Prospects of High Spatial Resolution Observations with ngVLA

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Abstract

We discuss the capability of spatially resolved observations of protoplanetary disks with ngVLA. Using a commonly used protoplanetary disk model, we estimate to what extent ngVLA can resolve the disk structures at a given distance from the central star. With ngVLA, spatially resolved observations of protoplanetary disks are possible with 1 hour integration at the frequencies of 20 GHz or higher, and the spatial resolution can go down to several tens of milliarcsec. Therefore, ngVLA is capable of obtaining similar quality images of protplanetary disks with ALMA, while at much lower frequency. Low frequency observations is useful in determing the disk physical structures (i.e., temperature, surface density and dust properties) in tandem with sub-mm ALMA data. Especially, ngVLA is a unique probe for the disk midplane of Earth-forming region (i.e., several au from the central star) and water snowline.

Key words: protoplanetary disks — planets and satellites: formation — radio continuum: stars

1. Introduction

Planet formation is one of major problems in astrophysics, and has been a topic of active debate for more than decades. Planets are considered to be formed in protoplanetary disks, which is a cold disk of gas and dust rotating around a young star. Dust grains are believed to grow to a planet within the disk over a few to ten million years.

The structures of protoplanetary disks are key to understand planet formation. Disk structures indicate where dust grains are concentrated, or where planets are formed. Until very recently, however, such structures have not been known due to their small sizes. Typical sizes of protoplanetary disks are of the order of $\sim$100 au. Situated at the distance of $\gtrsim$100 pc, the apparent size of protoplanetary disks is $\sim$1 asec. Therefore, it is necessary to have a telescope with the spatial resolution of at least ~ 0.1 asec to observe structures in disks. If we are to observe the scale comparable with our Solar System planets ($\lesssim$several tens of au), higher spatial resolution is required.

ALMA has made game-changing discoveries of protoplanetary disk structures thanks to its unprecedented sensitivity and spatial resolution at sub-mm and mm wavelengths. It is now known that the disks are full of ring-like structures (e.g., ALMA Partnership 2015, Andrews et al. 2019) and some disks show strong asymmetry (e.g., Fukagawa et al. 2013). The asymmetry of dust particles indicate the location where dust grains are strongly concentrated and ring gap structures can be an indirect signature of an already forming planet. We are now starting to see the planet formation activities in protoplanetary disks.

There are a number of advantages of going to longer wavelengths in the observations of protoplanetary disks. The most important is that the disk can be optically thin at longer wavelengths. Since dust grains are heavily concentrated in protoplanetary disks, the dust continuum emission can become optically thick even at sub-mm wavelengths (see Section 2) and it becomes difficult to observe structures at disk midplane, where planet formation takes place. Another merit of going to longer wavelengths is that the it is possible to observe larger grains, which are more likely to be involved in planet formation. Therefore, ngVLA, a high resolution instrument at mm- to cm-wavelengths, is an ideal tool for studying planet formation in protoplanetary disks.

However, emission at longer wavelengths is generally faint. Therefore, it is important to understand the limitation of ngVLA. In this memo, we discuss what can be observed with currently planned ngVLA specification by using a simple disk model and suggest possible science goals made available with ngVLA..

2. Typical Parameters of Protoplanetary Disks

We consider a simple disk model with the power-law radial distribution of dust grain surface density:

$$\Sigma_{\rm d}(r) = 10 \left(\frac{r}{1\ {\rm au}}\right)^{-3/2} \quad [{\rm g/cm^2}] \tag{1}$$

and temperature:

$$T(r) = 300 \ \left(\frac{r}{1\ {\rm au}}\right)^{-1/2} \quad [{\rm K}]. \tag{2}$$

Here, r is the distance from the central star and numerical factors are chosen based on the Minimum-Mass Solar Nebula model (Hayashi et al. 1985). This disk temperature indicates that the disk is geometrically thin, or the ratio of pressure scale height h and the disk radius r is much less than unity, i.e., $h/r \lesssim 0.1$.

We first note that the innermost region of protoplanetary disks is optically thick at sub-mm wavelength. The optical depth of the model disk is given by

$$\tau_\nu(r) = 100 \left(\frac{\nu}{10^3\ {\rm GHz}}\right) \left(\frac{r}{1\ {\rm AU}}\right)^{-3/2}, \tag{3}$$

where commonly used dust opacity κ of $10(\nu/10^3\ {\rm GHz})\ {\rm cm^2/g}$ is assumed (Beckwith et al. 1990)

Resolution $\theta_{1/2}$ [mas]	2.4 GHz	8 GHz	16 GHz	27 GHz	41 GHz	93 GHz
100	10.58	0.56	0.13	0.05	0.03	0.02
10	870.6	50.51	12.42	4.53	2.77	1.36
1	-	4.5×10^5	1466	350	207	126

Table 1. Brightness temperature RMS [K] with 1 hour integraton

with the spectral index β of unity. Only with the estimate of optical depth, the need of low frequency (long wavelengths) observations is evident when one has to probe the disk mid-plane. With this disk model, the expected surface brightness of the disk when viewed face-on can be calculated as

$$T_{b,\nu}(r) \sim T(r)\left(1 - e^{-\tau_\nu(r)}\right) \quad (4)$$

where $T_{b,\nu}(r)$ is the brightness temperature of the resolved disk image at the observing frequency of ν.

