New Frontiers in Protostellar Multiplicity with the ngVLA

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**Abstract.** The ngVLA will enable significant advances in our understanding of the formation and evolution of multiple star systems in the protostellar phase, building upon the breakthroughs enabled by the VLA. The high-sensitivity and resolution at 3 mm wavelengths and longer will enable closer multiple systems to be discovered in the nearby star forming regions. The ngVLA is incredibly important for multiplicity studies because dust opacity at short wavelengths (<3 mm) can hide multiplicity and the long wavelengths are needed to reveal forming multiples in the youngest systems. The samples sizes can be expanded to encompass star forming regions at distances of at least 1.5 kpc, enabling statistical studies that are on par with studies of field star multiplicity. We verify the capability of the ngVLA to detect and resolve multiple star systems at distances out to 1.5 kpc using empirical examples of systems detected by the VLA and scaling them to greater distances. We also use radiative transfer models and simulations to verify that the ngVLA can resolve close binary systems from their dust emission at these distances. The ngVLA will also have excellent imaging capability and the circum-multiple environments can also be examined in great detail.

1. **Introduction**

Star formation occurs as a consequence of dense gas clouds collapsing under their own gravity, once the gravitational force is able to overcome sources of support (e.g., thermal pressure, magnetic fields, turbulence; McKee & Ostriker 2007). The star formation process frequently results in the formation of two or more stars that comprise a gravitationally bound system, given that nearly half of Sun-like stars (in terms of stellar mass) are found in binary or higher-order multiple systems (Duquennoy & Mayor 1991; Raghavan et al. 2010). The degree of stellar multiplicity strongly depends on stellar mass. Stars more massive than the Sun have a higher fraction of multiplicity and stars less massive than the Sun have a lower degree of multiplicity, but still with a multiplicity fraction upwards of 25%; see Duchêne & Kraus (2013) for a recent review. Thus, multiple star formation is a common outcome of the star formation process for all stellar masses and a comprehensive understanding of star formation must account for multiplicity.
Recent surveys in the infrared, millimeter, and centimeter have also shown a high degree of multiplicity in the protostar phase (Connelley et al. 2008; Looney et al. 2000). Both the youngest protostars (Class 0 sources, André et al. 1993) and more evolved protostars (Class I), show a higher degree of multiplicity than field stars (e.g., Reipurth et al. 2004; Chen et al. 2013; Tobin et al. 2016b). The largest mass reservoir is available during the protostellar phase, making it the most promising epoch for companion star formation to occur (Tohline 2002). Thus, the distribution of field star multiplicity is likely derived from the primordial distribution of companions that form during the protostar phase. While the mechanisms of multiple star formation are still uncertain, the distribution of separations in the protostellar phase may reveal the signature of their formation process. The peak of the companion separation distribution for field solar-type stars is \( \sim 50 \) AU (Raghavan et al. 2010), but the formation route for these systems cannot be determined from evolved stellar populations alone because they have undergone Myr to Gyr of dynamical evolution. Moreover, not all systems that form as multiples may remain multiple throughout their lives, but they may still have formed in the presence of one or more companion stars (Sadavoy & Stahler 2017). Some companions can be ejected through dynamical interactions (e.g., Reipurth & Mikkola 2012) or become unbound after the dispersal of the star forming core. This means that the formation of nascent planetary systems may have been influenced by companion stars, even if they are no longer bound to the system. Thus, to reveal the origins of stellar multiplicity and its effects on proto-planetary systems, multiplicity must be characterized during the earliest stage of the star formation process.

There are two favored routes to explain the formation of multiple star systems: disk fragmentation due to gravitational instability (e.g., Stamatellos & Whitworth 2009; Kratter et al. 2010) and turbulent fragmentation within the molecular cloud (e.g., Padoan & Nordlund 2002; Offner et al. 2010). Disk fragmentation will preferentially result in the formation of close (\( < 500 \)AU) multiple star systems and requires a large (\( R_{\text{disk}} \sim 50 \) AU) and massive rotationally-supported disk to have formed around the primary star. Turbulent fragmentation can result in the formation of both wide and close multiple systems. In this scenario, the initial protostars form with separations \( \sim 1000 \) AU, and depending on their relative motions and masses they can migrate inward to radii \( \sim 100 \) AU (Offner et al. 2010), remain at wide radii, or drift further apart. However, the expected trends can only be revealed statistically, requiring large samples of protostars to be observed with spatial resolution better than 50 AU (the average field star separation). It is also important to point out that rotation of the protostellar cloud itself has also been suggested as a mechanism to form multiple star systems (Burkert & Bodenheimer 1993), but current observational evidence points more toward turbulence for the formation of wide companions (Lee et al. 2016).

