime of a PMS star with a disk (Dunham et al. 2014). Specifically, the Spitzer cores2disks survey along with the entire Spitzer Gould Belt survey contain only \( \sim 200 \) \(^1\) Class 0 and I protostars. Thus, to observe large numbers of protostellar disks, more populous star forming regions need to be observed and these are only present at distances \( \geq 400 \) pc. For example, Orion alone contains \( \sim 315 \) Class 0 and I protostars. The need to examine protostellar disks at 100s of pc distances makes their characterization difficult to achieve with the same mass sensitivity and spatial resolution as the more nearby proto-planetary disk systems. Moreover, high mass sensitivity is particularly difficult at long wavelengths where the dust emis-

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\(^1\)This number corresponds to sources with the most firm characterization based on bolometric temperature.
Protostellar Disks with the ngVLA

Figure 1. Spectrum from millimeter to centimeter wavelengths of a typical protostar in Orion. The emission from dust dominates at short wavelengths and free-free dominates at long wavelengths. The ngVLA will fully probe the transition from dust emission to free-free. The 8 mm to 1 cm bands have some free-free emission that is typically removed in current studies using power-law fits to the long wavelength emission. The ngVLA will enable improvements by spatially resolving the free-free emitting region(s). The points at 0.87 mm and 1.3 mm are from ALMA, the points at all longer wavelengths are from the VLA; the green star points are the flux densities between 8 mm and 1 cm with the extrapolated free-free contribution subtracted. Error bars are plotted with each point, but in most cases the statistical uncertainties are smaller than the points plotted.

Figure 1 shows an example radio spectrum of a protostar from the submillimeter to centimeter wavelengths which illustrates the expected spectral properties of protostar systems as a function of wavelength. Protostars often exhibit free-free emission that dominates at wavelengths >1 cm, but can can contribute to the overall flux density at 7.5 mm. Thus, multi-wavelength observations are important to measure and remove the contribution of free-free emission to the flux density at wavelengths where we aim to trace dust emission. We will discuss this aspect further in section 4. For the sake of discussion, throughout this chapter we will use the dust opacity normalization of 0.899 cm$^2$ g$^{-1}$ (dust only) at 1.3 mm from (Ossenkopf & Henning 1994), assuming $\beta=1$ for extrapolation to longer wavelengths (0.155 cm$^2$ g$^{-1}$ at 7.5 mm).

The advent of the Karl G. Jansky Very Large Array (VLA) with its enhanced continuum sensitivity has enabled surveys of protostellar disks at wavelengths between 6.7 mm and 1 cm. Dust emission is more optically thin than at shorter wavelengths and thus the emission better traces column density due to the power-law decrease of dust opacity with increasing wavelength (Hildebrand 1983). Two VLA Nascent Disk and Multiplicity (VANDAM) surveys have been carried out with the VLA toward the Perseus and Orion star forming regions, observing a total of over 200 protostar systems.
in each region. The VANDAM surveys took \( \sim 600 \) hours of time on the VLA. These surveys were conducted in Ka-band at a central wavelength of 9 mm, while observing at the highest possible angular resolutions, translating to spatial resolutions of \( \sim 15 \) AU and \( \sim 30 \) AU in Perseus and Orion, respectively. Example images of disks observed with the VLA are shown in Figure 2. Also note that the VANDAM: Perseus survey observed the entire sample at 4.1 cm and 6.4 cm, but we focus on the dust emission at 5.9 mm to 10 mm in this chapter. This corresponds to the proposed ngVLA band that is most similar to the wavelengths used in VANDAM and is centered at \( \sim 7.5 \) mm.

The VANDAM: Perseus survey detected candidate disks, meaning that extended dust continuum emission was resolved, toward only 12/42 Class 0 protostars and even fewer toward Class I protostars \( \sim 5/37 \) (Segura-Cox et al. 2018 submitted). We show examples of some of the well-resolved disks detected in the VANDAM: Perseus survey in Figure 2 (Segura-Cox et al. 2016). The disks in Perseus were further characterized by Tychoniec et al. (2018), focusing on the integrated dust emission at 9 mm toward all sources whether or not they were resolved. Tychoniec et al. (2018) found that Class 0 protostars tend to have more mass within radii \( < 100 \) AU relative to the Class I protostars. Furthermore, both Class 0 and Class I protostars had higher masses than the more-evolved proto-planetary disks (Class II sources). The low percentage of well-resolved disks toward Class 0 and I protostars may be due to both the limited spatial resolution and sensitivity of the VLA. The sensitivity may be especially limiting for Class I protostars as, due to their disk evolution, they have less overall mass (thus lower flux densities). The ability to observe at wavelengths of \( \sim 9 \) mm is extremely important for examining protostellar disks, especially around Class 0 targets. If they are compact (R\(< 50 \) AU) and massive (\( > 0.01 \) M\(_{\odot} \)), they are likely optically thick at shorter wavelengths, but remain optically thin at most radii at 9 mm. We show radial surface
density profiles for model protostellar disks and their corresponding radii where $\tau = 1$ in Figure 3, thereby underscoring that long wavelength observations of dust emission are essential to resolve and quantify the majority of the mass within protostellar disks. The opacity of disks at different wavelengths depending on mass and radius will be discussed in more detail in the following section.

