Why Expand the VLA?
Unique Radio Capabilities

- **Magnetic Fields**
  - Polarization
  - Faraday rotation
  - Zeeman splitting

- **Transient Sources**
  - Trace shocks and ejecta
  - Observe 24/7, regardless of weather, Sun, etc.
  - High resolution

- **Low Obscuration**
  - No dust
  - No bias
  - See inner cores, where the action is

- **The Evolving Universe**
  - Accretion ↔ outflow
  - Trace both thermal and non-thermal (AGN, HII, etc.)
  - Key lines

- **CO at z=6.4**

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The Expanded Very Large Array
Michael P. Rupen
NRAO/Socorro
Why Expand the VLA?
The Art of the Possible

• The VLA is still the most flexible and sensitive radio telescope in the world. But...
  – it’s over 30 years old: the first VLA antenna came on-line on 24 October 1975
  – major improvements are possible, at very little cost: keep the infrastructure (antennas, railroad track, buildings, …), but replace the electronics

The EVLA: Order-of-Magnitude Improvements

<table>
<thead>
<tr>
<th>Parameter</th>
<th>VLA</th>
<th>EVLA</th>
<th>Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensitivity (1σ, 12 hours)</td>
<td>10 µJy</td>
<td>1 µJy</td>
<td>10</td>
</tr>
<tr>
<td>Maximum BW per polarization</td>
<td>0.1 GHz</td>
<td>8 GHz</td>
<td>80</td>
</tr>
<tr>
<td># of frequency channels at max. bandwidth</td>
<td>16</td>
<td>16,384</td>
<td>1024</td>
</tr>
<tr>
<td>Maximum number of frequency channels</td>
<td>512</td>
<td>4,194,304</td>
<td>8192</td>
</tr>
<tr>
<td>Coarsest frequency resolution</td>
<td>50 MHz</td>
<td>2 MHz</td>
<td>25</td>
</tr>
<tr>
<td>Finest frequency resolution</td>
<td>381 Hz</td>
<td>0.12 Hz</td>
<td>3180</td>
</tr>
<tr>
<td>(Log) Frequency Coverage (1 – 50 GHz)</td>
<td>22%</td>
<td>100%</td>
<td>5</td>
</tr>
</tbody>
</table>

• EVLA cost is less than ¼ the VLA capital investment
• No increase in basic operations budget
Point-Source Sensitivity Improvements:
1-σ, 12-hours

Red: Current VLA, Black: EVLA Goals

Frequency - Resolution Coverage

- Continuous frequency coverage from 1 to 50 GHz
- Match instrument to science, not science to instrument!
- Blue area shows current VLA frequency-resolution coverage.
- Green area shows future EVLA coverage.
- Yellow letters and bars show band names and boundaries.
- Two low frequency bands (74 and 327 MHz) omitted
Bandwidth and Spectral Capabilities

• Combination of 2:1 bandwidth ratios and huge number of spectral channels
  ➔ instantaneous spectral indices, rotation measures, uv-coverage
  ➔ instantaneous velocity coverage (53,300 km/s vs. current 666 km/sec at 45 GHz)
  ➔ lines at arbitrary redshift

• Ridiculously flexible correlator
  ➔ 128 independently tunable sub-bands, vs. 2 now
  ➔ “zoom in” on the regions of interest, and leave one 2 GHz baseband for continuum

The Time Domain

• Dynamic scheduling
  ➔ use weather efficiently
  ➔ respond to transients

• Fast time recording: initially 100 msec; 2.6 msec possible

• Pulsars: 1000 phase bins of 200 μsec width, 15 μsec possible
  ➔ pulsar searches, timing, etc. with an interferometer!
Molecular Studies of High-Redshift Star-Forming Galaxies

• Currently:
  – 50 MHz (z range of 0.001 at 50 GHz!)
  – 8 spectral channels

➤ No z searches
➤ Very poor spectral resolution
➤ Resolve out wide lines, and add noise to narrow ones
➤ Each line must be done independently (CO, HCN, HCO+, …)

CO$_{J=3-2}$
Z = 6.42
Peak ~ 0.6 mJy
Carilli, Walter, & Lo

Molecular Studies of High-Redshift Star-Forming Galaxies

• EVLA:
  – 8 GHz (z=1.4 to 1.9 for CO J=1-0; z=3.8 to 4.8 for 2-1)
  – 16384 spectral channels (1 MHz res’n= 5.0 km/s)

➤ 200 km/s galaxy is 40 channels
➤ Every line at once
➤ Interferometry:
  • spatial res’n
  • excellent spectral baselines
**Quasar Absorption Line Surveys**

- **Unbiased line surveys:**
  - no dust obscuration
  - lots of *random* background sources
- **HI, CO, HCN, HCO+, …**
  ⇒ evolution of cosmic neutral baryons from $z=0$ to 3
  ⇒ large-scale structure
  ⇒ estimates of CMB temperature