A key difference in examining the formation of multiple stars at radio/millimeter wavelengths versus optical/infrared is that direct emission from the protostellar photosphere is not being detected. Instead, the dust emission from the individual circumstellar disks and/or free-free emission from the base of the protostellar jet are being probed. Thus, the observations are tracing fragmentation, but cannot directly confirm the protostellar nature of the multiple observed sources. Tobin et al. (2016b) examined the nature of the emission detected and concluded that multiple sources of emission very likely correspond to true multiplicity, but we note, however, that the possibility of a small percentage of false positives cannot be excluded. Nevertheless, observations at millimeter/centimeter wavelengths are generally the only available tool to study multiplicity toward such deeply embedded objects.
The multiplicity statistics of field stars have the benefit of large samples and are not subject to the same limitations of protostellar multiplicity studies. Nonetheless, it is useful to use the field multiplicity studies as a baseline for the survey requirements of future protostellar multiplicity studies. The most recent compendium of field solar-type star multiplicity had a sample of 454 stars in a volume limited sample, finding a total of 259 companions with an average companion separation of 50 AU in an approximate Gaussian distribution (Raghavan et al. 2010). Assuming that the field multiplicity distribution represents the distribution of protostellar multiplicity (it probably does not), we can use this distribution in order to estimate how many protostellar multiples would need to be detected in order to obtain the same level of statistical accuracy. Restricting the relevant parameter space to a separation range between 1 AU and 1000 AU, the Raghavan et al. (2010) sample contains ∼126 companion stars within this range. It is necessary to limit the parameter space in this regard because scales less than 1 AU will likely be difficult to examine for protostars and scales greater than 1000 AU will be dominated by clustering and not physical association. In order to observe 126 protostellar companions to match the sample size, at least 630 protostars must be observed if the average companion frequency of protostars is in this range is 20% (Tobin et al. 2016b). This would require that all protostars within the Gould Belt be observed, sampling over different star formation conditions. If the youngest (Class 0) protostars are required for such characterization, then there are much less than 630 in the entire Gould Belt (Dunham et al. 2014). Surveys of more distant, massive star forming regions are therefore required to observe this number of protostars in a single region.

2. Setting the Stage: The VANDAM Survey

A first large, systematic survey to examine protostellar multiplicity in an entire star forming region was carried out by the VLA Nascent Disk and Multiplicity (VANDAM) Survey (Tobin et al. 2015). This survey was carried out toward the Perseus star forming region, observing 45 Class 0 protostars (including possible objects in transition; Class 0/I), 37 Class I protostars, and 12 Class II young stars. All protostars were observed at a wavelength of 9 mm (33 GHz), at a uniform sensitivity of ∼9 μJy, and at a uniform resolution of 15 AU (0.065′′). From these data, we identified 18 systems that were multiple with companion separations <500 AU; 16 of these companions were new detections by the VANDAM survey. We also detected a number of systems with separations >500 AU as well as many hierarchical multiple systems. Some multiple systems had separations as small as ∼19 AU, near the limit of our spatial resolution. Figure 1 shows an example of a very close multiple system. Figure 2 then shows an example of a hierarchical system toward L1448 IRS3 where there is a triple, a binary, and a single system all within 5000 AU. The triple was revealed by ALMA to have a circum-multiple disk, strongly indicating that the system formed via disk fragmentation (Tobin et al. 2016a), and the system as a whole in Figure 2 illustrates how fragmentation is a multi-scale process.

