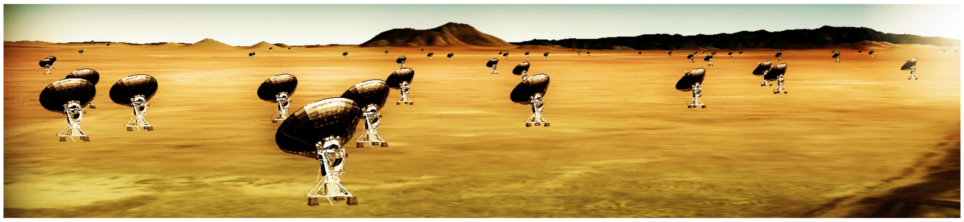

Next Generation Very Large Array Memo No. 5
Science Working Groups
Project Overview

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Abstract

We summarize the design, capabilities, and some of the priority science goals of a next generation Very Large Array (ngVLA). The ngVLA is an interferometric array with 10 times larger effective collecting area and 10 times higher spatial resolution than the current VLA and the Atacama Large Millimeter Array (ALMA), optimized for operation in the wavelength range 0.3cm to 3cm. The ngVLA opens a new window on the Universe through ultra-sensitive imaging of thermal line and continuum emission down to milliarcecond resolution, as well as unprecedented broad band continuum polarimetric imaging of non-thermal processes. The continuum resolution will reach 9mas at 1cm, with a brightness temperature sensitivity of 6K in 1 hour. For spectral lines, the array at $1''$ resolution will reach 0.3K surface brightness sensitivity at 1cm and 10 km s^{-1} spectral resolution in 1 hour. These capabilities are the *only* means with which to answer a broad range of critical scientific questions in modern astronomy, including direct imaging of planet formation in the terrestrial-zone, studies of dust-obscured star formation and the cosmic baryon cycle down to pc-scales out to the Virgo cluster, making a cosmic census of the molecular gas which fuels star formation back to first light and cosmic reionization, and novel techniques for exploring temporal phenomena from milliseconds to years. The ngVLA is

optimized for observations at wavelengths between the superb performance of ALMA at submm wavelengths, and the future SKA-1 at few centimeter and longer wavelengths. This memo introduces the project. The science capabilities are outlined in a parallel series of white papers. We emphasize that this initial set of science goals are simply a starting point for the project. We invite comment on these programs, as well as new ideas, through our public forum link on the ngVLA web page:

`https://science.nrao.edu/futures/ngvla`

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1 Introduction

Inspired by the ground-breaking results coming from the Atacama Large (sub)Millimeter Array, and the Jansky Very Large Array, the astronomical community is considering a future large area radio array optimized to perform imaging of thermal emission down to milliarcsecond scales. Currently designated the 'Next Generation Very Large Array,' such an array would entail ten times the effective collecting area of the JVLA and ALMA, operating from 1GHz to 115GHz, with ten times longer baselines (300km) providing mas-resolution, plus a dense core on km-scales for high surface brightness imaging. Such an array bridges the gap between ALMA, a superb submillimeter array, and the future Square Kilometer Array phase 1 (SKA-1), optimized for few centimeter and longer wavelengths. The ngVLA opens unique new parameter space in the imaging of thermal emission from cosmic objects ranging from protoplanetary disks to distant galaxies, as well as unprecedented broad band continuum polarimetric imaging of non-thermal processes.

We are considering the current VLA site as a possible location, in the high desert plains of the Southwest USA. At over 2000m elevation, this region provides good observing conditions for the frequencies under consideration, including reasonable phase stability and opacity at 3mm over a substantial fraction of the year (see JVLA and ngVLA memos by Owen 2015, Clark 2015, Carilli 2015, Butler 2002).

