The Next Generation Very Large Array:
Science in Nearby Galaxies
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Gastrophysics: Multi-Process and Multi-Scale

Extragalactic Medium (CGM and IGM)

Accretion

Diffuse, Mostly Atomic and Ionized Gas

Cloud Formation

Bound, Star Forming Clouds

Core Formation

Dense Cores

Stellar Feedback

Galactic Winds

Old Stars

Stellar Evolution

Young Stars

Star Formation

Leroy KISS talk
Game Changing, Qualitative Gains for Studies of Nearby Galaxy:

**Spectral Line Mapping:**
Map the diagnostic fingerprints of molecules and atoms in the cool ISM ~50x faster than ALMA

Enable major advances in our understanding of:
- astrochemistry
- the interstellar medium
- star formation
- dynamics

**Wide-Band Continuum Imaging:**
Simultaneously capture all major radio emission mechanisms in a single observation (synchrotron, free-free, dust, SZ effect)

Enable major advances in our understanding of:
- the physics of cosmic rays
- ionized gas
- dust
- hot gas around galaxies.

**Very High Resolution Imaging:**
- obtain a complete view of the Milky Way’s structure
- resolve actively forming high mass stars and track their motion
- resolve three dimensional motions of forming stars and nearby galaxies
The range 1.2 - 116 GHz offers a stunning range of diagnostic power with minimal sensitivity to temperature effects. The ngVLA is the next logical step beyond ALMA in spectroscopy.

- Molecular lines carry fingerprints of chemistry, temperature, density, presence of shocks, gas distribution, and kinematics. SiO, NH₃, HCN, HCO⁺, CS, CO and a host of other molecules have their fundamental transitions in the range 1.2-116 GHz, which are faint (10-100x fainter than CO)

- Even with ALMA, spectroscopy is a major time investment (the level zero goal of one Milky Way at z ~ 3) take a day. Under any reasonable scenario mm-wave spectroscopy will remain a vibrant field over the coming decades because the observations take so much time and the insight into physical conditions is irreplaceable.
Spectral Line Mapping Beyond ALMA

State of the Art: M51 in CO ($J=1$-$0$) at 1” and ~1 K per km s$^{-1}$ - Schinnerer et al. (2013) -- 200 hr with PdBI ~ 15 hr w/ ALMA ~ 12min with ngVLA

- For single lines in Band 3, the ngVLA is ~75x faster than ALMA

<table>
<thead>
<tr>
<th>Machine</th>
<th>Image rms 1 hr in a 1 km/s Channel</th>
<th>rms Brightness Temperature for a 1” Beam</th>
<th>Approximate Field of View (FWHM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALMA (40 dishes) - 345 GHz</td>
<td>2.0 mJy/bm</td>
<td>0.02 K</td>
<td>16”</td>
</tr>
<tr>
<td>NGVLA (VLA x 5) - 100 GHz (assumes VLA dish quality)</td>
<td>0.15 mJy/bm</td>
<td>0.019 K</td>
<td>56”</td>
</tr>
</tbody>
</table>

- For Band 7, an upgraded VLA achieves similar rms over >10 times the area compared to ALMA – and probes lower frequencies (lower ladder transitions) and so is less sensitive to the details of excitation.

- This is a bit pessimistic: if the dishes and system were optimized for ~3-4mm observations, should be able to map CO ~>50x faster than ALMA in Band 7.

- Combining with bandwidth (~x3 due to multiple tunings), this machine is up to ~150 times faster than ALMA at mapping lines!
Key Considerations For Spectral Line Mapping

- **Surface brightness sensitivity** - to study the cold ISM line sensitivities need *reach down into the K regime (even to <~ mK for exgal)*. It matters where the dishes sit, e.g., at 100 GHz the current “D” configuration is already ~ arcsecond.

- **Angular Resolution** - at the high end of the mm-wave band the angular resolution implied even by the current VLA configurations *is very high* (“A” is twice ALMA’s maximum baseline already).

- **Spectral Resolution** - Galactic (or highly resolved extragalactic) work will require *high (fraction of a km/s) spectral resolution* across large parts (but maybe not all) of the band.

