# ngVLA Science Book

November 7, 2017

# Contents

# Preface

bla bla

# Part I

# Executive Summary

# Chapter 1

# ngVLA Key Science Mission

Summary of Key science Goals from memo 19

# Chapter 2

# The ngVLA Science Requirements

See Level 0 Science Req. Doc.

- angular resolution and dynamic range
- point source continuum sensitivity
- point source line sensitivity
- image fidelity
- wavelength coverage
- phase calibration requirements
- flux calibration
- field of view and mapping speed

# Chapter 3

# Site Selection and Performance

Weather statistics for VLA site (3mm performance)

# Chapter 4

# The ngVLA Reference Design

Telescope baseline design

## 4.1 Antenna

## 4.2 Configuration

## 4.3 Receiver Configuration

## 4.4 Phase Calibration

## 4.5 Computing

## 4.6 Science Ready Data Products

# Chapter 5

# System Performance

Imaging Performance/Simulations
Dynamic Range
Surface Brigthness Sensitivity

# Chapter 6

# Education and Public outreach

bla bla

Secion 1.4 in PEP (see Suzy)

# Part II

# Introduction

# Chapter 7

# The present and future radio astronomy landscape

bla bla

# Chapter 8

# History of the Idea

EVLA Phase 2
New Mexico Array
NAA
SKA High

# Part III

# ngVLA Science Case

# Chapter 9

# Galaxy Ecosystems

## 9.1 Introduction

blah blah

## 9.2 Active and Star-Forming Galaxy Nuclei

### 9.2.1 Physics of Radio Jet-ISM Feedback

Authors: Kristina Nyland (Laura Chomiuk says: we should figure out if this goes best under galaxy ecosystems or the black hole section. I would argue for galaxy ecosystems, but we should make sure we're all on the same page)

### 9.2.2 Black Hole Accretion Probed by Linear and Circular Polarimetry

Authors: Christopher A. Hales (Laura Chomiuk says: this is also a section under Galaxy Evolution chapter)

### 9.2.3 A High-Resolution Kinematic View of Nearby Galaxy Nuclei

Authors: Betsy Mills (Laura Chomiuk says: I'm not sure what is meant here, but it's possible this fits in better under the black holes science goal?)

### 9.2.4 Thomson Scattering and 3D Plasma

Authors: Frazer Owen

### 9.2.5 Accurate Massive Black Hole Masses

Authors: Kristina Nyland (Laura Chomiuk says: we have a very similar section in the black holes chapter. i would argue that it fits in better under the black holes goal)

### 9.2.6 The Galactic Center Ecosystem

Authors: Mark Morris (Laura Chomiuk says: would this work better under the pulsars in the Galactic center goal?) (A.B.: I think this is more about molecular clouds and young star formation)

## 9.3 Extended Galaxy Emission and Intergalactic Gas

### 9.3.1 Atomic Hydrogen in the Local Universe

Authors: Walter, Stanimirovic et al.

### 9.3.2 Radio Continuum Emission from Galaxies: An Accounting of Energetic Processes

Authors: Eric Murphy, Mark Sargent

### 9.3.3 How Do Cold Galaxy Outflows Shape Galaxies?

Authors: A. D. Bolatto et al.

### 9.3.4 Galaxy HI Structure as Measured in Edge-On Galaxies

??

## 9.4 Molecular clouds and Dense Gas

### 9.4.1 Direct Measurements of Density and Temperature in Star-Forming Gas

Authors: Tony Wong

### 9.4.2 Parsec-Scale Cold Gas Structure Across the Whole Local Galaxy Population

Authors: Adam Leroy

### 9.4.3 A Complete Line Survey and Sub-Pc Map of Every Local Group Molecular Cloud

Authors: Adam Leroy

### 9.4.4 Gas Density Across the Local Universe

Authors: Adam Leroy

### 9.4.5 The Definitive Census of the Molecular ISM in the Milky Way

Authors: Erik Rosolowsky

## 9.5 Extranuclear Systems: Globular Clusters and HII Regions

### 9.5.1 Star Clusters, Super Star Clusters, and Nascent Globular Clusters

Candidate authors: A. Mioduszewski, C. Melis, T. Maccarone, K. Johnson?