Over the last year, the astronomical community has been considering potential science programs that would drive the design of a future large area facility operating in this wavelength range. These goals are described in a series of reports published as part of the ngVLA memo series, and can be found in the ngVLA memo series:

`http://library.nrao.edu/ngvla.shtml`

- Isella et al., 2015, 'Cradle of Life' (ngVLA Memo 6)
- Leroy et al., 2015, 'Galaxy Ecosystems' (ngVLA Memo 7)
- Casey et al. 2015, 'Galaxy Assembly through Cosmic Time' (ngVLA Memo 8)
- Bower et al. 2015, 'Time Domain, Cosmology, Physics' (ngVLA Memo 9)

The white papers will be expanded with new ideas, and more detailed analyses, as the project progresses (eg. a white paper on magneto-plasma processes on scales from the Sun to clusters of galaxies is currently in preparation). In the coming months, the project will initiate mechanisms to further expand the ngVLA science program, through continued community leadership.

Such a facility will have broad impact on many of the paramount questions in modern astronomy. The science working groups are in the process of identifying a number of key science programs that push the requirements of the telscope. Three exciting programs that have come to the fore thus far, and *that can only be done with the ngVLA*, include:

- **Imaging the 'terrestrial-zone' of planet formation in protoplanetary disks**: Probing dust gaps on 1AU scales at the distance of the nearest major star forming regions (Taurus and Ophiucus distance ~ 130pc) requires baselines 10 times that of the JVLA, with a sensitivity adequate to reach a few K brightness at 1cm wavelength and 9mas resolution. Note that these inner regions of protoplanetry disks are optically thick at shorter wavelengths (see section 4.1). The ngVLA will image the gap-structures indicating planet formation on solar-system scales, determine the growth of grains from dust to pebbles to planets, and image accretion onto the proto-planets themselves.

- **ISM and star formation physics on scales from GMCs down to cloud cores throughout the local super-cluster**: a centrally condensed antenna distribution on scales of a few km (perhaps up to 50% of the total collecting area), is required for wide field, high surface brightness (mK) sensitivity. The ngVLA covers the spectral range richest in the ground state transitions of the most important molecules in astrochemistry and astrobiology, as well as key thermal and non-thermal continuum emission process relating to star formation. The ngVLA will perform wide field imaging of line and continuum emission on scales from GMCs (100pc) down to clump/cores (few pc) in galaxies out to the Virgo Cluster.

- **A complete census of the cold molecular gas fueling the star formation history of the Universe back to the first galaxies:** octave bandwidth at $\sim$ 1cm wavelength, is required for large cosmic volume surveys of low order CO emission from distant galaxies (the fundamental tracer of total gas mass), as well as for dense gas tracers such as HCN and HCO+. The spatial resolution and sensitivity will also be adequate to image gas dynamics on sub-kpc scales and detect molecular gas masses down to dwarf galaxies.

In this summary paper, we present a general description of the project, basic design goals for sensitivity and resolution, and the unique observational parameter space opened by such a revolutionary facility. We emphasize that the ngVLA is a project under development. While the broad parameter space is reasonably well delineated, there are many issues to explore, ranging from element diameter to the number of frequency bands to the detailed array configuration, including consideration of VLBI-length baselines (see section 2.2). The science white papers are identifying the primary science use cases that will dictate the ultimate design of the telescope, in concert with the goal of minimization of construction and operations costs. The requirements will mature with time, informed by ALMA, the JVLA, the imminent JWST and thirty meter-class optical telescopes, and others.

2 Telescope specifications

2.1 Basic array

In Table 1 we summarize the initial telescope specifications for the ngVLA. As a first pass, we present numbers for an 18m diameter antenna, although the range from 12m to 25m is being considered. A key design goal is good antenna performance at higher frequency, eg. at least 75% efficiency at 30GHz. The nominal frequency range of 1GHz to 115GHz is also under discussion. The bandwidths quoted are predominantly 2:1, or less, although broader bandwidths are being investigated. Receiver temperatures are based on ALMA and VLA experience. We emphasize that these specifications are a first pass at defining the facility, and that this should be considered an evolving study.

