The Expanded Very Large Array

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NRAO/Socorro

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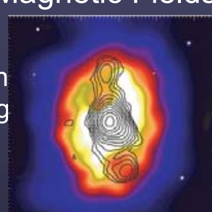
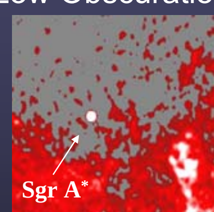
Why Expand the VLA?
Unique Radio Capabilities

Magnetic Fields

- Polarization
- Faraday rotation
- Zeeman splitting



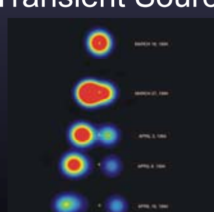
Low Obscuration



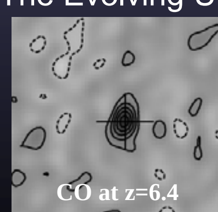
- No dust
  ➔ no bias
  ➔ see inner cores, where the action is

Transient Sources

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



The Evolving Universe



- Acrretion ⇔ outflow
- Trace both thermal and non-thermal (AGN, Hii, etc.)
- Key lines

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**

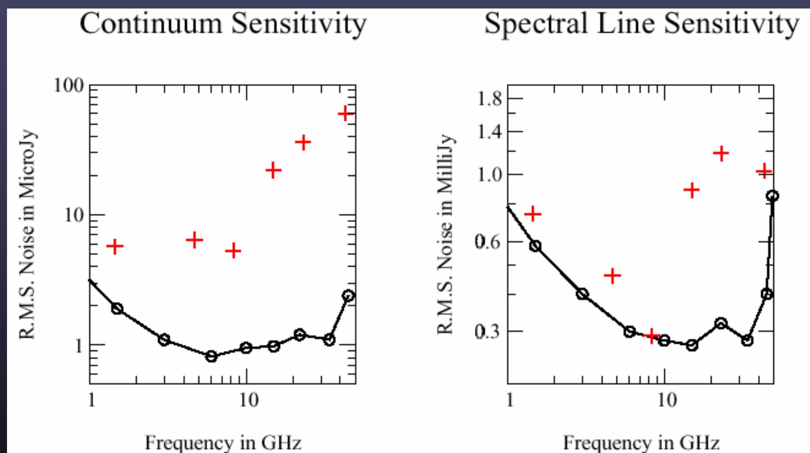
The EVLA: Order-of-Magnitude Improvements

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

- **EVLA cost is less than ¼ the VLA capital investment**
- **No increase in basic operations budget**

Point-Source Sensitivity Improvements : 1-σ, 12-hours

5

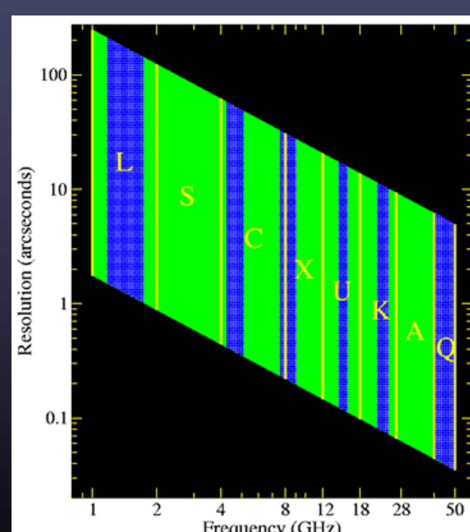


Red: Current VLA, Black: EVLA Goals

Frequency - Resolution Coverage

6

- **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

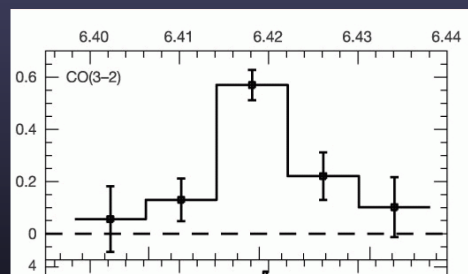
- Combination of 2:1 bandwidth ratios and huge number of spectral channels
  - ➔instantaneous spectral indices, rotation measures, uv-coverage
  - ➔instantaneous velocity coverage (53,300 km/s vs. current 666 km/sec at 45 GHz)
  - ➔lines at arbitrary redshift
- Ridiculously flexible correlator
  - ➔128 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**



