Low Frequency Interferometry

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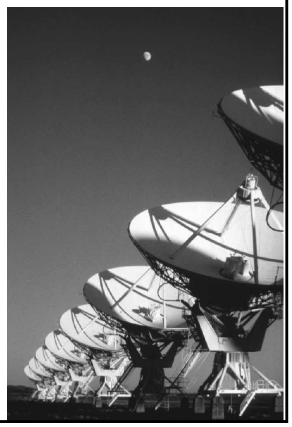
Ninth Synthesis Imaging summer School, Socorro, June 15-22, 2004



History of Low Frequency Astronomy

- Radio astronomy began at frequencies of ~ 20 MHz in the 30s with Karl Jansky
- First all sky map ever is at 200 MHz (Droge & Priester 1956)
- Low freq. receivers (dipoles) easy to make and cheap

However:

- Resolutions poor – degrees
  - => λ/D (wavelength / longest baseline length)
  - => Ionosphere
- Sensitivity low – dominated by Galactic background – sky noise
  - => $T_{sys} = T_{ant} + T_{rec}$
  - => synchrotron background due to several hundred MeV electrons spiraling in Galactic magnetic field

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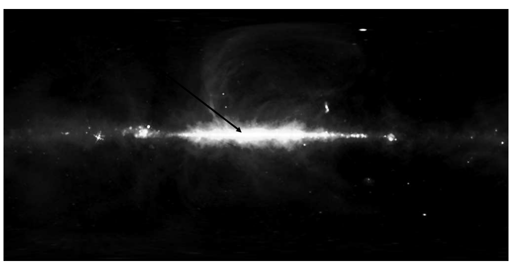
All-sky Map – 408 MHz

Best Tsys > 50 K
resolution ~ 0.85 degrees



Haslam et al. (1982)

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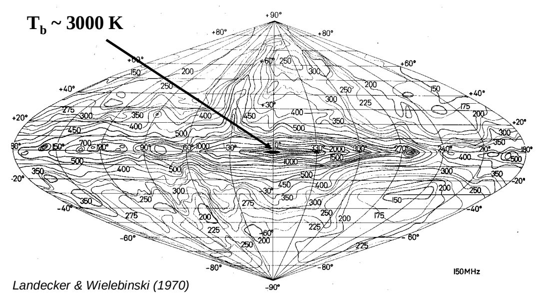
All Sky Map – 150 MHz

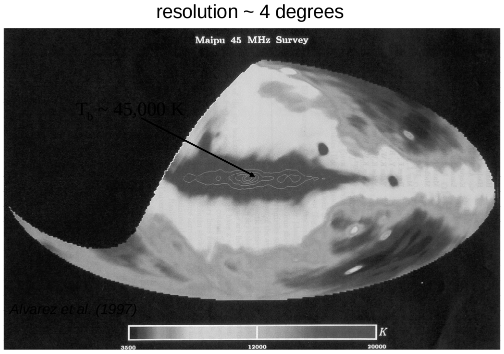
Best Tsys > 150 K
resolution ~ 2.2 degrees



Landecker & Wielebinski (1970)

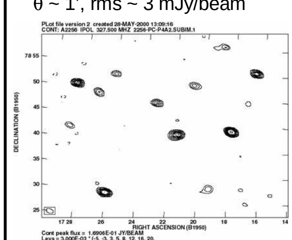
All-sky map, 45 MHz

Best Tsys > 3000 K
resolution ~ 4 degrees

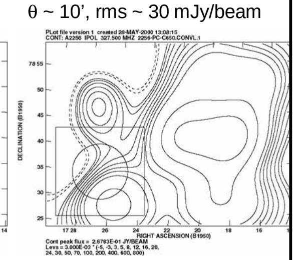


Low Angular Resolution: Limits Sensitivity Due to Confusion

θ ~ 1', rms ~ 3 mJy/beam



θ ~ 10', rms ~ 30 mJy/beam



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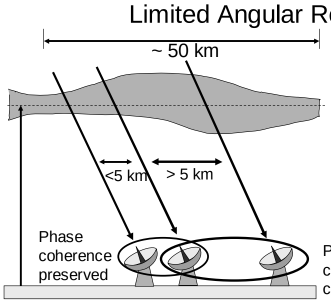
Ionospheric Structure: Limited Angular Resolution