Brightness sensitivity for an array is critically dependent on the array configuration. We are assuming an array of 300 antennas in this current configuration. The ngVLA has the competing desires of both good point source sensitivity at full resolution for few hundred km baselines, and good surface brightness sensitivity on scales approaching the primary beam size. Clark & Brisken (2015) explore different array configurations that might provide a reasonable compromise through judicious weighting of the visibilities for a given application (see eg. Lal et al. 2010 for similar studies for the SKA). It is important to recognize the fact that for any given observation, from full resolution imaging of small fields, to imaging structure on scales approaching that of the primary beam, some compromise will have to be accepted.

For the numbers in Table 1, we have used the Clark/Conway configurations described in ngVLA memos 2 and 3. Very briefly, this array entails a series of concentric 'fat-ring' configurations out to a maximum baseline of 300km, plus about 20% of the area in a compact core in the inner 300m. The configuration will be a primary area for investigation in the coming years. We have investigated different Briggs weighting schemes for specific science applications, and find that the Clark/Conway configuration provides a reasonable starting compromise for further calculation (see notes to Table 1).

2.2 VLBI implementation

The science white papers present a number of compelling VLBI astrometric science programs made possible by the increased sensitivity of the ngVLA. These include: Local Group cosmology through measurements of proper motions of nearby galaxies, delineation of the full spiral structure of the Milky Way, and measuring the masses of supermassive black holes and H_0.

The exact implementation of interferometry with the ngVLA on baselines longer than the nominal 300km array remains under investigation. These astrometric programs require excellent sensitivity per baseline, but may not require dense coverage of the UV plane, since high dynamic range imaging may not be required.

One possible implementation would be to use the ngVLA as an ultra-sensitive, anchoring instrument, in concert with radio telescopes across the globe. Such a model would parallel the planned implementation for submm VLBI, which employs the ultra-sensitive phased ALMA, plus single dish submm telescopes around the globe, to perform high priority science programs, such as imaging the event horizons of supermassive black holes (Akiyama et al. 2015). A second possibility would be to include out-lying stations within the ngVLA construction plan itself, perhaps comprising up to 20% of the total area out to trans-continental baselines. The cost, practicability, and performance of different options for VLBI will be studied in the coming year.

3 New Parameter Space

Figure 1 shows one slice through the parameter space covered by the ngVLA: resolution versus frequency, along with other existing and planned facilities.

Table 1: Next Generation VLA nominal parameters

	2GHz	10GHz	30GHz	80GHz	100GHz
Field of View FWHM (18m[a]) arcmin	29	5.9	2	0.6	0.51
Aperture Efficiency (%)	65	80	75	40	30
A^{b}_{eff} x10^4 m^2	5.1	6.2	5.9	3.1	2.3
T^{c}_{sys} K	29	34	45	70	80
Bandwidth[d] GHz	2	8	20	30	30
Continuum rms[e] 1hr, μJy bm^{-1}	0.93	0.45	0.39	0.96	1.48
Line rms 1hr, 10 km s^{-1}, μJy bm^{-1}	221	70	57	100	130
Resolution[f] FWHM milliarcsec	140	28	9.2	3.5	2.8
T^{g}_{B} rms continuum 1hr K	14	7	6	15	23
Line[h] rms 1hr, 1", 10 km s^{-1}, μJy bm^{-1}	340	140	240	860	–
T^{i}_{B} rms line, 1hr, 1", 10 km s^{-1}, K	100	1.8	0.32	0.17	–