3. Observability with ngVLA

We discuss to what extent the ngVLA can resolve the disk structure using the typical protoplanetary disk model introduced in the previous section. We calculate the brighness temperature of the disk at a given radius and compare it with the 1 hr continuum sensitivity provided in the ngVLA Reference Design Book (Table 1).

Figure 1 compares the expected signal from protoplanetary disks with the ngVLA design sensitivity. Each panel shows the RMS noise levels for different beam sizes with 1 hour integration in purple shadows and the expected signal in brightness temperature at a given radius with lines. For example, the red line in the Panel (a) of Figure 1 indicates the surface brightness of the disk at the location 10 au away from the central star. With 100 mas beam, the signal from 10 au from the central star can be detected with more than 10σ at $\gtrsim$16 GHz. Since the disk physical temperature is lower at the outer region of protoplanetary disks, the signal at $\sim$100 au from the central star can be detectable only at the highest frequency bands for the 100 mas beam.

Since the typical distance of the nearby star forming region is $\gtrsim$100 pc, the beam size of 100 mas corresponds to 10 au scale. With 100 mas beam, therefore, the structures at 100 au can be well resolved while it is possible to observed only large-scale structures at $\lesssim$ 30 au region. Therefore, the observability of disk structures at low frequency is the competition between the beam size and sensitivity. For higher spatial resolution, it is necessary to go for higher frequency where the disk is brighter.

The disk optical depth poses another limit of high resolution observations of the inner few au part of the disk. In the Panels (b) and (c) of Figure 1, we show the disk signal from $\lesssim$3 au. The curves become flat for high frequency since the disk becoms optically thick and the brightness temperature of the disk emission is limited by the physical temperature of the emitting region. For the beam size of 10 mas, or $\sim$ 1 au at the distance of 100 pc, the disk signal is detectable for frequency higher than $\sim$20 GHz. For the beam size of 1 mas, weak detection is expected only at the highest frequency of ngVLA bands.

In summary, ngVLA has potential to probe protoplanetary disk structures down to several au scales. With 1 hour integration, the disk structures at $\sim$ 30 au from the central star can be resolved down to several tens of milliarcsec, or less than 10 au at the distance of 100 pc, at frequencies higher than $\sim$20 GHz. The structures at $\sim$3 au from the central star can be resolved down to $\sim$ 10 mas, or 1 au at the distance of 100 pc, at the frequency higher than $\sim$ 20 GHz.

4. Possible Science Cases

Following up the discussion in the previous section, we briefly present two possible science cases on the spatially resolved observations of protoplanetary disks made available with ngVLA.

4.1. Disk Dynamical Structures at Neptune-forming Region

With ngVLA, it is possible to resolve the disk at several au scales and the disk emission at r $\sim$30 au can be detected with more than $\sim 10\sigma$. At 30 au from the central star, the pressure scale height of protoplanetary disks is expected to be $\lesssim$ 3 au and therefore, the disk structures with the scale comparable to the pressure scale height can be resolved. Since the pressure scale height of the disk is the distance traveled by sound wave within one Kepler rotation period, it can be regarded as the characteristic length scales of the dynamical processes in the disk, such as disk instability and/or disk-planet interaction. For example, a massive planet embedded in a disk opens a gap with the width of several pressure scale heights (e.g., Kanagawa et al. 2017).

The spatial resolution is similar to what current ALMA can typically observe at $\gtrsim$200 GHz (e.g., ALMA Partnership 2015). With ngVLA, we expect have similar quality images at frequencies $\sim$10 times lower than ALMA. Having spatially resolved wide band data provides us with rich information about physical structures of disks. In dust continuum emission, disk temperature, surface density and dust opacity are always degenerated at a single band observations (see Equation 4). With multiple band observations of wide frequency coverage, it is possible to break the degeneracy (Kim et al. 2020). It is important to have both high frequency bands (e.g., ALMA Band 7 or higher) that probe temperature and the low frequency bands to probe surface density. With much better spatial resolution and sensitivity than ALMA at 100 GHz, ngVLA will play a crucial role in understanding icy-planet forming region ($r \sim$ 30 au) of protoplanetary disks.

