Early EVLA Science Use Cases

EVLA Advisory Committee Meeting, March 19-20, 2009

Rick Perley

EVLA Project Scientist

Atacama Large Millimeter/submillimeter Array

Expanded Very Large Array

Robert C. Byrd Green Bank Telescope

Very Long Baseline Array

NRAO

WIDAR Growth

- All Station and Baseline Boards will be here by end of 2009
- All available EVLA antennas connected to WIDAR in January 2010.
- 256 MHz BW OSR Observing begins in Q1 2010.
  - Previous talks have described the two basic correlator setups which will define OSRO capabilities.
- We plan to follow the SAGE recommendation that expanding observing BW should have the highest priority.
- Proposed schedule for WIDAR bandwidth expansion:
  - 2 GHz by March 2010, 8 GHz by summer 2010.
  - Availability of these bandwidths will be under the RSRO program.

WIDAR Correlator Setups

- The initial correlator setup will be the simplest – all subbands with the same width and channelization -- the 'fundamental homogeneous correlator setup'.
  - This simplest mode will enable an enormous range of original science.
- Planned correlator setup enhancements are:
  - Recirculation: T3 2010
  - Independent Subband Tuning: T1 2011
  - Flexible Resource Realloction: T2 2011
- What kinds of science are enabled by these setup capabilities?

The Fundamental Homogeneous WIDAR Setup

- All 64 subband pairs have the same width and frequency resolution, arranged to fill the entire available bandwidth.
  - Filling the entire bandwidth is not a requirement.
- There are no ‘resource reallocation’ capabilities – no trading sub-bands for more channels.
- Recirculation will be available – either on or off for all subbands.
- Requantization is at 4 bits.
- Two polarization modes only:
  - Dual (RR,LL) and Full (RR, RL, LR, LL)
- The correlator backend (CBE) will permit time and frequency averaging – homogeneously for all subband pairs.
- One subarray only.

Summary of Wide-band Coverage:

- For dual (RR,LL) polarization, with no recirculation
- For full polarization, resolutions are 2 x poorer.

	Freq.	IF BW	SBW	# SBP	Δν	Δv	Nch per	Nch
	GHz	GHz	MHz		kHz	km/s	spctrm	total
L	1—2	1.024	16	64	125	25	128	16384
S	2—4	2.048	32	64	250	25	128	16384
C	4—8	4.096	64	64	500	25	128	16384
X	8—12	4.096	64	64	500	15	128	16384
U	12—18	6.144	128	48	1000	20	128	12288
K	18—26.5	8.192	128	64	1000	13	128	16384
A	26.5—40	8.192	128	64	1000	9	128	16384
Q	40--50	8.192	128	64	1000	6.5	128	16384

- The data rate is 6.2 MByte/sec for 10-second integration (4.8 at U-band)
- The resulting data volume is 22 GB in 1 hour (17 GB at U-band)

Full-Band Coverage, with Recirculation.

- Recirculation is scheduled for availability in T3 2010.
  - Recirculation doubles the number of channels for each halving of the sub-band width
- There will be no changes to Q, Ka, K and Ku bands, since the full 128 MHz sub-band width is required to provide full band coverage.
- For dual polarization, capabilities in L, S, C and X bands become:

	Freq.	IF BW	SBW	# SBP	Δν	Δv	Nch per	Nch	Rate (10 s avg)	
	GHz	GHz	MHz		kHz	km/s	spctrm	total	MB/sec	GB/Hr
L	1—2	1.024	16	64	15.6	3.1	1024	131072	50	178
S	2—4	2.048	32	64	62	6.3	512	65536	25	89
C	4—8	4.096	64	64	250	12.5	256	32767	12	45
X	8—12	4.096	64	64	250	7.5	256	32767	12	45

- **For full polarization, channel widths/resolutions are doubled.**

Some Science Applications

- Even this most basic setup enables a huge range of new science capabilities. Some examples:
  - ~1 μJy/beam sensitivity continuum observations over the full primary beam.
  - Wide-band high-redshift surveys of molecules in absorption and emission.
  - Deep polarimetric imaging and RM analysis of bright sources and clusters.

Deep Continuum Imaging

- The full-band homogeneous WIDAR setup will permit distortion-free full sensitivity imaging:
  - At all bands
  - In full polarization
  - In all configurations
  - To the first null of the primary beam.
  - With manageable data rates and volumes.
- Note however that reaching thermal noise at the lower frequency bands will require implementation of more sophisticated imaging algorithms than are now available.
- What kinds of observations might result?