[a]Under investigation: antenna diameters from 12m to 25m are being considered.
[b]300 x 18m antennas with given efficiency.
[c]Current performance of JVLA below 50GHz. Above 70GHz we assume the T_{sys} =60K value for ALMA at 86GHz, increased by 15% and 25%, respectively, due to increased sky contribution at 2200m.
[d]Under investigation. For much wider bandwidths, system temperatures are likely to be larger.
[e]Noise in 1hour for given continuum bandwidth for a Clark/Conway configuration (ngVLA memo 2 and 3) scaled to a maximum baseline of 300km, using Briggs weighting with R=0. Using R=1 decreases the noise by a factor 0.87, and using R=-1 increases the noise by a factor 2.5.
[f]Synthesized beam for a Clark/Conway configuration scaled to a maximum baseline of 300km, using Briggs weighting with R=0. For R=1, the beam size increases by a factor 1.36, and for R=-1 the beam size decreases by a factor 0.63.
[g]Continuum brightness temperature corresponding to point source sensitivity (row 6) and resolution of Clark/Conway configuration, using Briggs weighting with R = 0 (row 8).
[h]Line rms in 1hr, 10 km s^{-1}, after tapering to 1" resolution for the Clark/Conway configuration.
[i]Line brightness temperature rms in 1hr, 10 km s^{-1}, after tapering to 1" resolution for the Clark/Conway configuration.

The maximum baselines of the ngVLA imply a resolution of better than 10mas at 1cm. As we shall see below, coupled with the high sensitivity of the array, this resolution provides a unique window into the formation of planets in disks on scales of our own Solar system at the distance of the nearest active star forming regions, eg. Taurus and Ophiucus.

Figure 2 shows a second slice through parameter space: effective collecting area versus frequency. In this case, we have not included much higher and lower frequencies, eg. the SKA-1 will extended to much lower frequency (below 100MHz, including SKA-Low), while ALMA extends up to almost a THz.

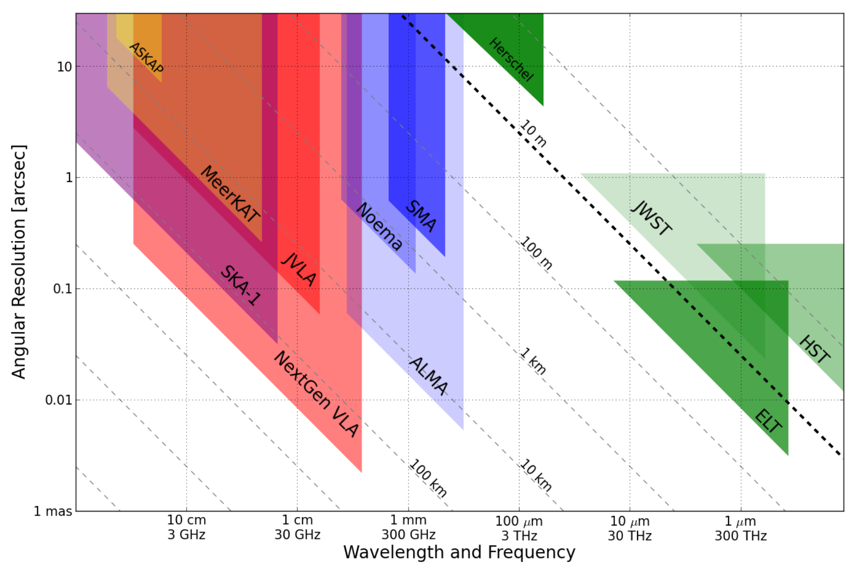

Figure 1: *Spatial resolution versus frequency set by the maximum baselines of the ngVLA, and other existing and planned facilities across a broad range of wavelengths.*

Given the collecting area and reasonable receiver performance (Table 1), the ngVLA will achieve sub-μJy sensitivity in the continuum in 1 hour at 1cm (30GHz). This implies that, at 1cm, the ngVLA will obtain 6K brightness temperature sensitivity with 9mas resolution in just 1 hour!