$CO_{J=3-2}$
z = 6.42
Peak ~ 0.6 mJy

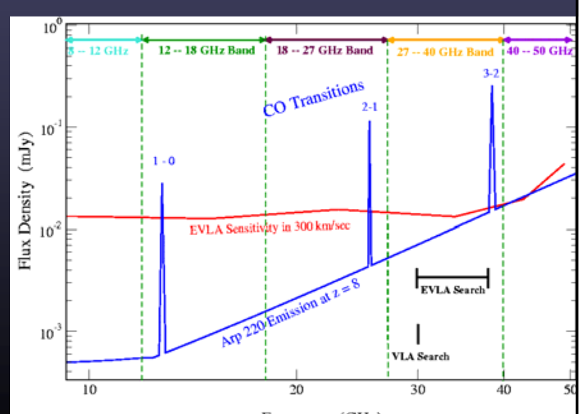
Carilli, Walter, & Lo

- ➔ 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+, …)

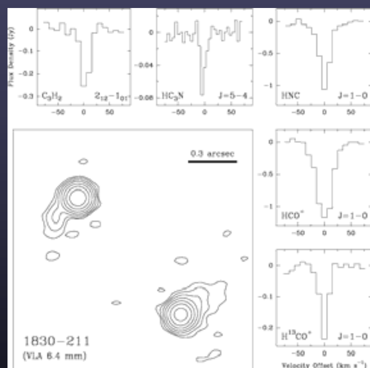
Molecular Studies of High-Redshift Star-Forming Galaxies

- **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



Absorption lines at z=0.88582
towards PKS 1830-211 (C. Carilli)

- Unbiased line surveys:
  - no dust obscuration
  - lots of *random* background sources
- HI, CO, HCN, HCO+, …

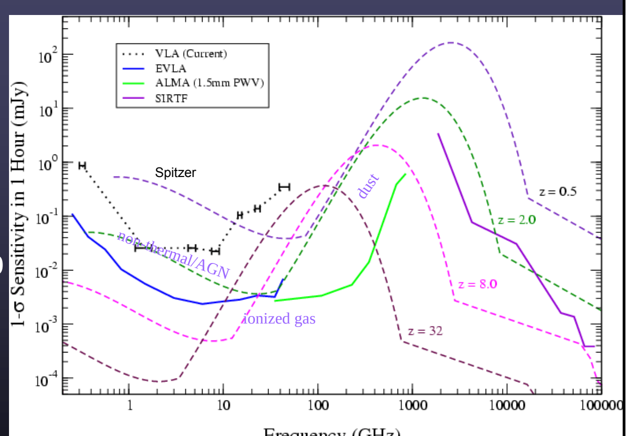
⇒ evolution of cosmic neutral baryons from z=0 to 3

⇒ large-scale structure

⇒ estimates of CMB temperature

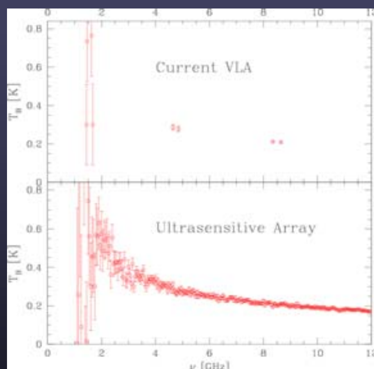
Star-Forming Galaxies at High Redshift

- 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

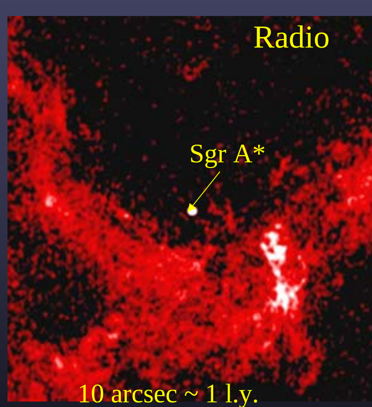


3x8 hours on a typical spiral galaxy

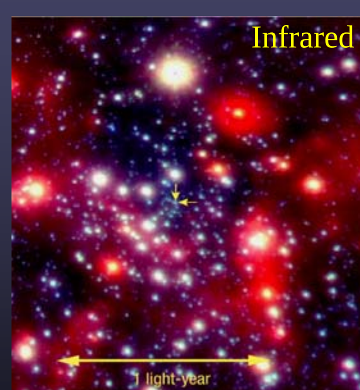
In **one** observation of a galaxy:

- deepest radio continuum image yet made, with spectral index too
- image *all* (UC) HIIs & 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



VLA: 1 cm (Zhao)



VLT / NACO 1.6-3.5 microns

Strong Gravity and Black Hole Accretion: The Galactic Center

15

EVLA: the radio view

- **100s of pulsars** with Porbit<100 yr
  - higher frequency to avoid dispersion due to ionized gas
  - image fidelity (SgrA*: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

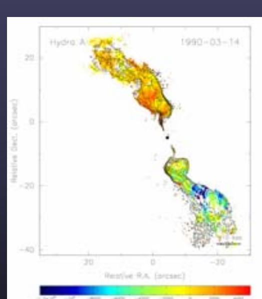
➔ Detailed accretion estimates

➔ Gas vs. stellar motions

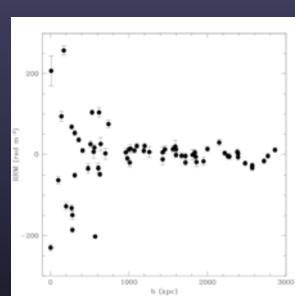
Magnetic Fields in Galaxy Clusters

16

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



Rotation measures towards Hydra A (G. Taylor)

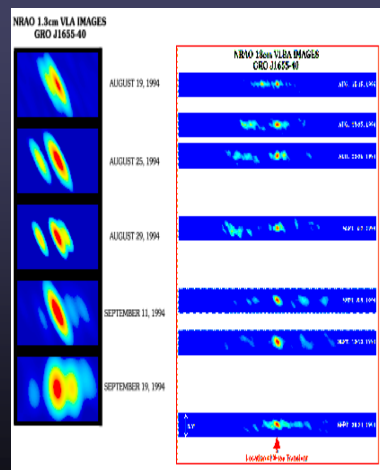


Residual RM towards 22 Abell clusters (T. Clarke)

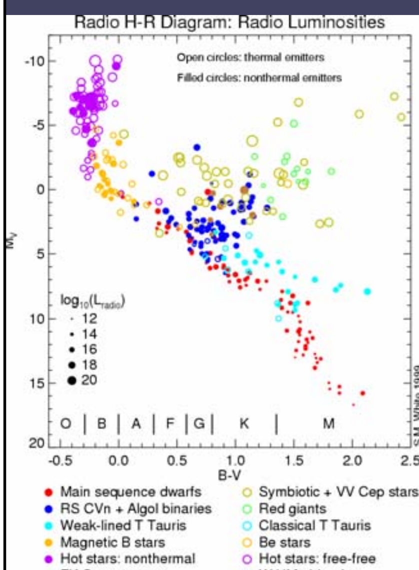
- unambiguous rotation measures
- much less depolarization
- >100 sources per beam (vs. current 1-2) for scattering & polarization studies
- >20 RRMs per cluster for >80 clusters!

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



Stars detected with the VLA (S. White)

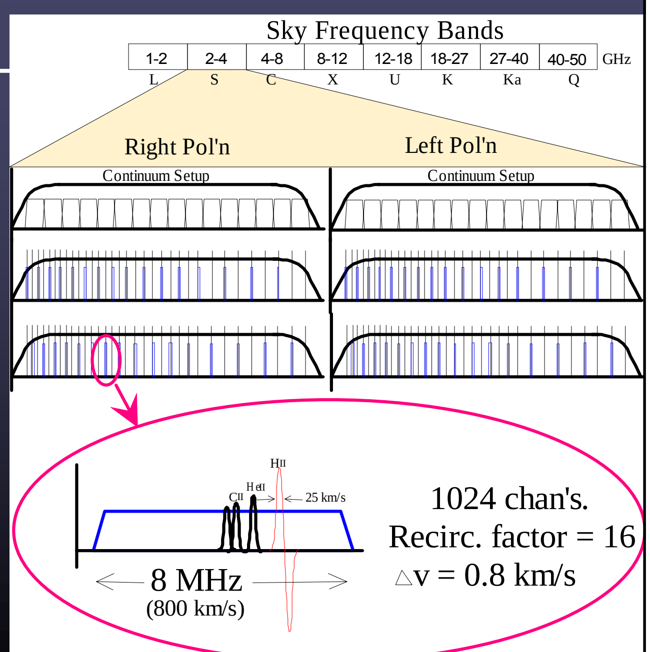
- first detections of ordinary stars like the Sun
- track radio emission from young stars (10^6 to 10^7 years)
- flares in pre-main-sequence stars