Example: Continuum Detections at Ka-Band

- What can $\sigma \sim 1\mu$Jy/beam get?
  - HII region from Arp 220 at z = 1.
  - Thermal gas + dust from a submm galaxy at z ~ 2.5
  - Dust emission from a submm galaxy at z >6.
- Background confusing sources not a problem. Limited imaging/deconvolution required.
- Setup:
  - D or C Configuration
  - Wideband continuum, dual polarization, 8 GHZ BW/polarization.
  - CBE averaging will reduce data volume to less than 3 GB/hour.
  - Standard observing, calibration.
  - Single imaging plane.
- Same arguments apply to most high-frequency deep detection observations at other bands. .

Hi-z Molecular Line Surveys

- The 8 GHz-wide instantaneous frequency coverage will be a boon to molecular line surveys
- No longer will we be restricted to observing galaxies with known redshifts, with a correlator barely able to cover the linewidth.
- Example science include:
  - CO emission line surveys for early galaxies in K, Ka, Q bands.
  - Molecular absorption surveys towards known bright quasars.

Homogeneous Setup for Hi-z Surveys

- The 'homogeneous' wide-bandwidth setup provides excellent velocity resolution with manageable data rates.
- For CO 1-0, and dual polarization:

	Band range	z_L	z_U	Δz	Δv	Nchan
	GHz				Km/sec	per polarization
U	12—18	8.6	5.4	3.2	20	6144
K	18—26.5	5.4	3.3	1.97	13	8192
A	26.5—40	3.3	1.88	0.81	9	8192
Q	40 – 50	1.88	1.30	0.48	6.5	8192

- Note that higher-order CO transitions (from higher redshifts) are also included.
- Data rate is 6.2 MB/sec for 10-second averaging (except 4.8 @ U-band)
- Data volume in one hour is 22 GB (17 at U-band).

Example: Blind 30 – 38 GHz Surveys

- Current observations suggest a large population of very gas rich galaxies without extreme starbursts at $z > 1.5$.
- Big Picture Goal: A complementary view of the gaseous evolution of early galaxies, needed to match the well-quantified study of stellar evolution of galaxies.
- Conduct an unbiased grid search over 30 – 38 GHz:
  - CO 1-0: $z = 2$ to 2.8; CO 2-1: $z = 5.0$ to 6.7; CO 3-2: $z = 8.0$ to 10.5
- A 100-pointing blind mosaic would cover ~1000 galaxies at $z>2$, with a 5-σ detection in a few hundred hours of CO with sensitivity ~few x 10^{10} solar masses.
- Or, select 100 known objects of the Cosmos field, and search these fields for serendipitous objects.
- Complementary observations with ALMA, HST, VLT, etc.
- Will also provide continuum measurements of dust and gas, with spectral information.

Example: Redshifted Molecular Absorption in Ka and Q Bands

- ‘Blind’ surveys of known radio loud quasars.
- Search for redshifted molecular absorption at frequencies from 32 – 48 GHz (Ka and Q Bands)
  - In CO and HCO+ 1-0: z from 0.86 to 2.6
  - In CO and HCO+ 2-1: $z > 2.72$
- Provides an unbiased estimate of molecular gas content of the universe, and its redshift evolution.
- Can detect molecular absorbers to probe evolution of fundamental constants.
- Even 5 minutes integration will provide detections against 15 mJy background sources!
- Calibration and imaging very straightforward for this experiment.

Full-Band Redshift Coverage –H_2O Maser

- The rest frequency is 22.23 GHz.
- Shown are the coverage with and without recirculation.

	Band range	z_L	z_U	Δv	Nchan per pol.	Δv	Nchan per pol.
	GHz			Km/s	Dual Pol	Km/s	Dual Pol.
				No recirculation		With recirculation	
S	2 – 4	10.1	4.6	25	8192	6.25	32768
C	4 – 8	4.6	1.8	25	8192	12.5	16384
X	8 – 12	1.8	0.85	15	8192	7.5	16384
U	12 – 18	0.85	0.23	20	6144	20	8192
K	18 – 26.5	0.23	0.0	13	8192	13	8192