We note that there are other aspects of telescope phase space that are relevant, including field of view and mapping speed, configuration and surface brightness sensitivity, bandwidth, T_{sys}, etc... Given the early stage in

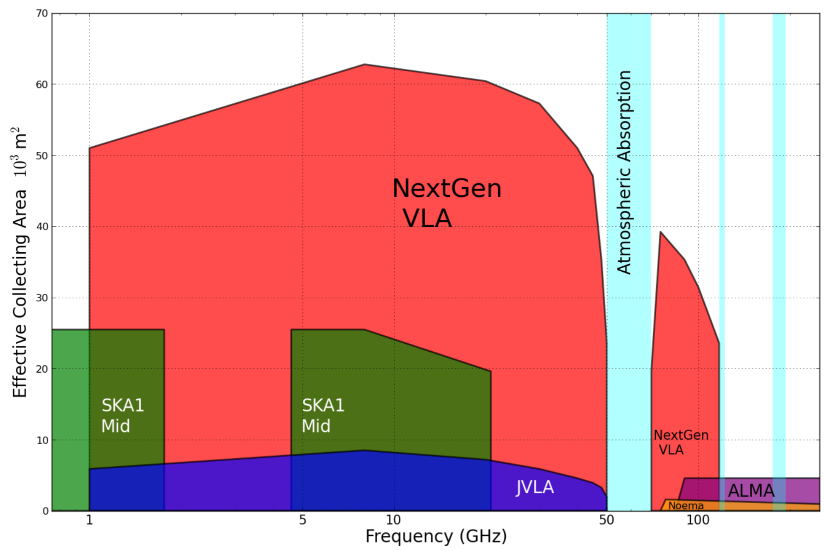

Figure 2: *Effective collecting area versus frequency for the ngVLA, and other existing or planned facilities operating in a comparable frequency range. We have not included much higher and lower frequencies, eg. the SKA-1 will extended to below 100MHz (including SKA-Low), while ALMA extends up to close to a THz.*

the design, we have presented the two principle and simplest design goals, namely, maximum spatial resolution and total effective collecting area. A deeper consideration of parameter space will depend on the primary science drivers that emerge in the coming years.

4 Science Examples

In the following, we highlight some of the science that is enabled by such a revolutionary facility. These three areas are among the high priority goals identified by the science working groups, and in particular, these are the goals that have been best quantified to date. We note that the most important science from such a revolutionary facility is difficult to predict, and perhaps the most important aspect of the science analysis is simply the large volume of unique parameter space opened by the ngVLA (Figs 1 and 2).

4.1 Imaging terrestrial-zone planet formation

With the discovery of thousands of extrasolar planets, and the first high resolution images of protoplanetary disks with ALMA, the field of extrasolar planets and planet formation has gone from rudimentary studies, to a dominant field in astrophysics, in less than a decade. This remarkable progress promises to continue, as ALMA comes into full operation, and with future space missions targetting planet detection, such as the High Definition Space Telescope, for which the primary science goals are direct imaging of terrestrial planets and the search for atmospheric bio-signatures.

The first high resolution images from ALMA of the protoplanetary disk in HL Tau are clearly game-changing (Brogan et al. 2015). The ALMA images show a dust disk out to 100AU radius, with a series of gaps at radii ranging from 13 AU to 80AU. These gaps may correspond to the formation zones of planets. Coupled with JVLA imaging at longer wavelengths, these HL Tau images usher in a new era in the study of planet formation.

While revolutionary, there are limitations to the current capabilities of ALMA and the JVLA in the study of protoplanetary disks. First, for ALMA, the inner 10AU of protoplanetary disks like HL Tau become optically thick at wavelengths of 3mm and shorter. Second, for the JVLA, the sensitivity and spatial resolution are insufficient to image the terrestrial-zone of planet formation at the longer wavelengths where the disks become optically thin.