4.2. Disk Overall Structures at Earth-Forming Region

From the results in Section 3, ngVLA is capable of resolving the disk within $r \sim 3\ au$ by several to ten beams. Therefore, with ngVLA, for the first time, it is possible to spatially resolve the Earth-forming regions in protoplanetary disks. The structures that extend over the disk scale can be probed. Since the

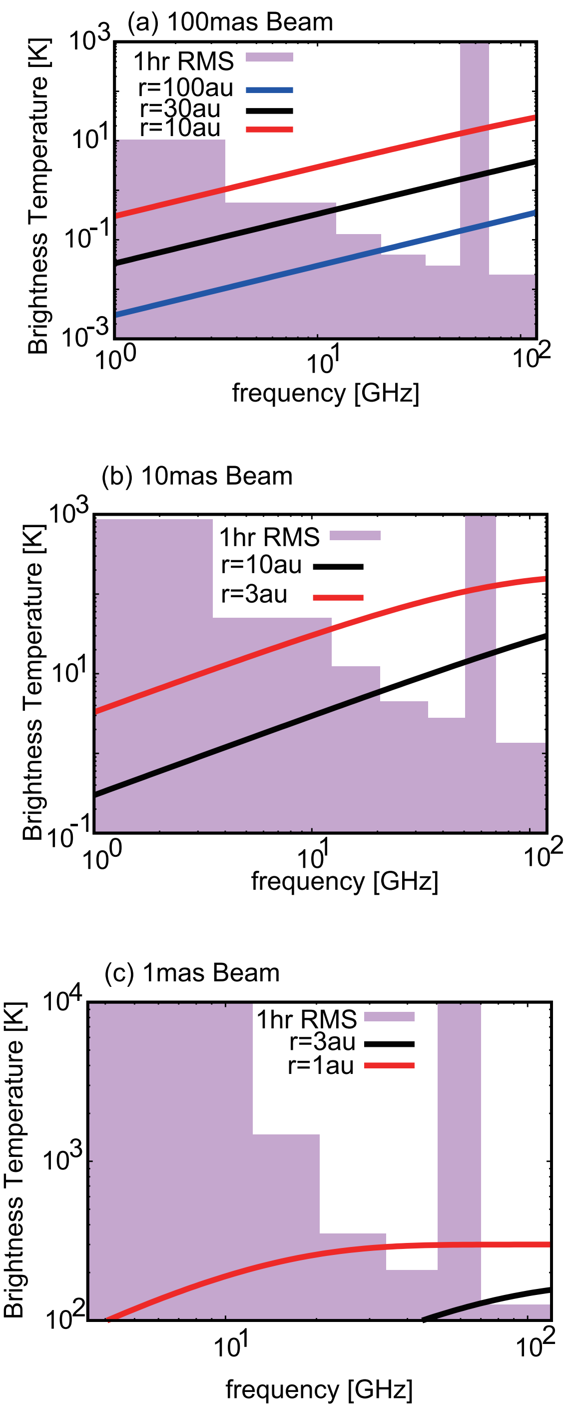

Fig. 1. The expected signal and RMS with 1 hour integration for 100 mas (a), 10 mas (b), and 1 mas (c) resolution.

disk is expected to be optically thick at $r \lesssim 3$ au from the central star in sub-mm wavelengths, ngVLA will be a unique facility to probe the disk midplane in such regions.

There are several interesting observational indications about the innermost several au region of protoplanetary disks. One example is the inner disk of transitional disks. A transitional disk object is the young star having a circumstellar disk with an inner cavity and is considered to be in the late stage of disk evolution (e.g., Espaillat et al. 2014). However, some transitional disks have inner disks of less than several au in radius within their large inner cavities (e.g., Fukagawa et al. 2013, Kudo et al. 2018). This is a mystery since standard viscous evolution timescale is short at the inner part of the disk. If there is a planet at the innermost radii, it can prevent disk materials to migrate onto the central star by forming a gap (e.g., Zhu et al. 2012).

Another interesting feature expected at several au from the central star is the snowline, which is a condensation front of water ice expected at 2–3 au from the central star. Rocky dust particles are expected interior to the snowline while icy dust at larger radii. Rapid change of dust properties will result in the change of dust opacity and therefore a ring-like feature may be observed (e.g., Zhang et al. 2015, Okuzumi et al. 2016). Currently, water snowline is investigated for stars exhibiting a burst phase (Cieza et al. 2016), where the snowline goes to much outer radii due to high activity of the central star. With ngVLA, it will be possible to probe the snowline around normal stars, providing us with insight of planet formation and dust evolution.

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