Polarimetry and RM Synthesis

- The large EVLA bandwidth and high channelization will enable fabulous polarimetry.
- This can be done on large bright galaxies, or on 'empty' fields containing clusters, or for galactic plane surveys in obscured regions.
- Range of potential RM is very high: (in rad/m^2)
  - (f = fractional polarization, SNR = Stokes I SNR in full continuum)

Band	RM Max	RM Min
L	75000	30/(f * SNR)
S	300000	120/(f * SNR)
C	12000000	480/(f * SNR)

Example: Cluster Polarimetry

- By measuring the RM of background sources through a rich cluster, information on cluster magnetic field strength and topology is obtained.
- At L-band, RM sensitivity ~ 30/(f*SNR) rad/m^2.
- Expect RMs of ~10 to 200 rad/m^2.
- About 35 background sources in every L-band primary beam should be strong enough for RM measurement accurate to 1 rad/m^2.
- Obvious early target would be the Coma cluster.
  - About 30 lines of sight through ~1 Mpc scale.
- High spatial resolution not needed => data rates can be kept manageable, and imaging algorithms simple.

The Next Step – Flexible Tuning with Adjustable Sub-band Widths.

- Individual tuning of each of the 64 sub-band pairs is scheduled for RSRO availability in T1 2011.
  - Each of the 64 sub-band pairs would be digitally tunable to any given frequency within the input bandwidth.
  - The sub-band width and spectral resolution of each will also be variable.
- This will enable greatly improved capabilities in studying spectral emission of atomic and molecular emission from specific regions, where:
  - Full bandwidth coverage is not needed, and/or
  - Adjustable spectral resolution is advantageous.

B-Field Determination using Zeeman Splitting

- Zeeman splitting of RR lines offer a way to measure the magnetic fields of HII regions.
- The splitting is very weak – 2.8 Hz/μG, so high sensitivity is required.
- 'Stacking' (summing) multiple lines is the solution.
- Basic requirements are:
  - Dual polarization
  - Velocity resolution of ~1km/sec
  - Velocity span exceeding 50 km/sec (or 50 channels).
- The number of RRL per band is shown in the table:

Band	L	S	C	X	U	K	A	Q
# lines	38	32	24	12	11	9	9	4

S-Band Stacked Recombination Lines.

- A likely scenario uses S-band, where there are 32 RRL.
  - Depending on when this correlator capability is enabled, C-band may be a more desirable band.
- Setup – using recirculation:
  - 32 sub-band pairs are set to 8 MHz width, providing 2048 channels/spectrum with 3.9 kHz resolution.
  - The sub-band span is sufficient to cover HeII and CVI, as well as HI.
  - 32 sub-band pairs still remain for other assignments – continuum, or observe other transitions?
- This setup produces 131072 channels for the 32 utilized sub-bands alone --- a large data rate of ~50 MB/sec.
- An alternate route would use 500 kHz sub-bands, without recirculation. The 32 'spare' sub-bands would then cover the He and C lines separately. The data rate is reduced by a factor ~8.

Molecular Line Emission Studies of Massive Star-Forming Regions

- Claire Chandler has proposed two K-band experiments:
  1. Studies of a Massive Star-Forming Region
     - 32 molecular transitions, to be observed at 0.2 km/sec, and
     - 8 RRLs, to be observed with 1 km/sec, and
     - some reasonable amount of continuum.
  2. Studies of a Cold Dark Cloud.
     - 54 molecular transitions (mostly heavy molecules) requiring 0.01 km/sec resolution, plus
     - Some reasonable amount of continuum

– Can the EVLA do all this?

  – Yes! (with ease)