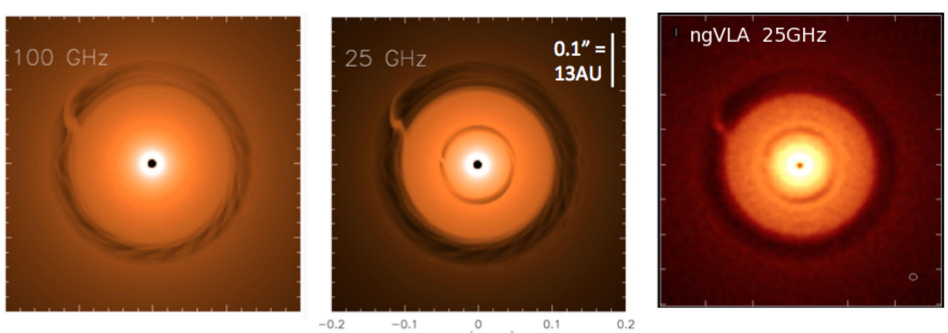

Figure 3: *Models and images of a $\sim$ 1Myr old protoplanetary disk, comparable to HL Tau, at a distance of 130pc. This 'minimum mass solar nebula disk' has a mass of 0.1$M_\odot$ orbiting a 1 $M_\odot$ star. The model includes the formation of a Jupiter mass planet at 13AU radius, and Saturn at 6AU. The left frame shows the model emission at 100GHz, the center frame shows the 25GHz model, and the right shows the ngVLA image for a 100hour observation at 25GHz with 10mas resolution. The noise in the ngVLA image is 0.1μJy, corresponding to 1K at 10mas resolution.*

The ngVLA solves both of these problems, through ultra-high sensitivity in the 0.3cm to 3cm range, with milliarcsecond resolution. Figure 3 shows a simulation of the ability of the ngVLA to probe the previously inaccessible scales of 1AU to 10AU. This simulation involves an HL-Tau like protoplanetary disk, including the formation of a Jupiter mass planet at 13AU radius, and Saturn at 6AU. Note that the inner ring caused by Saturn is optically thick at 3mm. However, this inner gap is easily visible at 25GHz, and well imaged by the ngVLA. Moreover, the ngVLA will have the sensitivity and resolution to image circum-planetary disks, ie. the formation of planets themselves via accretion. In parallel, the ngVLA covers the optimum frequency range to study pre-biotic molecules, including rudimentary amino acids such as glycine (see Isella et al. 2015 for more details).

Next Generation Synergy: The High Definition Space Telescope has made its highest priority goals the direct imaging of terrestrial-zone planets, and detection of atmospheric biosignatures. The ngVLA provides a perfect evolutionary compliment to the HDST goals, through unparalleled imaging of terrestrial zone planet formation, and the study of pre-biotic molecules.

4.2 The dense gas history of the Universe

Using deep fields at optical through radio wavelengths, the evolution of cosmic star formation and the build up of stellar mass have been determined in exquisite detail, from the epoch of first light (cosmic reionization, $z > 7$), through the peak epoch of cosmic star formation ('epoch of galaxy assembly', $z \sim 1$ to 3), to the present day (Madau & Dickinson 2014). However, these studies reveal only one aspect of the baryonic evolution of galaxies, namely, the stars. What is currently less well understood, but equally important, is the cosmic evolution of the cool, molecular gas out of which stars form. Initial in-roads into the study of the cool gas content of galaxies has been made using the JVLA, GBT, Plateau de Bure, and now ALMA. These initial studies have shown a profound change in the baryonic content of star forming galaxies out to the epoch of galaxy assembly: the gas baryon fraction (the gas to stellar mass ratio) increases from less than 10% nearby, to unity, or larger, at $z \sim 2$ to 3 (Genzel et al. 2015, Carilli & Walter 2013). This profound change in galaxy properties with redshift is likely the root-cause of the evolution of the cosmic star formation rate.