Compared to shorter λ:

Maximum antenna separation:
< 5 km (vs. >10^3 km)

Angular resolution:
$\theta > 0.3°$ (vs. < 10^{-3} °)

Sensitivity *confusion limited*:
rms ≥ 1–10 Jy (vs. < 1 mJy)

=> Over time push for higher resolution and sensitivity meant shorter λ

Recent revolution due to advances in:
(self) calibration, imaging, and overall computing power

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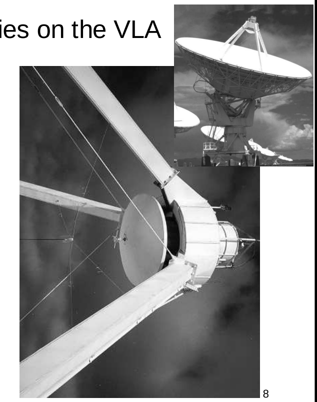
Low Frequencies on the VLA

- Two Receivers:
  - 330 MHz = 90cm
    - PB ~ 2.5^O (FOV ~ 5^O)
  - 74 MHz = 4m
    - PB ~ 12^O (FOV ~ 14^O)
- Can take data simultaneously
- Max 330 MHz resolution 6"
- Max 74 MHz resolution 25"
- Other telescopes GMRT, DRAO, MRT, etc



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Low Frequencies on the VLA

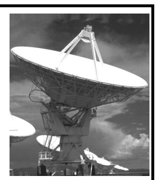

Table 4: **VLA Sensitivity**

Frequency (GHz)	Band Name approximate wavelength	letter code	System Temperature[1] (K)	Antenna Efficiency[2] (%)	RMS (10 min) Sensitivity (mJy)
0.073 - 0.0745	400 cm	4	1000-10000	15	150[(3)]
0.3 - 0.34	90 cm	P	150-180	40	1.4[(3)]
1.24 - 1.70	20 cm	L	35	55	0.056
4.5 - 5.0	6 cm	C	45	69	0.054
8.1 - 8.8	3.6 cm	X	35	63	0.045
14.6 - 15.3	2 cm	U	120	58	0.19
22.0 - 24.0	1.3 cm	K	50 - 80	40	0.10[(4)]
40.0 - 50.0	0.7 cm	Q	80	35	0.25[(5)]

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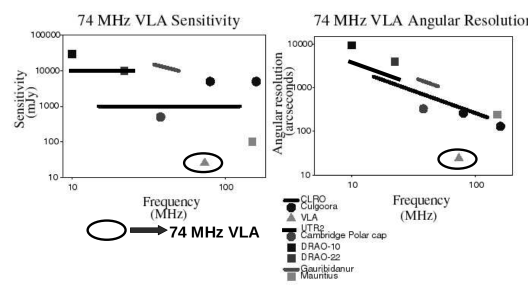
74 MHz VLA: Significant Improvement in Sensitivity and Resolution



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Difficulties with Low Frequency Observations

- Bandwidth smearing
  - Distortion of sources with distance from phase center
- Interference:
  - Severe at low frequencies
- Large Fields of View
  - Non-coplanar array (*u*,*v*, *& w*)
  - Calibrators
  - Large number of sources requiring deconvolution
- Phase coherence through ionosphere
  - Corruption of coherence of phase on longer baselines
  - Imperfect calibrator based gain calibration
- Isoplanatic Patch Problem:
  - Calibration changes as a function of position

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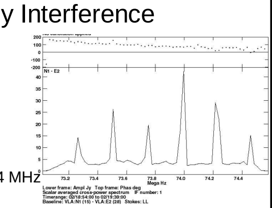
Radio Frequency Interference