Massive star-forming region – Goals and Requirements

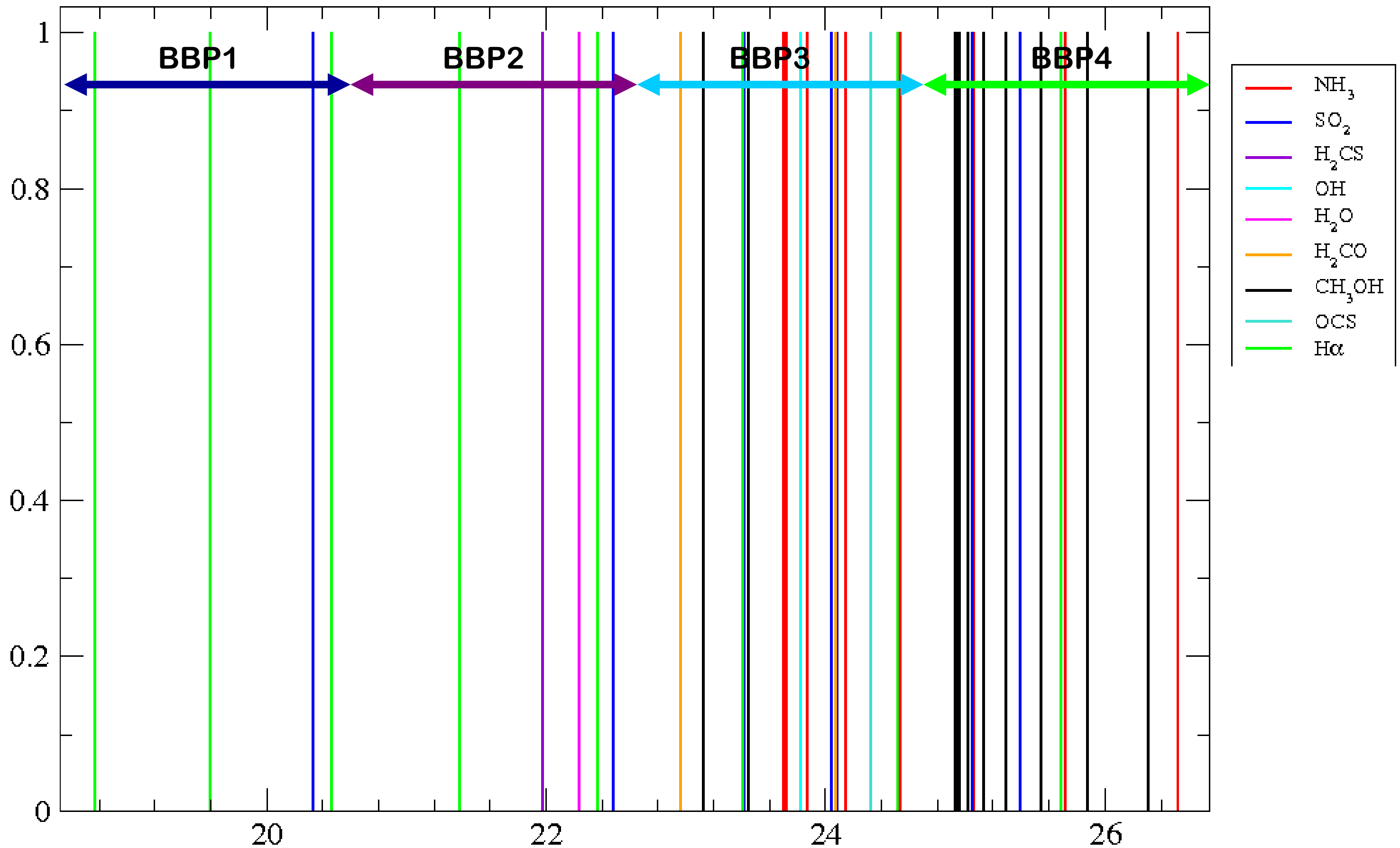
- observe high-density tracers NH_3, all available transitions from (1,1) to (8,8), and CH_3OH;
  - gives density and temperature structure of hot cores (very young, massive, protostars)
- observe shock tracers, interaction of protostars with surrounding cloud: transitions of SO_2, H_2O, OCS, H_2CS, H_2CO, OH
- observe radio recombination lines and continuum emission from a nearby HII region
- spectral resolution required for molecular lines: 0.2 km/s
- spectral resolution required for RRLs: 1 km/s
- need as much line-free continuum as possible for the free-free emission

Massive SFR – Correlator Setup

- Tune the four available baseband frequency pairs to:
    1. 18.6 – 20.6 GHz which covers 3 RRL + 1 Mol (12 SBP free)
    2. 20.6 – 22.6 GHz which covers 2 RRL + 3 Mol (11 SBP free)
    3. 22.6 – 24.6 GHz which covers 2 RRL + 14 Mol (all SBP used)
    4. 24.6 – 26.6 GHz which covers 1 RRL + 14 Mol. (1 SBP free)
- Set the 32 SBPs covering the molecules to a BW = 16 MHz, providing 1024 channels in both RR and LL.
- Set the 8 SBPs covering the RRLs to BW = 32 MHz, providing 512 channels in both RR and LL.
- This leaves 24 SBPs to cover the continuum (at 128 MHz BW each), or for other transitions.
- A total of 79872 channels … a high data rate of 30 MB/sec with 10 sec averaging.
    – Could reduce this rate to more manageable size by averaging.