Despite the advances enabled by the VLA surveys, they are not without limitations. Due to the increased distance to Orion, the VANDAM: Orion survey had 2.2× less mass sensitivity than the Perseus survey, despite spending 2× more time on source. The VANDAM: Orion survey used 240 hours in the VLA A-configuration to observe 100 Class 0 protostars, accounting for ~50% of the available array time at high-frequencies. Thus, high-sensitivity at ~8 mm wavelengths toward large protostar samples at a distance of ≥400 pc requires a significant utilization of available observing time for the current VLA; the time required quickly becomes unrealistic for protostars at much greater distances.

The ngVLA is needed to further advance studies of disks because ALMA will also not be as sensitive to long wavelength dust emission as the ngVLA. Using ALMA at 3 mm, 1 hour of integration will achieve a sensitivity of 15 $\mu$Jy. Assuming a distance of 230 pc, this translates to a 1σ mass sensitivity of 1.6×10^{-4} $M_\odot$. Therefore, ALMA Band 1 (~7.5 mm) will only be about as sensitive as the current VLA. The ngVLA will reach 1σ mass sensitivities of 5.0×10^{-5} $M_\odot$ and 8.2×10^{-6} $M_\odot$ at wavelengths of 7.5 mm and 3 mm, respectively. Thus, the ngVLA will be vastly superior to ALMA at these long wavelengths for the characterization of dust emission from protostellar disks. However, these mass estimates assume that all emission is within one beam. We will conduct a more realistic assessment of the ngVLA’s ability to detect resolved disks in the following section.
3. Detectability of Protostellar Disks with the ngVLA

The VANDAM: Perseus survey was able to detect disks with total masses > 0.025 M\(_\odot\) (gas+dust, assuming a gas-to-dust ratio of 100:1 and a 5\(\sigma\) detection limit) and resolve disks with observed radii > 10 AU at a wavelength of 8 mm (Segura-Cox et al. 2018). However, most of the resolved disks have masses > 0.1 M\(_\odot\). The sensitivity of the ngVLA will enable a ~10\(\times\) leap in both resolution and sensitivity. In order to quantitatively characterize the ability of the ngVLA to detect and resolve disks toward both nearby and distant star forming regions, we have computed a small suite of radiative transfer models at wavelengths of 7.5 mm and 3 mm, varying luminosity (1.0, 10.0, 100.0 L\(_\odot\)), disk radius (3.0, 10.0, 30.0, 100.0, 300.0 AU), and disk mass (10\(^{-4}\), 10\(^{-3}\), 10\(^{-2}\), 10\(^{-1}\) M\(_\odot\)). The disks are assumed to have a radial surface density profile proportional to R\(^{-1}\), scale height (H/R) of 0.1 at 1 AU, and flaring H \(\propto\) R\(^{1.15}\); the disk density profiles are truncated at the specified radii and do not exponentially drop-off. All models have a surrounding envelope with a mass of 0.1 M\(_\odot\) and a radius of 1500 AU. The dust opacities we use are derived from Woitke et al. (2016) and have a maximum particle size of 1 mm, yielding dust mass opacities of 0.15 cm\(^2\) g\(^{-1}\) and 1.35 cm\(^2\) g\(^{-1}\) at 7.5 mm and 3 mm, respectively. Radiative transfer was computed with the RADMC3D code (Dullemond et al. 2012), and model images were generated at three distances (230, 400, and 1500 pc) and three viewing geometries (i = 25, 45, and 75\(^\circ\)). We simulated ngVLA observations of these models with the CASA simobserve task using the full ngVLA configuration, assuming 1 hour on source and the estimated noise of 0.26 \(\mu\)Jy from this same integration time (ngVLA Memo #17).