However, studies of the gas mass in early galaxies, typically using the low order transitions of CO, remain severely sensitivity limited, requiring long observations even for the more massive galaxies. The sensitivity and resolution of the ngVLA opens a new window on the gas properties of early

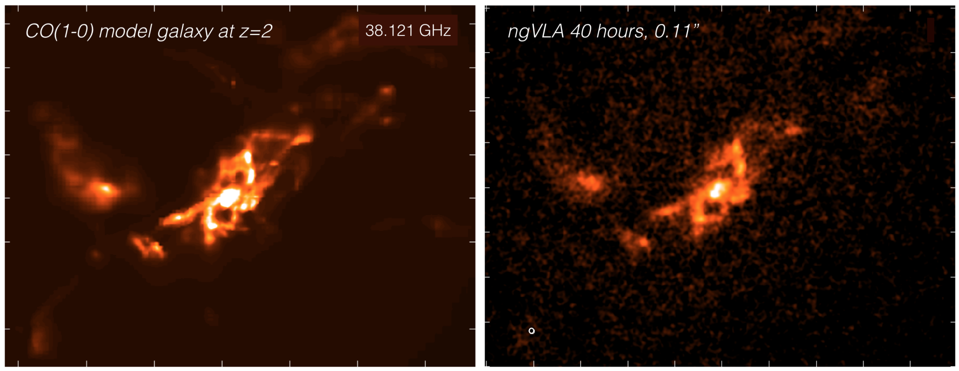

Figure 4: *Left: A model of the integrated CO 1-0 emission from a massive z=2 galaxy from the cosmological zoom simulations of Narayanan et al. (2015). The total SFR* $= 150$ $M_\odot$ *year*$^{-1}$*, and the stellar mass* $= 4 \times 10^{11}$ $M_\odot$*. The native resolution (pixel size) is 30mas, and the peak brightness temperature is 14K. The fainter regions have* $T_B \geq 0.1K$*. Right: the ngVLA image of the field assuming a 8 x 5hour synthesis using only antennas within a 15km radius (about 50% of the full array for the Clark/Conway configuration, and using Briggs weighting with R=0.5. The rms noise is 5*μ*Jy beam*$^{-1}$*, and the beam size is* 0.11"*. One tick mark* = 1"*. The peak surface brightness is 0.18 mJy beam*$^{-1}$*.*

galaxies, through efficient large cosmic volume surveys for low order CO emission, and detailed imaging of gas in galaxies to sub-kpc scales (see Casey et al. 2015). The ngVLA will detect CO emission from tens to hundreds of galaxies per hour in surveys in the 20GHz to 40GHz range. In parallel, imaging of the gas dynamics will allow for an empirical calibration of the CO luminosity to gas mass conversion factor at high redshift.

Figure 4 shows a simulation of the CO 1-0 emission from a massive z=2 galaxy from the cosmological zoom simulations of Narayanan et al. (2015), plus the ngVLA simulated image. The ngVLA reaches an rms noise of 5μJy beam^{-1} (over 9MHz bandwidth and 40hours), and the beam size is 0.11" = 0.9kpc at z=2, only using antennas within 15km radius of the array center. The ngVLA can detect the large scale gas distribution, including tidal structures, streamers, satellite galaxies, and possible accretion. Note that the rms sensitivity of the ngVLA image corresponds to an H_2 mass limit of 3.3×10^8 $(\alpha/4)$ $M_\odot$. Further, the ngVLA has the resolution to image the gas dynamics on scales approaching GMCs. For comparison, the JVLA in a similar integration time would only detect the brightest two knots at the very center of galaxy, while emission from the high order transitions imaged by ALMA misses the extended, low excitation, diffuse gas in the system.

Next Generation Synergy: With new facilities such as thirty-meter class optical telescopes, the JWST, and ALMA, study of the stars, ionized gas, and dust during the peak epochs of galaxy formation, will continue to accelerate. The ngVLA sensitivity and resolution in the 0.3cm to 3cm window is the required complement to such studies, through observation of the cool gas out of which stars form throughout the Cosmos.

4.3 Ultra-sensitive, wide field imaging

Science working group 2 ('Galaxy ecosystems'; Leroy etal. 2015) emphasized the extraordinary mapping speed of the ngVLA in line and continuum, for study of the gas and star formation in the nearby Universe. The frequency range of the ngVLA covers, simultaneously, multiple continuum emission mechanisms, from synchrotron, to free-free, to cold (or spinning) dust. These mechanisms are key diagnostics of star formation, cosmic rays, magnetic fields, and other important ISM properties. This range also covers low order and maser transitions of most astrochemically important molecules, such as CO, HCN, HCO^+, NH_3, H_2O, CS...