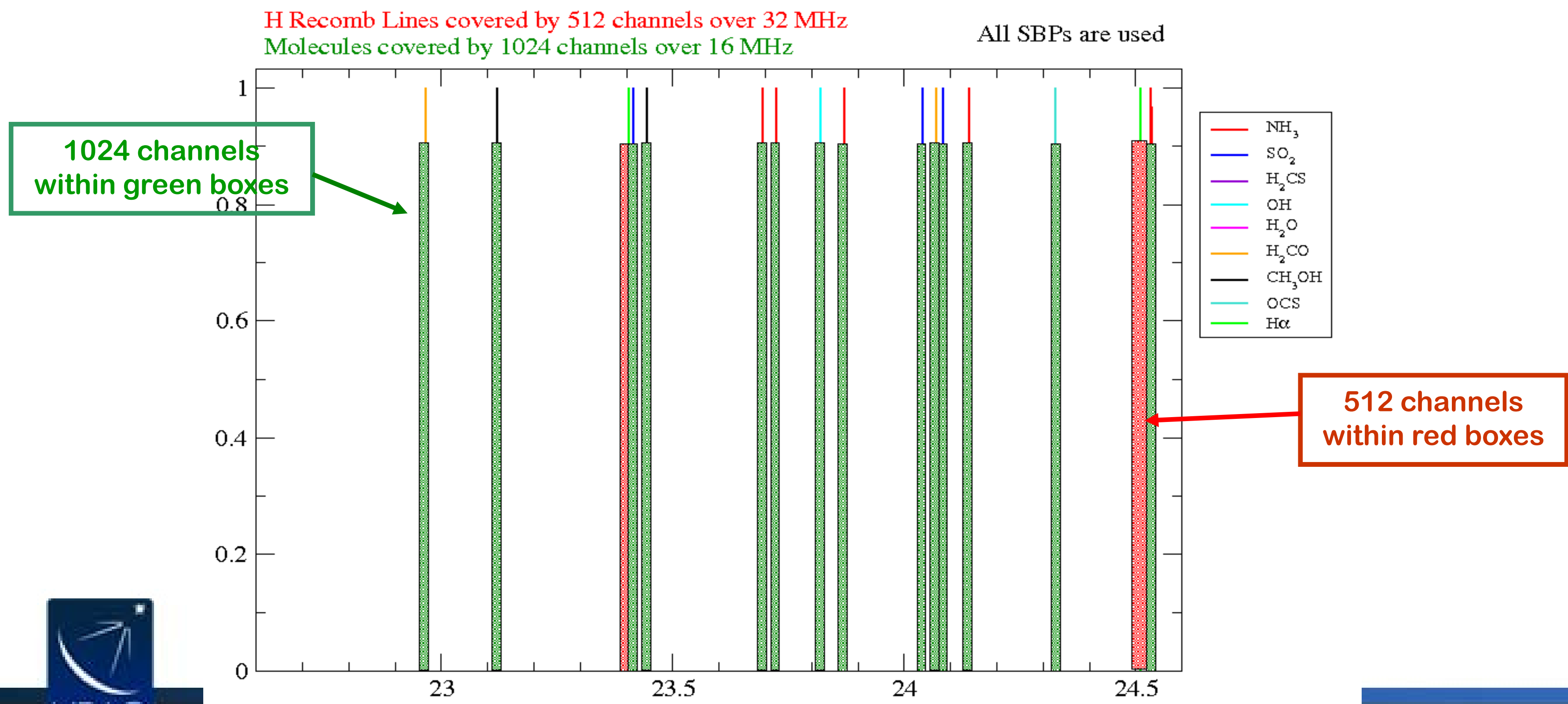
The Entire Spectrum

- Showing the distribution of the SFR lines, color coded by species.
- The spans for the four BBPs are as shown.



Within BBP #3:

- Showing a ‘close-up’ of the coverage within one of the BBPs.
- The green rectangles show the SBP frequency coverage for the molecules.
- The red rectangles shows the (wider) SBP coverage for the RRLs.



And Beyond …

- Looking further ahead, other capabilities to be enabled will include:
  - Complete sub-band flexibility
  - Full Pulsar capabilities
  - Phased Array VLBI
  - Planetary and solar observing
  - 8 or more independent subarrays
  - Millisecond dump rates