A subset of these models are shown in Figure 4 at a wavelength of 7.5 mm, distances of 230 pc, 400 pc, and 1.5 kpc, and at an inclination of 75\(^\circ\). At distances of 230 pc and 400 pc, disks with masses of >0.001 M\(_\odot\) toward protostars with luminosities of 10 L\(_\odot\) can be detected and resolved. We note, however, that at a mass of 0.001 M\(_\odot\), the 300 AU radius disk is not as well detected due to the mass being spread over a larger disk size. We also find that disks with radii of 3 and 10 AU can also be detected for a disk mass as small as 0.0001 M\(_\odot\).

At a distance of 1.5 kpc and the same luminosity, disks with masses of 0.1 M\(_\odot\) can be detected and resolved at all radii, and at a mass of 0.01 M\(_\odot\) the disks with R\(_{\text{disk}}\) \leq 100 AU can still be detected. Disks with masses much below 0.01 M\(_\odot\) are not well-detected in a 1 hour observation. While optimal imaging parameters will depend on the radii and mass of each disk, the visibility data themselves can be utilized to fit the disk radii with greater accuracy from the images alone, given the possible limitations of maximum recoverable scale and surface brightness. The ngVLA will enable the physical structure of protostellar disks with radii as small as ~3 AU to be characterized in the nearby star forming regions. The ngVLA is the only facility that will be able to do this given the necessity of very high angular resolution and long-wavelengths; this will be a major advance in the capability of examining small-scale structures in protostellar systems.

Furthermore, observations at 3 mm (not shown for brevity) enable the detection of all the disks detected at 7.5 mm (Figure 4), but lower mass disks will be able to be detected as well given the factor of ~6 - 16\(\times\) increase in flux density going from 7.5 mm to 3 mm (depending on dust opacity spectral index). The 3 mm band will be especially effective for the detection of disks in star forming regions out to 1.5 kpc, as disk masses of 0.001 M\(_\odot\) can be detected more robustly. Thus, both the 7.5 mm and 3 mm ngVLA bands will be essential to further characterizing disks in the protostellar phase, and the
Figure 4. Model images of protostellar disks at 7.5 mm computed for a three distances 230 pc (top), 300 pc (middle), and 1500 pc (bottom). For each distance we have generated synthetic observations for a variety of radii and disk masses and run through a simulated observation of 1 hr with the full ngVLA configuration. UV-tapering has been applied to the disks with $R_{\text{disk}} \geq 30$ AU at the level of $R_{\text{disk}}/5.0$ translated to angular units.
full ngVLA will enable disks to be detected and resolved out to star forming regions at distances of at least 1.5 kpc. This capability will greatly expand the number of disks that can be observed compared with the current VLA by enabling significantly smaller radii and masses to be detected and resolved. By including all star forming regions out to ~1.5 kpc (e.g., Cygnus-X; Kryukova et al. 2014), more than 1000 additional protostars and their disks will be accessible to the ngVLA. Moreover, the 100s of protostars star-forming regions at distances of 400 pc or less (Dunham et al. 2014) will be able to have their disks resolved, where only unresolved observations were possible with the current VLA.

Optical depth is another significant advantage of the ngVLA over other millimeter interferometers like ALMA that primarily operate at wavelengths shorter than 3 mm. The surface density profiles for the modeled disks are shown in Figure 3 with horizontal lines marking the surface density corresponding to $\tau = 1$ for wavelengths between 7.5 mm and 0.45 mm. Due to the fixed grid of masses and varying radii, the surface density profiles are larger for smaller disk radii. However, it can be seen that 7.5 mm wavelengths can trace about 10× higher surface densities than at 1 mm before becoming optically thick. The opacity can be significant even at 7.5 mm, particularly for disks with $M_{\text{disk}} = 0.1 \, M_\odot$. For the 100 and 300 AU radius and $M_{\text{disk}} = 0.1 \, M_\odot$ disks, only the inner few AU are optically thick at 7.5 mm, while the entire 100 AU disk is optically thick at 1 mm. The disks with radii between 10 and 30 AU and $M_{\text{disk}} = 0.1 \, M_\odot$ are optically thick out to ~10 AU in both cases, but lower mass disks in this range of radii are only optically thick in their inner few AU. However, these disks are completely optically thick at 1 mm and 0.45 mm until the disk masses are ~0.0001 $M_\odot$. Note that $\tau$ in Figure 3 is calculated for an inclination of 0° (face-on), and intermediate to edge-on inclinations will have substantially more opacity for a given surface density profile. Therefore, we can conclude that 7.5 mm wavelengths are not necessarily immune to issues of opacity, but they are significantly less affected than 1 mm and 0.45 mm. This will enable ngVLA to significantly improve on the characterization of protostellar disks, while the ability of ALMA to probe their structure is more limited.