The separations of all companion stars detected in the VANDAM survey, are shown as a histogram in Figure 3. Two features are obvious: 1) there appears to be two peaks, one at ∼75 AU and another >1000 AU, and 2) the separation distribution is in excess of the field, except for separations between ∼300 AU and ∼1000 AU. It is argued in Tobin et al. (2016b) that this bimodality results from both disk fragmentation (∼75 AU part) and turbulent fragmentation (>1000 AU part) happening to produce the observed distribution. There are a lower number of detected companions between
Figure 1. Images of Per-emb-2 (IRAS 03292+3039) at 9 mm from the VLA at increasing resolution from left to right. The left panel, with the lowest resolution and most sensitivity to extended structure, shows significant/structured emission surrounding a bright source that we interpret as the position of the main protostar; the middle and right panels zoom-in on the region outlined with a dashed box. The middle panels with higher resolution have resolved-out the extended structure and only detect the bright peak at the position of the protostar; however, the source appears extended at this resolution. The highest resolution image in the right panel shows that the source is resolved into two sources separated by 18.5 AU. The contours in each panel are \([-6, -3, 3, 6, 9, 12, 15, 20, 25, 30, 35, 40, 50, 60, 70, 80, 90, 100, 150]\) × \(\sigma\), where \(\sigma = 7.3 \mu Jy, 9.6 \mu Jy, 11.9 \mu Jy\) from left to right at 9 mm.

∼300 AU and ∼1000 AU, indicating that neither formation mechanism is efficient at these scales.

While this survey of Perseus represents a major advance, it was limited in terms of the number of sources. Considering uncertainties, the distribution could be consistent with a flat separation distribution (when considering the logarithm of the separation). Thus, it is clear that greater numbers are required and more than one star forming region needs to be examined in order to understand if this is a common distribution or an outlier. However, Perseus still offers an excellent template for studies of multiplicity to larger samples and more distant star forming regions. It remains to be seen if the separation distribution observed toward Perseus is ‘universal,’ and its implications for the formation mechanisms of multiple stars are just beginning to be understood (Tobin et al. 2016a; Lee et al. 2016; Offner et al. 2016).

Expanding on the discussion at the end of the Section 1, it will be important to determine if the observed bimodality is statistically significant. One way to do this is to obtain enough statistics such that the uncertainties in the individual bins of Figure 3 are statistically distinct. Assuming the same distribution of companion separations in Perseus, the bin at 1.875 log(AU) will be inconsistent with the bin at 2.375 log(AU) at the 4\(\sigma\) level when the sample size reaches ∼500. Thus, samples in excess of 500 protostars are needed to statistically distinguish between bimodal and log-flat distributions.

A challenge to observing larger numbers of protostars is that the most populous star forming regions are more distant. Orion is ∼400 pc away and the VLA offers a best spatial resolution of ∼30 AU at 8 mm, this is just a bit better that the typical separation of field solar-type stars and there are likely to be more multiple systems
Figure 2. Image of the L1448-N or IRS3 region at 9 mm from the VLA. L1448 IRS3B is a close triple, L1448NW (L1448 IRS3C) is a binary, and L1448 IRS3A is single at the limit of our resolution. Both L1448 IRS3B and L1448NW are Class 0 sources while L1448 IRS3A is a Class I system. Separations written inside the figure are relative to L1448 IRS3B.

lurking at separations below 30 AU. Perseus has at least three systems with separations ~20 AU (Figures 1 and 3). Another limiting issue in Orion is that sources are 3× fainter due to the increased distance, so observing with the same sensitivity requires 9× more observing time as compared to Perseus. It quickly becomes impractical to observe even more distant star forming regions with sensitivity to protostars having typical luminosities (i.e., 1-3 L\(_{\odot}\); Fischer et al. 2017).