### 9.5.2 Radio Recombination Lines from HII Regions

Candidate authors: Dana Balser, Amanda Kepley

## 9.6 Life and Death of Stars

### 9.6.1 Stellar Photospheres and Activity

Candidate author: G. Harper

### 9.6.2 Novae

Candidate authors: L. Chomiuk

### 9.6.3 Evolved Stars

Candidate authors: L. Mathews, M. Claussen?

### 9.6.4 Planetary Nebulae

Candidate author: R. Montez?

### 9.6.5 Supernova remnants

Candidate lead authors: Laura Chomiuk?? If too busy, maybe Carlos Badenes or Laura Lopez??

### 9.6.6 Cataclysmic Variable Stars

Candidate lead author: D. Coppejans

### 9.6.7 Shaping of Stellar Outflows

Candidate lead author: J. Linford with help from L. Chomiuk, J. Sokoloski, N. Smith, A. Ziljstra, M. Rupen, A. Mioduszewski (good use of thermal imaging at mas scales!)

Laura Chomiuk says a BUNCH of the science that is currently in the 'Additional Science' chapter should be moved here.

# Chapter 10

# Galaxy Evolution

## 10.1 Introduction

bla bla

## 10.2 Large Scale Surveys: Searching for Galaxies and Black Holes at High Redshift

### 10.2.1 CO as a Redshift Beacon

Authors: Roberto Decarli, Chris Carilli

### 10.2.2 Continuum Surveys

Authors: Amy Barger, Eric Murphy, Mark Sargent, Jim Condon

### 10.2.3 [CII] 158um line emission from z=15 to 20 galaxies

Authors: Chris Carilli, Eric Murphy

## 10.3 Cold Gas in High-$z$ Galaxies

### 10.3.1 The Molecular Gas Budget

Authors: Roberto Decarli, Chris Carilli

### 10.3.2 The Dense ISM

Authors: Roberto Decarli

## 10.4 The Environments of High-$z$ Galaxies and their Growth

### 10.4.1 Mapping High-z CO Gas

Authors: Chris Carilli, Eric Murphy

### 10.4.2 Low-surface-brightness CO

Authors: Bjorn Emonts

### 10.4.3 Observing magnetized galaxy evolution at $z < 0.5$ and beyond

Authors: Christopher A. Hales

## 10.5 Feedback in the Early Universe and the Growth of Black Holes

### 10.5.1 Observing AGN feedback over cosmic time through deep, individual observations

Authors: Katherine Alatalo

### 10.5.2 Investigating Quasar Mode Feedback through the SZ effect

Authors: Mark Lacy

### 10.5.3 Probing Obscured MBH Accretion and Growth at Cosmic Dawn

Authors: Kristina Nyland

### 10.5.4 Black hole accretion probed by linear and circular polarimetry

Authors: Christopher A. Hales

# Chapter 11

# Star Systems in Formation

## 11.1 Introduction

bla bla

## 11.2 Star Forming Cores and Filaments on a Galactic Scale

### 11.2.1 Star Count measurements of the Star Formation Rate in the Galaxy

### 11.2.2 Protostellar Multiplicity

### 11.2.3 Stucture and Dynamics of Jets from YSOs and HII Regions

### 11.2.4 Magnetic Fields as a Regulating Influence on Star Formation

### 11.2.5 Tracing deuteration in starless and protostellar cores

## 11.3 Individual Stars in Formation

### 11.3.1 Complex Molecules in Hot Molecular Cores

### 11.3.2 Detection of Massive Star Forming Objects through Maser Imaging

### 11.3.3 Detecting Infall in High Mass protostellar objects

### 11.3.4 Examining Disk Formation at high resolution

### 11.3.5 Disk Winds

### 11.3.6 Polarization science in cores and disks

# Chapter 12

# Planet Formation

## 12.1 Introduction

bla bla

## 12.2 Resolved Structure in Protoplanetary Disks

## 12.3 Particle Evolution at the H2O snowline

### 12.3.1 Use of the NH3 snowline as a proxy for water

## 12.4 Characterizing Planet-Disk Interactions

## 12.5 Detecting organic content in the protoplanetary disk midplane

## 12.6 Polarization of Protoplanetary Disks

## 12.7 Circumplanetary Disks

## 12.8 Resolved Substructures in Protoplanetary Disks

*Sean M. Andrews, David J. Wilner, and Andrea Isella*

In the "core accretion" paradigm for planet formation, terrestrial planets and giant planet cores are created by a successive chain of the collisional agglomeration of solids over 20 orders of magnitude in size within a few Myr. Early in that process, the standard theoretical assumptions introduce two fundamental obstacles to that growth. The first is related to the migration of mm/cm-sized particles; as these solids decouple from the gas disk they move inwards faster than they can collide and grow. The second is that the timescales for assembling "planetesimals" ( km scale bodies) is too long, given the migration and destructive impacts of their precursors. The potential solution to both issues is to locally concentrate the solids, halting their migration and slowing their relative velocities to promote rapid growth to large sizes. The key factor needed to make this happen is that the pressure profile of the gas disk is not smooth: local pressure maxima, induced by abrupt variations in disk properties, dynamical effects, or hydrodynamic instabilities, are predicted to