The ability to detect these low-mass, small radius disks is also extremely important for the characterization of multiple star systems from the emission of their circumstellar disks. This capability is described in more detail in the Chapter ‘New Frontiers in Protostellar Multiplicity with the ngVLA.’ Furthermore, while we do not specifically address the likelihood of substructure in protostellar disks, growing numbers of proto-planetary disks exhibit a variety of substructure when observed with sufficiently high resolution in the dust continuum (ALMA Partnership et al. 2015; Andrews et al. 2016; Sheehan & Eisner 2018, Andrews et al. 2018 in prep.). Therefore, it is entirely possible that protostellar disks themselves will also not have smooth structures. The higher-resolution at longer wavelengths of the ngVLA will be crucial for characterizing whether or not protostellar disks exhibit significant substructure. This is because, as discussed previously, the more massive protostellar disks are largely opaque at shorter wavelengths and the longer wavelengths with lower opacity are more ideal to reveal substructure if present.

4. Characterizing Early Grain Growth

The ability to detect and resolve disks with a variety of radii in the nearby star forming regions makes it possible to characterize the spectral index of dust emission both in the
limit of integrated flux densities and spatially-resolved emission throughout the disks. With a shortest wavelength of 3 mm, the ngVLA can characterize the spectral index of dust emission at least between 3 mm and 1 cm. The sensitivity of the >1 cm wavelength ngVLA bands will also have the capability of detecting and resolving dust emission. This capability is incredibly important because the rate of growth for solids in disks can be examined as a function of evolution through the protostellar phase. However, at wavelengths >1 cm dust emission becomes more difficult to detect due to the power-law decrease in flux density of dust emission at longer wavelengths, thus the ngVLA is crucial to enable the detection of dust emission at wavelengths >1 cm because the current VLA does not have the needed angular resolution or sensitivity.

The ability to measure the spectral index of dust emission over a wide range of wavelengths is important because it is connected to both the maximum dust grain sizes and the slope of the assumed power-law dust size distribution; dust grains are most efficiently detected when observed at a wavelength comparable to their size. Through radiative transfer modeling, using the same techniques that generated the images in Figure 4, the dust emission over a wide range of wavelengths can be used to determine the maximum particle sizes. Such studies are currently possible toward a few select systems, but the limited sensitivity of the VLA makes detection of dust emission out to large disk radii and low disk masses challenging. Furthermore, the low angular resolution of the current VLA at long wavelengths means that characterizing dust emission at wavelengths of several cm must use integrated flux densities. Resolved studies of disk spectral indices have been done for a few of the most nearby disk-hosting PMS stars (Pérez et al. 2012, 2015). Doing such modeling for protostars spanning the full range of evolution will enable the rate of grain growth to be understood, and we will learn whether or not this is a linear/universal process, or if it varies strongly between protostars. However, in order to accomplish this, greater sensitivity and resolution than are possible with the VLA are needed to sufficiently resolve the inner regions of protostellar disks and accurately separate free-free emission from dust emission.

Separating the free-free jet emission from dust emission is incredibly important, especially for examining dust emission at >1 cm (Figure 1). The resolution of the ngVLA will enable the dust emission to be resolved from the free-free emission out to wavelengths of several cm. However, the disk needs to be well-resolved for this to be possible. Compact free-free emission is expected to originate from the inner ∼10 AU (Anglada et al. 1998) and the ngVLA will have a spatial resolution of ∼11.5 AU in the 3.75 cm (8 GHz) band for protostars at a distance of 230 pc. Thus, the emission from the two distinct processes can be separated spatially with multi-wavelength observations, and the region containing free-free emission can be isolated and removed from the analysis. This is not possible with the angular resolution of the current VLA and will be an unique capability of the ngVLA. We also note that free-free emission can also originate from a disk wind, but without the ngVLA we cannot fully characterize the nature of free-free emission to properly account for it. Finally, free-free emission is can still contribute at wavelengths <1 cm (Figure 1), and the higher angular resolution at shorter wavelengths will help further characterize its nature.