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**Star-Forming Galaxies at High Redshift**

- **Sensitive to:**
  - *Synchrotron* emission: AGN, SNR
  - *Free-free* emission: Hii regions
  - *Thermal* dust emission
- **Resolution 50 mas: 200 pc @ z=10**
- **Imaging:** 1 arcsec over 30 arcmin @ 1.5 GHz
- **EVLA+ALMA give complete galaxy SED’s**
  - 3 orders of magnitude of frequency
  - large range of redshift

Arp220 SED scaled to high redshifts.
Galaxies Closer to Home

In one observation of a galaxy:
- deepest radio continuum image yet made, with spectral index too
- image all (UC) HII & SNRs
- map HI emission & radio recombination lines
- measure magnetic field orientation, Faraday rotation, and Faraday depth
- absorption measurements against 100s of background sources
  - also rotation measures!
- simultaneous “blind” HI survey

Strong Gravity and Black Hole Accretion: The Galactic Center

Radio

Infrared

Sgr A*

10 arcsec ~ 1 Ly.

VLA: 1 cm (Zhao)

VLT / NACO 1.6-3.5 microns
EVLA: the radio view

- 100s of pulsars with $\text{Porbit} < 100$ yr
  - higher frequency to avoid dispersion due to ionized gas
  - image fidelity ($\text{SgrA}^* : \text{pulsar} = 1e6 : 1$)
  - 10's mas astrometry
  - millisecond pulsar timing
- complete survey & monitoring of OH/IR stellar masers
  - detailed rotation curve
- 3D motions of ionized gas
  - free-free emission + radio recombination lines
- magnetic field structures and strength

- Mass and spin of a supermassive black hole
  - deviations from elliptical orbits
- Extended dark matter distribution
- Tests of GR in ultra-strong regime
- Detailed accretion estimates
- Gas vs. stellar motions

Magnetic Fields in Galaxy Clusters

with X-rays, map magnetic fields & electron density in detail across entire, individual clusters

- unambiguous rotation measures
- >100 sources per beam (vs. current 1-2) for scattering & polarization studies
- >20 RRM per cluster for >80 clusters!

Rotation measures towards Hydra A (G. Taylor)

Residual RM towards 22 Abell clusters (T. Clarke)
Galactic Black Holes: 
The Accretion/Outflow Connection

- Ubiquity of jets
- Monitoring
  - continuous multi-freq. coverage
  - work at 45 GHz → 50mas res'n
  - triggering VLBI
- Polarization
- Going deeper
  - faint source imaging
  - typical rather than 20σ sources
  - other disk states
  - other source types (e.g., ULXs, low-luminosity XRBs, NS, etc.)

Stars

- first detections of ordinary stars like the Sun
- track radio emission from young stars (10^6 to 10^7 years)
- flares in pre-main-sequence stars
**Magnetic Fields in the ISM**

- **Zeeman splitting** of H recombination lines directly measures ISM magnetic fields.
- Splitting is weak – 2.8 Hz per $\mu$G ➔ stack multiple lines.
- 2-4 GHz band: 31 recombination lines
  - Each typically 250 kHz wide ➔ ~0.4% of the total band.
  - Need 10 kHz resolution.
- So, either 400,000 channels…or zoom in with WIDAR!

**WIDAR Setup**

- Each line individually targeted.
- H, He, C lines all within 4 MHz sub-band.
- Res’n 15.6 kHz (1.6 km/sec).
- Each of 62 spectra gets 256 channels.
- Or: use 8 MHz sub-bands with 4192 channels ➔ 0.2 km/sec resolution.

Sky Frequency Bands

- Right Pol'n
- Left Pol'n
- Continuum Setup

- 1024 chan's.
- Recirc. factor = 16
- $\Delta v = 0.8$ km/s
Magnetic Fields in the ISM

- EVLA resolution provides images of:
  - gas density,
  - temperature,
  - metallicity,
  - B-fields (Zeeman)
- Sensitivity (12 hr, 5σ):
  - $\Delta S_{\text{line}} \sim 0.1 \text{ mJy}$ (stacked, integral)
  - $\Delta B \sim 150 \mu\text{Gauss}$.
- Orion, W3, Gal. Center …

Hundreds of Spectral Lines at once!