effectively slow and trap these particles to very high concentration levels. The only way to test this hypothesis for aiding planetesimal formation is to directly characterize localized concentrations of solid particles in disks. The ideal tracer is the 30-100 GHz continuum, which strikes the best balance in sensitivity (emission still bright), optical depth (low enough to reliably estimate densities), and angular resolution (high enough to resolve fine-scale features at disk radii as small as 1 AU). A modest survey could be used to understand the underlying physical mechanisms that control the prevalence, forms, scales, amplitudes, spacings, and symmetry of disk substructures and their presumably crucial roles in the planet formation process.

Deep imaging of the radio continuum in two wide bands (bandwidths of 20-30 GHz are sufficient) centered around 100 GHz (W) and 35 GHz (Ka) would be required for both raw sensitivity and robust constraints on spatial variations of the spectral index. Very high angular resolutions of 1.5 mas (corresponding to 0.2 AU for the nearest protoplanetary disks, with a typical distance of 140 pc) are required to resolve the types of features that are theoretically predicted down to a disk radius of 1 AU. Those resolutions require baseline lengths of 1000 km in the Ka band. The benchmark spatial scale of the gas pressure peaks induced dynamically or by hydrodynamic instabilities corresponds to the vertical scale height, typically 10a FWHM 0.2 AU at a radius of 1 AU. So the resolution driver is the ability to spatially resolve the typical substructures down to a disk radius of 1 AU. Measurements over wide bandwidths at both ends of the 30-100 GHz range permit an estimate of the optical depth and spectral index of the emission, crucial to understanding the strength of the pressure maxima responsible for concentrating the particles. The lower frequency data are much more likely to be optically thin, and thereby serve as fundamentally important tracers of the solid densities in those concentrations. If high concentration levels can be measured, we could rule on the likelihood that fast-acting instabilities (like the streaming instability) are dominant players in the formation of planetesimals. The conservative sensitivity goal would be to firmly detect (at 5-sigma) a 10gas density variation expected in scenarios that might trap particles (e.g., weak vortices, dynamical perturbations from a very low-mass companion, etc.). For the background emission, we consider a notional disk with a temperature of 200 K and optical depths of 0.4 at 100 GHz and 0.1 at 30 GHz at a radius of 1 AU. The corresponding surface brightnesses are 0.04 and 1 microJy/beam at

30 and 100 GHz, respectively. To detect a 10noise level of 0.0008 and 0.02 microJy/beam at 30 and 100 GHz, respectively. Those numbers are strikingly far outside the notional ngVLA technical guidance. We feel obliged to present an alternative that would still go a long way toward answering these same pressing questions, but for larger radii in the disk. A more feasible goal focuses on the substructures that halt inward migration and concentrate particles to high dust-to-gas ratios at these larger radii. This is perhaps more relevant to connecting observations with the shortcomings of the theory, but less directly relevant to terrestrial planet formation. A goal of resolving substructures with scaleheight dimensions at a radius of 10 AU requires an angular resolution of 15 mas (2 AU). The same goal of detecting 10% variations (at 5-sigma) in the surface brightness on these scales would require RMS noise levels of 0.02 and 0.7 microJy/beam at 30 and 100 GHz, respectively. This goal is compelling because it would have good synergy with matching resolution observations using ALMA Band 6 (230 GHz). That would give considerably more leverage to measurements of the spectral index in these particle concentrations (both due to the large frequency lever and the potential to measure the temperature at an optically thick wavelength). Note that all of these numbers scale with the expected optical depth variation up to 100% levels, where the 100 GHz emission would saturate around an optical depth of unity. In any cases, long-term monitoring observations would be of extraordinarily high value for any substructures detected with a clear azimuthal asymmetry. The motions of such features compared to their expected Keplerian orbital rates can help illuminate the natures of the underlying source of the pressure maximum responsible for the particle trap. A displacement of 1 beam would take 2 weeks or 1 year at 1 or 10 AU, respectively, for the observing scenarios highlighted above.