Figure 5 shows an ngVLA simulation of the thermal free-free emission in the 30GHz band from a star forming galaxy at 27Mpc distance, with a moderate star formation rate of 4 $M_\odot$ year^{-1}. The ngVLA will image the free-free emission with a sensitivity adequate to detect an HII region associated with a single O7.5 main sequence star at the distance of the Virgo cluster! In general, the combination of spectral and spatial resolution will allow for decomposition of the myriad spectral lines, and various continuum emission mechanisms, on scales down to a few parsecs at the distance of Virgo, thereby enabling Local-Group-type science throughout the local supercluster.

4.4 Exploring the Time Domain

The ngVLA is being designed for optimal exploitation of the time domain. Fast triggered response modes on minute timescales will be standard practice. Commensal searches for ultra-fast transients, such as Fast Radio Bursts or SETI signals, will also be incorporated into the design. And monitoring of slow transients, from novae to AGN, will be possible at unprecedented sensitivities, bandwidths, and angular resolutions. The 2cm and shorter capabilities will be complimentary to the SKA-1 at longer wavelengths, in particular for the broad band phenomena typical of fast and slow transients.

The broad band coverage and extreme sensitivity of the ngVLA provides a powerful tool to search for, and characterize, the early time emission from

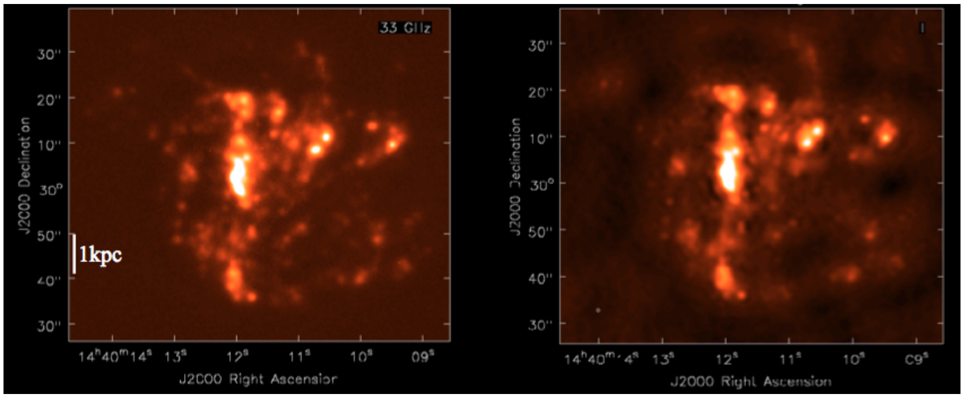

Figure 5: *Left: a model for the thermal free-free emission from NGC 5713 at a distance of 27Mpc with a SFR = 4 $M_\odot$ year^{-1}. The model was estimated from Hα imaging at a native resolution of 2". The peak brightness temperature is 150mK, and the fainter knots are about 1mK. Right: The ngVLA image for 10hrs integration, with a bandwidth of 20GHz, centered at 30GHz. The rms is 0.1μJy beam^{-1}. Note that the ngVLA image has been restored with a beam of* 0.5".

processes ranging from gravity wave EM counter-parts to tidal disruption events around supermassive black holes as well as probing through the dense interstellar fog in search of Galactic Center pulsars. The system will also provide unique insights into variable radio emission associated with 'exo-space weather,' such as stellar winds, flares, and aurorae. Moreover, many transient phenomena peak earlier, and brighter, at higher frequencies, and full spectral coverage to high frequency is required for accurate calorimetry. Full polarization information will also be available, as a key diagnostic on the physical emission mechanism and propagation effects.

We invite the reader to investigate the science programs in more detail in the working group reports, as well as to participate in the public forums and meetings in the on-going development of the ngVLA science case.

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