Magnetic Fields in the ISM

- **Zeeman splitting** of H recombination lines directly measures ISM magnetic fields
- Splitting is weak – 2.8 Hz per μG ➔ stack multple 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

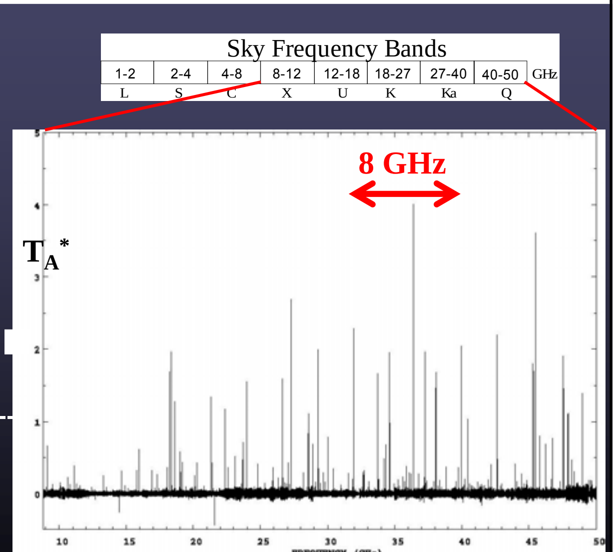


Magnetic Fields in the ISM

- EVLA resolution provides images of:
  - **gas density,**
  - **temperature,**
  - **metallicity,**
  - **B-fields (Zeeman)**
- Sensitivity (12 hr, 5σ):
  - ΔSline ~ 0.1 mJy (stacked, integral)
  - **Δ B ~ 150 μGauss**.
- 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**



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

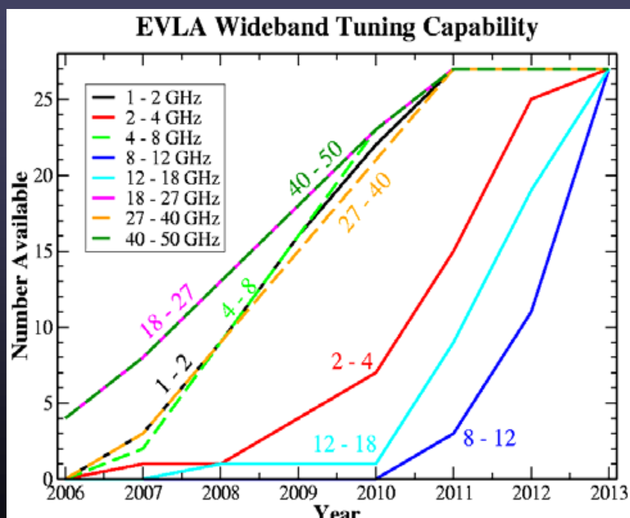
- Six antennas currently withdrawn from VLA service, and being outfitted with new electronics.
  - Two fully outfitted & available upon request
  - Two being outfitted with final electronics, and are being intensively tested. Available for astronomical use by late summer.
  - Two others in early stages 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

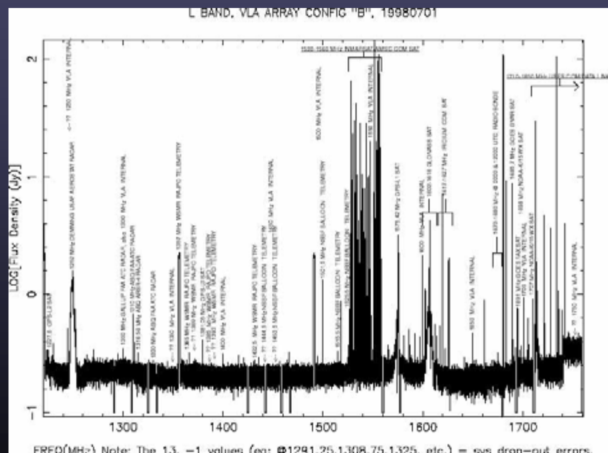
- **Test prototype correlator** **mid 2007**
  - Four antenna test and verification system
  - *Not available for science*
- **Correlator installation and testing begins** **mid 2008**
  - Capabilities will rapidly increase until mid 2009.
- **Correlator Commissioning begins** **mid 2009**
  - VLA's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

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 correaltor 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 $\Rightarrow$ 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**