The ngVLA is the only facility that can probe optically thin continuum emission on these scales to constrain the mechanisms that create and contents of particle traps. In principle it is also the facility with the most resolution at long wavelengths, although perhaps will not be sensitive enough to exploit the goals of this specific kind of program at those resolutions.

There is natural synergy with the long baselines of ALMA at higher frequencies for identifying structures (at few AU scales) with higher contrasts, but quantitative constraints on the solid surface densities and measurements at sub-AU resolution are not possible with that facility (of course, we'll leave it up to the ngVLA team to decide if they are possible in this case). No other facility in the long-term timeframe will be able to probe small-scale disk density structures at sufficiently high angular resolution to compete with an ngVLA optimized for this use case.

## 12.9 Particle Evolution at the H2O Snowline

*Jonathan P. Williams, Paola Pinilla, & Sean M. Andrews*

Water is perhaps the most important astrobiological molecule. The pileup of particles at the water snowline is potentially a critical trigger for planet formation. Measuring other molecules that are also released provides a window into icy planetesimal composition.

The water snowline in an accreting protoplanetary disk around a sun-like star is at 5-10 au. We therefore require high angular resolution, ¡ 50mas, but also need to map well beyond the snowline so require a maximum recoverable scale ¿ 500mas. To meet the combination of resolution and low dust optical depth suggests the ideal wavelengths for this experiment is at 30 GHz and we would measure the spectral index across the 20 GHz bandwidth. For a fiducial disk, the emission is predicted to be strong and the sensitivity requirements are not stringent: 5 $\mu$Jy/beam will suffice (for a distance of 100 pc).

To search for and locate the 23 GHz inversion transition from NH3 released at the snowline is best carried out through spectro-astrometry rather than direct mapping. This requires a high spectral resolution, 0.2 km/s, similar to the thermal broadening. The predicted line flux is 150 $\mu$Jy per 0.2" beam per channel. That is a challenging aspect of the program, but the payoff is high.

Only ngVLA provides the required very high resolution imaging at millimeter-centimeter wavelengths to study the dust properties across the H2O snowline. ALMA can measure the spectral index from 1.3mm to 3mm at comparable angular scales in long integrations but the dust emission can become optically thick at these wavelengths, which prevents the grain properties from being determined.

The emission from trace molecules, such as NH3, that are released as the ice evaporates will be faint and detection requires a large collecting area. ALMA may be able to do complementary work of other molecules that are mixed with the water ice such as CO.

These observations can inform planet formation models at orbital radii of a few au, where there is already much information on exoplanet demographics. It will complement direct imaging studies of such planets with ELT and WFIRST. Moving forward, there are no planned facilities that will be able to supersede these observations.

# Chapter 13

# Solar System

## 13.1 Introduction

bla bla

## 13.2 The Sun

### 13.2.1 Solar Chromosphere

### 13.2.2 Solar Flares

## 13.3 Giant Planets

### 13.3.1 Giant Planet Atmospheres

### 13.3.2 Syncrotron Radiation from Giant Planets

### 13.3.3 Probing Saturn's Rings

## 13.4 Planetary Radar

## 13.5 Probing the Primordial Solar System

### 13.5.1 Surface Emission from Small Bodies

### 13.5.2 Molecular Emission from the Near Nucleus Coma of Comets

## 13.6 Spacecraft Telecommunications

# Chapter 14

# Planetary Systems and Life

## 14.1 Introduction

## 14.2 Prebiotic Molecules in the Galaxy

## 14.3 Star-Planet Interactions and the Impact on Habitability

## 14.4 Detection of Exoplanets through Astrometry

## 14.5 SETI Searches for evidence of Life in the Galaxy

## 14.6 Debris disks: windows into planetary systems

### 14.6.1 Water in planetary systems: the content and origin of hydrogen in evolved disks

### 14.6.2 The spectral slope and size distribution of particles

# Chapter 15

# Pulsars in the Galactic Center and Beyond

## 15.1 Overview

Pulsars in the Galactic Center represent clocks moving in the space-time potential of a supermassive black hole, which would enable qualitatively new tests of theories of gravity. More generally, pulsars offer the opportunity to constrain the history of star formation, stellar dynamics, stellar evolution, and the magnetoionic medium in the Galactic Center. The high stellar densities in the Galactic Center region likely result in three-body interactions producing compact object binaries more extreme than those found in globular clusters, enabling hitherto impossible studies of General Relativity in a variety of sources. More generally, the ngVLA can make fundamental contributions to studies of gravitational waves and other tests of theories of gravity.