- 414 lines (8 to 50 GHz)
- 38 species
- EVLA offers
  - Spatial resolution
  - Spectral baseline stability
  - Full polarization (Zeeman splitting!)
- EVLA can observe 8 GHz at once – an average of 80 lines at 10 km/s velocity res’n (30 GHz)
- EVLA can “target” many (~60) lines at once

Sky Frequency Bands

TMC-1 (Nobeyama: Kaifu et al. 2004)
**EVLA: Cost and Timescale**

- Proposal (EVLA-I) submitted to NSF in 2000
  - Funding started in 2001 following NSB approval.
  - Completion by 2012
- A cooperative project:
  - $57M from NSF, over eleven years
  - $15M from Canada, (correlator, designed and built by HIA/DRAO)
  - $2M from Mexico, and
  - $8M from re-directed NRAO operational budget
- A second proposal (EVLA-II) was submitted in April 2004
  - Goal: to improve the spatial resolution by a factor 10
  - $115M, over 7 years
  - The NSF recently (Dec 2005) declined to fund this proposal

**EVLA Project Status**

- Six antennas currently withdrawn from VLA service, and being outfitted with new electronics.
  - Two fully outfitted & available upon request
  - Two being outfitted with final electronics, and are being intensively tested. Available for astronomical use by late summer.
  - Two others in early stages of outfitting.
- Antennas will be cycled through the conversion process at a rate six per year, beginning in 2007.
- Except for special testing, no more than three antennas will be out of service at any one time during construction phase.
**Major Future Milestones**

- **Test prototype correlator** mid 2007
  - Four antenna test and verification system
  - *Not available for science*
- **Correlator installation and testing begins** mid 2008
  - Capabilities will rapidly increase until mid 2009.
- **Correlator Commissioning begins** mid 2009
  - VLA’s correlator turned off at this time
  - New correlator capabilities will be much greater at this time.
- **Last antenna retrofitted** 2010
- **Last receiver installed** 2012

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**New Capabilities Timescale**

- The old correlator will be employed until the *new correlator* achieves full 27-antenna capability – mid 2009.
- Full band tuning available starting next year
- Note also much-improved spectral stability
- Limited dynamic scheduling has begun
Challenges:
Radio Frequency Interference

Challenges:
Data Processing

• Data rates
  – peak from correlator backend: ≈25 MB/s
  – 8-hour “peak” observation ~ 700 GB (average is factor 10 lower)
  – data for 1 year ~ 80 TB

• Analysis
  – data flagging
  – sources everywhere
  – full (wide!) bandwidth synthesis (must account for spectral index, pol’n, rotation measure, etc.)
  – high-fidelity imaging (10 mJy ⇒ 10^4:1)
Challenges: Ease of Use

- Much more complex and capable system
  - correlator modes
  - "wide-open" bands
  - lots of data
  
  ➔ How do we make this power available to multi-wavelength users?
  - data volumes
  - "end-to-end" processing
  - imaging pipelines
  - readily accessible archive, NVO

EVLA Spin-offs

- Correlator for eMERLIN
- Renewed (international!) radio collaborations
  - common problems of data volume, deep imaging, etc.
- Centimeter/millimeter connection
  - similar timescales for EVLA & ALMA
  - similar techniques
  - comparable instruments, and complementary information on much shared science
- Opportunities as the VLA winds down
  - spectral line: e.g., deep HI images or surveys
  - time-dependent science: space telescopes, transient science, etc.
  - Note Oct06 call for Large Proposals!
**Challenges: Looking Ahead**

- Higher resolution: how can we tie in the VLBA?
  - bring high bandwidth (= sensitivity) to the world array
- Higher sensitivity: more collecting area for spectral line studies (the Square Kilometer Array)
  - requires economies of scale, for the antennas, the feeds & receivers, the correlator, etc. etc.
  - the EVLA as a pathfinder

**Challenges: Strengthening the US Community**

- NSF funds radio astronomy through grants
  - budget is very tight compared to NASA
  - no direct tie to telescopes
  - unhealthy perception of competition between instruments (esp. NRAO) and science
- Fabulous new instruments --- now we have to make sure they are used as fully as they can be!
  - international collaboration
  - obviously wonderful science
  - make it easier to use
  - more direct ties to space instrumentation (cf. Chandra)
  - innovative approaches within NRAO
NRAO and You

• Staff support/collaboration
• These schools
• Travel support for US observers (NRAO and foreign telescopes)
• Page charges
• Paid sabbatical/summer visits
• Postdocs
  – Traveling & resident Jansky fellows
• Student support
  – GBT projects
  – grad students (2 mos.-2 years, full support)
  – undergraduates (Co-Op Program up to 1 semester/year; summer REU)
• Aggressively pursuing other innovative programs
• At last, we will be hiring!

A New Era for Radio Astronomy

• After a long dry spell, telescopes galore
  – GMRT, SMA, eVLBI
  – EVLA, ALMA, ATA, eMERLIN, LWA, LOFAR, Australian initiatives, LMT, ...
• Looming on the horizon: the Square Kilometer Array
• This is the perfect time to be a graduate student!
  – get in on the ground floor
  – influence “first science”, software design, how the arrays operate
  – a unique opportunity to mix technology, software, and science