Finally, it is important to highlight that in the V ANDAM survey, the spatial association of young stars was observed and not boundedness, which could not be evaluated from the data at hand. Many (or most) of the companions shown in Figure 2 at separations > 1000 AU do not likely reflect bound systems. Some could be line of sight associations (more frequent with increasing separation), or when they finish accreting material, outflows may have removed enough mass such that they are unbound. The closer companions (< 500 AU) have a higher likelihood of being bound, but even so, interactions may alter or destroy some of these multiple systems. Thus, the observed companion separation distribution in the protostellar phase may reflect the initial com-
J. J. Tobin, P. Sheehan, D. Johnstone

Figure 3. Histogram of companion star frequency versus separation for the entire sample of multiple sources in Perseus. The dashed curve is the Gaussian fit to the field star separation distribution from Raghavan et al. (2010). The vertical dot-dashed line corresponds to the approximate resolution limit of the VLA in A-configuration (∼15 AU) toward Perseus at a distance of 230 pc.

Companion separation distribution and it will dynamically evolve over Myr to Gyr toward the field star separation distribution.

The ngVLA has excellent potential to evaluate the boundedness of systems with <50 AU separations. The angular resolution in the nearby regions will uncover closer multiple systems, and the positional accuracy granted by the increased angular resolution will enable the orbital motion of <50 AU companions to be measured on time scales of ∼5 years. Such analysis can incorporate previous VLA data as needed to establish likely orbital solutions with an extended time baseline. Such measurements of binary/multiple orbits will also offer constraints on the protostar masses.

3. Examining Close Multiplicity Studies out to ≥1.5 kpc

The ngVLA offers a number of features that overcome the limitations of the current VLA. The full array will provide an angular resolution of 0.01″ at 7.3 mm and 0.014″ at 1.1 cm (ngVLA Memo #17). These two wavelength bands are ideal for examining protostellar multiplicity because they probe both dust and free-free emission. The addition of free-free emission to the dust emission makes the protostars themselves stand out, enhancing their detectability. The dramatically increased resolution of the ngVLA will enable the range of separations to be expanded, with better sensitivity to close companions. For Perseus (d=230 pc), we will be able to look for companions down to 2.3 AU separations. Toward Orion (d=400 pc), the separation limit will be pushed down to 4 AU, and in more distant, more populous star forming regions (e.g., Cygnus-X at 1500 pc) the separation limit will be 15 AU. The ngVLA will enable us to examine separations in these distant Galactic star forming regions down to the same scale that we are currently able to do in Perseus!
Angular resolution improvements alone, however, are not sufficient to address questions of protostellar multiplicity, because these studies require statistics and not a few case studies. With the drastic increase in the number of antennas, and hence the collecting area, projected for the ngVLA, it is important to consider the detectability of protostellar multiple systems in progressively more distant star forming regions. Using IRAS 03292+3039 from Perseus (Figure 1) as a case study, current VLA observations detect sources A and B with peak flux densities of 170 $\mu$Jy beam$^{-1}$ and 130 $\mu$Jy beam$^{-1}$, respectively. If a similar system were located at the distance of Cygnus-X, their respective flux densities would be 4 $\mu$Jy and 3 $\mu$Jy. These flux densities are completely impractical to observe at 30 GHz for the current VLA; reaching a S/N of 10 with the VLA would take 10 days! However, the ngVLA can reach a sensitivity of 0.26 $\mu$Jy beam$^{-1}$ ($S/N\sim10$) in 1 hour on-source. Thus, detecting such faint and close companions in massive, distant star forming regions will be routine with the ngVLA because the increased sensitivity.

We have concentrated on the capabilities of the ngVLA at $\sim7.3$ mm because of the ability to directly compare with data from the VANDAM surveys. However, the 3 mm band of the ngVLA also holds significant potential to enable studies of multiplicity out to star forming regions even more distant than Cygnus-X. At 3 mm, most emission will be from pure dust emission, and the brightness of this emission increases steeply with decreasing wavelength $\lambda^{-(2+\beta)}$ (increasing with frequency $\nu^{2+\beta}$), where $\beta$ is the dust opacity spectral index which is typically observed to be between 0 and 2 in disks (e.g., Ricci et al. 2010). IRAS 03292+3039 was also observed with ALMA at 3 mm using 14 km baselines, obtaining nearly the highest resolution offered by the facility at 3 mm. The 3 mm flux densities of the two companions were 1200 $\mu$Jy and 1050 $\mu$Jy, respectively. Scaling these to the distance of Cygnus-X they could be detected with $S/N>20$ with the ngVLA in 1 hr on-source with a sensitivity of 0.86 $\mu$Jy beam$^{-1}$. At an even greater distance of $\sim3$ kpc, they could be detected with a $S/N=8$ in 1 hr as well! Thus, the increased sensitivity of the ngVLA, coupled with the higher angular resolution will radically enhance the study of multiple star formation. Furthermore, the addition of a 3 mm band to the ngVLA would be particularly advantageous for the detection of multiple protostars in even more distant regions than possible with the 7.3 mm band due to the better resolution and the fact that dust emission increases steeply with decreasing wavelength.