## 15.2 The Galactic Center

Authors: Bower, Lazio, Chatterjee, Wharton, Cordes, Ransom, Demorest, ...

Laura Chomiuk says: this is currently also under Galaxy Ecosystems (with suggested author Mark Norris). I would argue it fits in better here, and it doesn't need to be in two places.

## 15.3 Gravitational Waves

Authors: Chatterjee, Lazio, Ransom, Demorest, Cordes, ...

## 15.4 Magnetars and Neutron Star Astrophysics

Candidate author: TBD. Alexander van der Horst?

# Chapter 16

# The Formation and Evolution of Stellar and Supermassive Black Holes in the Era of Multi-Messenger Astronomy

## 16.1 Overview

While black holes are now clearly demonstrated to exist on practically all mass scales, the astrophysics of how these objects form and grow remains a mystery. LIGO is now detecting black holes that are substantially more massive than previously known stellar mass black holes, and observing black hole-black hole mergers—although we do not know how black hole binaries form. While supermassive black holes (SMBHs) are thought to be widespread in galaxy centers, we do not understand how their growth was seeded or how (and how often) these extreme objects merge. The ngVLA, with its high sensitivity and high resolution, can address all of these outstanding questions.

## 16.2 Hunting for Black Hole Binaries in the Milky Way and Local Universe

XRBs in the Galaxy, in globular clusters, and local galaxies.

Candidate lead author: T. Maccarone with L. Chomiuk

## 16.3 Accretion and Jets in Local Compact Objects

Where is our niche here, relative to SKA? Michael has run imaging simulations of jets and maybe even accretion disks

Candidate lead author: D. Coppejans with help from G. Sivakoff, S. Heinz, M. Rupen

## 16.4 Black Hole Growth and Feedback

Candidate lead author: K. Nyland – maybe A. Kapińska can help a bit, too?

### 16.4.1 Intermediate-Mass Black Holes in Globular Clusters

Authors: Joan Wrobel (This was imported over from Galaxy ecosystems)

## 16.5 Precision Black Hole Masses

Candidate lead author: J. Braatz

## 16.6 Supermassive Black Hole Seeds

Can ngVLA address early SMBHs?

Candidate lead author: E. Gallo with help from A. Reines and R. Plotkin

## 16.7 Tidal Disruption Events

Candidate lead author: ?? Sjoert van Velzen??

## 16.8 Supermassive Black Hole Pairs and Binaries

How the ngVLA can find pairs and how ngVLA could find EM counterparts to LISA sources.

Candidate lead authors: S. Burke-Spolaor, V. Ravi, J. Schnittman – also willing to help, T. Bogdanovic, L. Blecha

## 16.9 Black Hole/Neutron Star Mergers as traced by Gravitational Waves

Hot button issue: Joe Lazio should decide (possibilities include: N. Lloyd-Ronning, Alessandra Corsi, Wen-Fai Fong, Kate Alexander, Gregg Hallinan, Brian Metzger)

## 16.10 Supernovae and Long Gamma-Ray Bursts

i.e. engine-driven supernovae, which fits in here because the engine may be a black hole (or magnetar)

Candidate authors: R. Margutti, A. Corsi –Laura Chomiuk think this could go under the black holes chapter- moving it there.

# Chapter 17

# Cosmology

## 17.1 Overview

In this chapter, we consider additional topics to which the ngVLA could make substantial contributions but which do not fit into the high-level themes.

Laura Chomiuk proposes turning this into a cosmology chapter and then dividing the other science between Galaxy Ecosystems and Black Holes.

## 17.2 Megamaser Cosmology

Candidate lead author: J. Braatz (or in BH section?)

## 17.3 Gravitational Lensing

Candidate lead author: TBD

## 17.4 Real-Time Cosmology

Candidate lead author: maybe A. Truebenbach and J. Darling

## 17.5 Variations of Fundamental Constants

Candidate lead author: N. Kanekar?

## 17.6 Cosmology

Candidate lead author: Philip Bull

## 17.7 Intensity Mapping

Candidate lead author: Garrett “Keato” Keating