- **uv Matching** – over a decade in frequency means that a single physical telescope configuration produces a wide range of wavelength spacings - *matching the upper and lower parts of the band*. 
Continuum Science Beyond the Jansky VLA

- **Why We Care:** between ~1.2 and 116 GHz all major radio emission mechanisms contribute to the SED at similar levels. Sensitive, wide-band, high resolution observations in this regime let us understand the *physics of dust, ionized gas, cosmic rays, magnetic fields, and hot gas.*

- **The Leap Forward:** The proposed instantaneous bandwidth, collecting area, and baselines (all ~5-10x VLA), should capture new regimes in continuum science: faint, extended emission, SZ effect in new places, full dust+thermal+non-thermal SED at once.

ngVLA is an unprecedented machine that uses the full radio continuum to study astrophysics. By contrast:

- ALMA is mostly optimized for dust emission
- SKA should be a synchrotron machine
- **the ngVLA maps them all simultaneously, making it a physics tool!**
Robust Maps of Star Formation in Nearby Galaxies

M51 at 33GHz (free-free emission)

JVL A 64hr (> 5σ)

ngVLA 32hr (> 5σ)

Model 33GHz from Hα
- units: μJy/bm for θ_S = 1”
- 15m dishes
- 8GHz bandwidth
- 2hr/ptg: rms ~ 400 nJy/bm
- <A_V> ~ 3 mag (Scoville+ 2001)
- Equivalent map would take ~200 to 300x longer with JVLA (i.e., ~2500 hr !!!).

Direct measure of ionizing photon rate without [NII] or extinction corrections
**Key Continuum Considerations**

- **Bandwidth:** *Wide instantaneous bandwidth is a major enabler*, with resolution (beyond ~2 MHz or so) secondary.

- **Brightness Sensitivity:** As with lines (but not the same numbers) the ability to detect a diffuse, faint glow (at high resolution) is key to a lot of science and this means *brightness sensitivity is key to a lot of science*. This comes from a more filled (compact) array.

- **uv coverage and frequency:** Again, the wide spectral coverage means that the *interaction of frequency and antenna position might complicate creation of a continuous SED*. But this is a secondary concern.

- **Polarization:** For both line and continuum (but especially continuum), *wide band polarization capabilities will be key* to study the morphology and magnitude of magnetic fields.
The Power of the ngVLA
Bandwidth: Continuum and Lines at the same time
High Enough Resolution to see Evolution

M51 CO & Hα

HII regions in M66
ALMA + JVLA

Brightest CO
Brightest Hα
Overlap


HCO⁺ contours on 33GHz
HCN contours on 95GHz

PEAKS OF CURRENT STAR FORMATION OFFSET FROM SITES OF FUTURE STAR FORMATION

MURPHY ET AL. IN PREP.
The orbits and fate of the Local Group galaxies remain uncertain – need proper motions ~10’s of km/s at ~1Mpc

ngVLA will deliver 3D imaging of dynamics of LG for dark matter, real-time cosmology

Very Long Baseline Science Beyond the “HSA” (VLBI μas astrometry)

- We know very little about the far-side structure of the MW
- ngVLA will provide a complete view of the large scale structure of MW

Much of the science requires ~20% of collecting area at long baselines.
**Key Very Long Baseline Numbers**

- **Baseline length** - a few hundred km and a few thousand km offer qualitatively different science (few hundred km great for star formation, *a few thousand needed for “super” version of current science*). Designing in very long baseline science offers advantages compared to post-hoc construction of next generation VLBI networks.

- **Frequency coverage** - *High frequency might be less of a driver for the very long baseline applications*. It’s possible that the key masers and continuum applications could be achieved with ~5 - 50 GHz coverage. Heterogeneous design? At least not a driver.

- **Spectral Resolution** - Spectral resolution is important (masers) but not necessarily over the whole band. It’s not totally clear that the VLBI applications drive the frequency setup.

- **Collecting Area at Long Baselines** - sensitivity dominates considerations for VLBI science, *to do qualitatively new work large amounts of collecting area* at Earth-spanning baseline lengths are required.
Food for thought and Implications for Design / Science Requirements:

- The current VLA is already ~3x ALMA’s collecting area.
- A 5x VLA concept ~2x more collecting area than the re-baselined SKA1-MID.
- Brightness sensitivity is key for many line and continuum requirements (D/C-configuration w/ a lot more collecting area already optimized for 100GHz “thermal” (~K) line science.
- $uv$-coverage matching complicates “ratio science” *(movable vs. lots of dishes)*
- Mapping speed / mosaicking - *small dishes*
- Frequency coverage - high end of the mm band a line driver, 100 GHz a driver for continuum but not 115 GHz, high frequency less key for VLBI applications.
- Spectral resolution - be ambitious with correlator / computing specs, this project will gestate for a long time.
- Even in “next generation” mode, the HI and CO (+isotopologue) lines represent irreplaceable workhorse lines.