ALMA can add to the characterization of dust growth with its equivalent angular resolution at shorter wavelengths. While small disks and the inner radii of large disks will be optically thick (Figure 3), ALMA observations should be more sensitive to the outer regions of protostellar disks where the concentration of large grains is expected to be lower. This is because grain growth is slower at larger radii, having lower densities,
and the radial drift process is expected to move large particles to smaller radii (Weiden- 
schilling 1977). Therefore, in the regions where the dust emission is not optically thick, 
short wavelength observations from ALMA will be helpful to characterize dust growth 
at all disk radii, especially if the dust emission is more compact at longer wavelengths 
(Pérez et al. 2012, 2015; Segura-Cox et al. 2016).

Furthermore, the ngVLA may not be able to probe the transition from the envelope 
to disk as well as ALMA, because the envelope will have significantly lower column 
density and thereby low surface brightness. On top of that, if the envelopes have mostly 
small dust grains < 10 µm, the dust emission drops much faster in wavelength than it 
does in the disk due to the smaller grains. Thus, ALMA will enable the connection 
of the disk to the infalling/rotating envelope to be better understood through both the 
observations of shorter wavelength dust and molecular lines tracing envelope and disk 
kinematics. The ngVLA then will be the ideal instrument for examining the presence 
and structure of the disks around protostars to smaller radii. This will complement 
ALMA's ability to examine the structure of proto-planetary disks around more evolved 
young stars.

5. Uniqueness of ngVLA Capabilities

The ngVLA will have extraordinary capabilities to examine disks toward protostars 
throughout the Class 0 and I phases. It is crucial to examine the disks at long wave-
lengtshes where the dust emission is optically thin over a large range of radii to probe 
nearly the entire disk mass reservoir. Moreover, the ngVLA will be able to fully resolve 
young disks with radii as small as ~3 AU in the nearby star forming regions. While 
ALMA can reach such spatial scales at short wavelengths, the disks around protostars 
are likely to be optically thick at such small radii (Figure 3), making it impossible for 
ALMA to examine the internal structure of their protostellar disks in many cases.

Due to the optical depth of disks (Figure 3), the radial distribution of dust particle 
sizes cannot be explored with short wavelength data from ALMA. Longer wavelength 
observations and ~10 mas resolution are crucial to map the radial distribution of dust 
emission. While ALMA has 3 mm receivers and is expected to have ~1 cm receivers 
(Band 1) in the future, the best angular resolution at 3 mm is ~0.05″, and ~0.14″ at 
1 cm. Thus, ALMA at 3 mm will only have the spatial resolution that VANDAM had 
with the VLA toward Perseus at 8 mm, and ALMA will have lower angular resolution at 
1 cm; ALMA will not be able to improve upon the resolution of the VANDAM survey at 
wavelengths where dust emission is less affected by opacity. Furthermore, ALMA will 
be significantly less sensitive than the ngVLA at these same wavelengths; see section 
2. In summary, the ngVLA will be superior to ALMA in examining protostellar disks 
at wavelengths of 3 mm and longer.

Lastly, the ngVLA will be able to examine the vertical settling of large dust grains 
for edge-on disks. In nearby star forming regions, (e.g., Taurus, Oph at 140 pc), edge-
on disks can be observed to determine how settled the disk midplanes are. The disk 
midplanes can be examined from 3 mm to 1 cm to see if there is variation with wave-
lenghth in the vertical extent of the dust emission. If the vertical structure of the dust 
emission is approximately H/R ~0.1, then at a radius of 14 AU the vertical height of 
the dust at 7.5 mm can be resolved (assuming 0.01″ resolution at 140 pc). This study 
also cannot be done with ALMA at shorter wavelengths because the disk midplanes are 
opaque (Lee et al. 2016). Through modeling, it can be determined if the dust emission
is more concentrated in the disk midplanes going to longer wavelengths, consistent with expectations of dust settling (D’Alessio et al. 2006) and low levels of turbulence in the disks (e.g., Flaherty et al. 2017).

6. Summary

The ngVLA will enable a new revolution in the study of protostellar disks with the ability to probe the spatial structure of protostellar disks, where many of these disks cannot be resolved with current instrumentation. The ngVLA will enable us to resolve dust emission from disks that are as small as 3 AU in the nearby star forming regions and examine the full spatial extents of protostellar disks using emission from optically thin dust. Together, this information will enable us to determine the spectral index and thereby the sizes of the emitting dust grains to be characterized as a function of radius, and perhaps height for edge-on disks. The ngVLA will enable the structure and early grain growth of protostellar disks to be better understood, in addition to how quickly the conditions for planet formation are established in disks.

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