Obtaining sensitive images will still take a few hours of time with overheads toward the more distant star forming regions, but star forming regions at greater distances occupy less area of the sky in terms of their solid angle. The wide field of view offered by the ngVLA (a factor of 2 increase in solid angle over the VLA), coupled with the increased sensitivity, means that many more protostars can be captured in a single pointing than in the nearby star forming regions, this will somewhat offset the need for longer integrations times because more sources will be observed in a single observation.

While ALMA of course has unmatched sensitivity to dust emission at shorter wavelengths, the shorter wavelength becomes a disadvantage when attempting to study the youngest protostars. On scales less than $\sim$100 AU, the dense inner envelope or disks of protostars can be opaque at wavelengths as long as 1.3 mm and 3 mm, hiding small-scale multiplicity (see Chapter ‘Exploring Protostellar Disk Formation with the ngVLA’). Moreover, at higher frequencies the field of view of ALMA becomes small, making it unable to simultaneously observe as many protostars at high resolution. Thus the ngVLA capability of 0.01" or better resolution at wavelengths between 2 cm and
3 mm is an absolutely unique and critical capability to examine the formation of multiple stars during the early stages of protostellar evolution.

Because detection of dust emission from the small circumstellar disks in multiple systems is the most well-defined route to detection, it is important to further demonstrate their detectability. We ran a few radiative transfer models of protostars with small disks in binary star systems and simulated their observation with the full ngVLA using the CASA simobserve task. The modeling is described in more detail in the Chapter ‘Exploring Protostellar Disk Formation with the ngVLA.’ We show the results of our simulations in Figure 4, where we have simulated the observation of two protostars, separated by 5 AU, each with a 1 AU radius and 0.001 $M_\odot$ disk. These protostars are simulated at a distance of 400 pc, and they can be well-detected by the ngVLA with $S/N = 20$ in 1 hr. We also computed a model for a 15 AU separation binary system at a distance of 1.5 kpc and each disk having a radius of 3 AU and a mass of 0.01 $M_\odot$. The 1.5 kpc binary can be detected by the ngVLA with $S/N = 10$ in 1 hr. Thus, the ngVLA will enable the detection of extremely close binary protostars with separations as small as 3 AU (at 230 pc) from their dust emission alone, under the assumption that circumstellar disks have radii of order their separation/3 (Artymowicz & Lubow 1994). However, if each component has some free-free emission, in addition to the dust, they can likely be resolved at closer separations and their disks would not need to be as massive.

In addition to the ngVLA’s ability to examine extremely close companions, the imaging capabilities of the ngVLA are superb enough to enable circum-multiple environments to be characterized. Using an ALMA image at 0.87 mm of L1448 IRS3B system, a triple system with a surrounding circum-multiple disk with spiral structure (Tobin et al. 2016a), we scaled the surface brightness assuming optically thin dust emission and $\beta=1$, implying a flux density scaling as $\lambda^{-3}$ (see discussion in preceding paragraphs). Then we simulated a 1 hour observation at 3 mm, and a 2 hour observation at 7.3 mm using the 168 antenna ‘Plains array,’ keeping the distance at 230 pc. We show the results of modeling in Figure 5; the structure observed at 0.87 mm is fully recovered with high fidelity at 3 mm and the image is also well-recovered at 7.3 mm but with lower $S/N$ due to the fainter dust emission. Thus, the ngVLA will also enable the imaging of circum-multiple environments simultaneously while probing for multiplicity. At 3 mm and 7.3 mm, the sensitivity of the ngVLA will superior to that of ALMA at these wavelengths and have higher angular resolution even with only the ‘Plains’ array. The circum-multiple emission is more likely to be optically thin at these wavelengths as compared to shorter wavelengths with ALMA.

