Terrestrial zone exoplanets and life

Brenda Matthews (NRC Canada)
The “Cradle of Life” SWG for the ngVLA produced over 30 science use cases, encompassing:

- Planet formation
- Astrochemistry of star-forming clouds, cores and disks
- Star formation
- Polarization of star-forming clouds, cores and disks
- Solar system science
- SETI
- Exoplanets
- Space weather
- Debris disks
- Satellites and telecommunications
Science use case authors of this talk

- Tim Bastian
- P. Brandon Carroll
- L. Ilsedore Cleeves
- Jim Cordes
- Steve Croft
- Robin Garrod
- Manuel Güdel
- Gregg Hallinan
- Andrea Isella
- Joseph Lazio
- Jeff Linsky
- Ryan Loomis
- Brett McGuire
- Ian Morrison
- Karin Öberg
- Rachel Osten
- Andrew Siemion
- Zsolt Paragi
- Luca Ricci
- Jill Tarter
- Jackie Villadsen
- David Wilner
- Jason Wright
ALMA imaging of protoplanetary disks

- Imaging of substructure in disks has been one of the most substantial successes of ALMA
Limitations of ALMA: resolution and opacity

• ALMA cannot effectively image disk substructures within 5 AU in the HL Tau

• Optical depth and resolution make this impossible for ALMA

1 AU = 7 mas
Simulations with the ngVLA

- Hydrodynamical simulations + ray tracing produce a model of the disk for input disk structure, star and planet properties (Li+ 2005, 2009)
- Simulate ALMA and ngVLA observations to show ngVLA’s optimal scale for protoplanetary disks
Optimal ngVLA resolution

Jupiter @ 5au, $M_{\text{disk}} = 0.006 M_{\text{Sun}}$, $d = 140$ pc

All these $b_{\max}$ values produce disk emission of too low surface brightness to definitively detect the signature of the planet in the disk.

Optimal $b_{\max}$ is $150 – 200$ km. Signatures of the planet are robust with S/N ~7 in the outer ring. An outer taper of 5 mas has been applied.
Planets at 5 AU

ngVLA at 3mm will identify gaps and substructures for planet masses as low as \(10 \, M_{\text{Earth}}\)

ALMA @ 0.87mm

ngVLA @ 3mm
beam = 5 mas
rms = 0.5 uJy/beam

ngVLA @ 1cm
beam = 16 mas
rms = 0.15 uJy/beam

Slide courtesy of Luca Ricci
Planets closer than 5 AU

ALMA @ 0.87 mm

The ngVLA at 3mm will be able to resolve gaps due to giant planets down to 1 AU from the central star

ngVLA @ 3mm
beam = 5 mas
rms = 0.5 uJy/beam
There are many 10s of sources with fluxes exceeding the model flux in each of these regions, > 70 in Taurus & Ophiuchus, > 50 in the ONC. At 700 pc, we will resolve protoplanetary disks in Cepheus OB2, OB3, OB4.
Time variability in disks

1 frame per month
• Full orbit in 12 years
• Probe of triggered planet and planetary system formation

• Also enables detection of circumplanetary disks
• $M_{cpd} = 10^{-4} M_{\text{planet}}$, $r_{cpd} = 0.4 r_{\text{hill}}$, $M_{\text{acc}} = 10^{-7} M_{\text{planet}} / \text{yr}$

ngVLA @ 3mm
beam = 5mas
rms = 0.2 uJy/bm

Jupiter @ 5 AU, $\alpha_{\text{visc}} = 10^{-5}$

Slide courtesy of Luca Ricci
Prebiotic molecules

• The ngVLA will enable detection of new complex organics
• Search for N, O and S-bearing small aromatic molecules
  • These are the direct precursors to amino acids, biogenic molecules such as sugars and chiral molecules
• ngVLA is the facility that puts this science within reach

• Deeper surveys at low resolution will soon not be useful
  • Line confusion is being reached with ALMA and GBT
  • No new discoveries are possible

See Poster by B. McGuire 342.23
Complex molecule bonanza!

Shows just some of the species that would be detectable to the ngVLA. All lines shown lie below practical detectable limits in current surveys.

Simulation of six complex organic molecules in a 5" source at $T_{ex} = 100$ K, $\Delta V = 3$ km s$^{-1}$, and $N_T = 5 \times 10^{13}$ cm$^{-2}$. The simulation assumes the source completely fills the beam.
Organic molecules in disks

- Map out the organic content of the TW Hya disk midplane
- Many molecules of interest common in the Solar nebula:
  - CH$_3$OH, CH$_3$CHO, HCOOH, HNCO, HC$_3$N and CH$_3$CN (Mumma & Charnley 2011; Roy+ 2015)
- Many of these may be building blocks of RNA (Powner+ 2009)
- Tests of chemical habitability of forming planets
  - Are there water and soluble organic molecules on the surface?

Predicted spectral of TW Hya using the output of the astrochemical code of Cleeves+ 2015 andrews+ 2016
Habitability of terrestrial planets: impact of space weather

- Coronal mass ejections (CMEs) around young stars may be many orders of magnitude stronger than Solar, impacting the habitability of planets.

- Many targets will be TESS detected M stars, which likely suffer more extreme effects of planetary habitability than Solar type stars.

- Lower frequency arrays can detect emission from ejected plasma and infer rates and velocities, but they cannot measure the mass loss; this will be a new capability of the ngVLA.

- By measuring CMEs and mass loss, the impact on the orbiting terrestrial planet can be directly inferred.

See poster by R. Osten 342.18
Current SETI searches are limited to looking for transmitters that are brighter than humanity’s most powerful omnidirectional transmitters, or for those that concentrate large amounts of power into a narrow beam.
SETI

- SETI hypothesis: intelligent civilizations exist and have developed microwave transmitters
- Test requires wide frequency coverage, high sensitivity and fast survey speed
- Search for life through technology comparable to our own
- Arecibo’s radar signal would be detectable by the ngVLA at kpc distances
- Signals are narrow, need resolutions of a few Hz → SKA & ngVLA!
- ngVLA will complement SKA I-LOW and SKA I-MID as the only facilities with the capabilities to detect transmissions produced with comparable power to those on Earth
Simulations show that the ngVLA observing at 3 mm with baselines out to 200 km will detect substructures in protoplanetary disks down to planetary masses of $10 \, M_{\text{Earth}}$ and radial separations of 1 AU.

- ngVLA will yield a treasure trove of spectral lines from prebiotic molecules.
- Detection of the organic chemical inventory of the nearest disks will be measurable.
- ngVLA can measure the mass loss in CME events and infer the impact on terrestrial planets.
- SETI searches with ngVLA and SKA will be able to detect emission from standard Earth emitters at kpc distances.
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