The ngVLA will open up three exciting regions of parameter space in protostellar multiplicity studies. It will conduct high-S/N imaging toward nearby star forming regions (i.e., Perseus, Taurus) with enough angular resolution to search for companion protostars that have ~5× smaller separation than can be examined with the VLA. The ngVLA will also enable studies of protostellar multiplicity to obtain far greater statistics through the simultaneous observation of larger numbers of protostars in more distant regions (e.g., Cygnus-X) with the same or better sensitivity than is currently possible toward the nearby regions. Finally, the ngVLA can examine the environments around multiple star systems with high-S/N, with best results at the shortest wavelengths.
Figure 4. Synthetic ngVLA observations of binary systems comprised of emission from compact circumstellar disks. The left panel is at a distance of 400 pc having $R_{\text{disk}} = 1$ AU and $M_{\text{disk}} = 0.001 M_\odot$, and the right pane is at a distance of 1.5 kpc $R_{\text{disk}} = 3$ AU and $M_{\text{disk}} = 0.01 M_\odot$. Thus, these models demonstrate the feasibility of detecting small disks in multiple star systems at close separations.

Figure 5. Synthetic ngVLA observations of the triple system L1448 IRS3B using only the 168 antenna ‘Plains’ array. These simulations used a scaled ALMA 0.87 mm image as the model (left) and utilize the maximum bandwidth available for the respective ngVLA bands, 40 GHz (3 mm; middle) and 20 GHz (7.3 mm; right). The 3 mm simulation is one hour on-source and is imaged using Briggs weighting, robust=0.5, and a taper at 2000 k$\lambda$; the 7.3 mm simulation is two hours on-source and the rest of the imaging parameters are the same as the 3 mm.
4. Synergies with Other Facilities

While the ngVLA will be able to identify very close multiple systems perhaps out to 3 kpc, ALMA will be very useful in characterizing the immediate surroundings of multiple star systems. The brighter dust emission at shorter wavelengths may make ALMA an ideal complement to very high resolution studies with the ngVLA, both in the dust continuum and molecular lines, provided that the dust emission is not too optically thick. ALMA will be able to provide access to the necessary molecular lines to characterize the immediate environs around proto-multiple systems. This is because many of the most abundant, disk-tracing molecules have their strongest rotation transitions at wavelengths shorter than 3 mm; the ngVLA will only be able to access the \((J = 1 \rightarrow 0)\) transitions for most molecules, and these transitions do not generally have the brightest emission in the warm \((>20 \text{ K})\) regions in the immediate vicinity of protostars. Furthermore, ALMA dust continuum observations can detect circum-multiple disks around the protostar that might have column densities too low to detect with the ngVLA, but as shown in Figure 5 the ngVLA will have this capability as well.

The more distant star forming regions have a disadvantage relative to the nearby ones in that their protostellar content is not as well-characterized due to the low resolution \((>1''\) of previous mid-to-far-infrared surveys. The James Webb Space Telescope will undoubtedly survey numerous massive star forming regions and infrared dark clouds (IRDCs) that harbor significantly more young stars than the nearby regions at wavelengths between 10 and 28 \(\mu\)m. Thus, by the time the ngVLA is conducting early science, the protostellar content of more distant star forming regions is likely to be much more well-characterized, enabling the multiplicity results obtained by the ngVLA to be put into a similar context as the results toward nearby star forming regions.

5. Summary

The ngVLA will open a new window into the study of multiplicity during the protostellar phase, providing a much clearer picture of where most companion stars are forming. Thus, the ngVLA will improve our understanding of just how many stars and proto-planetary disks begin their lives initially as part of a multiple system and how multiplicity affects the evolution of planetary systems, whether or not the system remains a multiple in its main sequence life. The increased resolution of the ngVLA will enable both closer multiples to be detected than previously possible for protostellar systems, and coupled with the increased sensitivity, larger numbers of multiple star systems can be observed in order to obtain statistics that equal or surpass that of the field solar-type stars.

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Protostellar Multiplicity with the ngVLA

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