- As at cm wavelengths, natural and man-generated RFI are a nuisance
  - Getting "better" at low freq. relative BW for commercial use is low
- At VLA: different character at 330 and 74 MHz
  - 74 MHz: mainly VLA generated
    => the "comb" from 100 kHz oscillators
  - 330 MHz: mainly external
  - Solar effects – unpredictable
    - Quiet sun a benign 2000 Jy disk at 74 MHz
    - Solar bursts, geomagnetic storms are disruptive => 10^9 Jy!
    - Ionospheric scintillations in the late night often the worst
  - Can be wideband (C & D configurations), mostly narrowband
- Requires you to take data in spectral line mode
  - RFI can usually be edited out – tedious but "doable"

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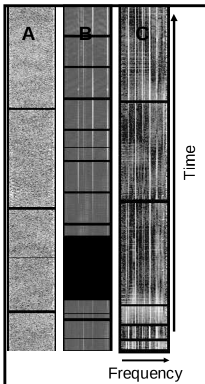
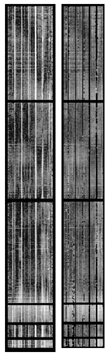
RFI Excision



before after



RFI excision "doable" but tedious

Example using AIPS task "FLGIT"

Unfortunately, still best done by hand!

AIPS: SPFLG

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Bandwidth Smearing

Fractional BW x # of θ_{synth} beams from phase center

$(\Delta\nu/\nu_o)x(\theta_o/\theta_{synth}) \sim 2 \Rightarrow I_o/I = 0.5$

=> worse at higher resolutions

Freq. (MHz)	BW (MHz)	A-config. θ_{synth} (")	Radius of PB_{FWHM} (')	θ_{MAX} (') for 50% degredation
74	1.5	25	350	41
330	6.0	6	75	11
1420	50	1.4	15	1.3

Solution: spectral line mode => already essential for RFI excision

Rule of thumb for full primary beam imaging in A config. with less than 10% degradation:

74 MHz channel width < 0.06 MHz
330 MHz channel width < 0.3 MHz
1420 MHz channel width < 1.5 MHz

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Large Fields of View (FOV) I

Noncoplanar baselines: *(u,v, **and w**)*

- Important if FOV is large compared to resolution
  - => in AIPS multi-facet imaging, each facet with its own θ_{synth}
- Is essential for all observations below 1 GHz and for high resolution, high dynamic range even at 1.4 GHz

AIPS Tip:

- Experience suggests that cleaning progresses more accurately and efficiently if EVERY facet has a source in it.
- Best not to have extended sources spread over too many facets

=> often must compromise

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Large Fields of View (FOV) II

Calibrators:

- Antenna gain (phase and amplitude) and to a lesser degree bandpass calibration depends on assumption that calibrator is a single **POINT** source
- Large FOV + low freq. = numerous sources everywhere
- At 330 MHz, calibrator should dominate flux in FOV: extent to which this is true affects absolute positions and flux scale
  - => Phases (but not positions) can be improved by self-calibrating phase calibrator
  - => Always check accuracy of positions

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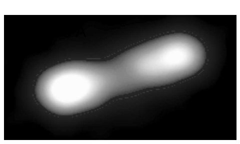
Large Fields of View (FOV) III

Calibrators

- There are no point-like calibrators below 100 MHz!
  - => Must use source with accurate model for bandpass and instrumental phase **CygA**, CasA, TauA, VirgoA
- Then can try NVSS model, or other previous low freq. image (i.e. 330 MHz) of the field but be cautious! If field is dominated by thermal sources this will not work well and possibly not at all
- Positions can be off by significant amount (10s of arcseconds), especially if model is not a good representation of 74 MHz emission



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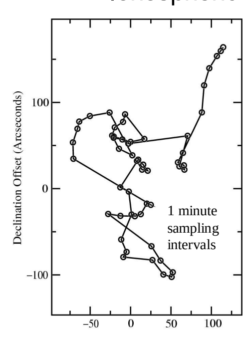
Ionospheric Refraction



- Both global and differential refraction seen.
- Time scales of 1 min. or less.
- Equivalent length scales in the ionosphere of 10 km or less.

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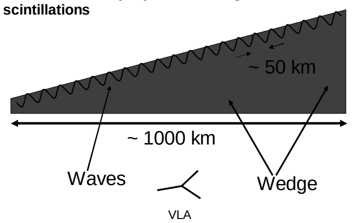
Ionospheric Effects

Wedge Effects: Faraday rotation, refraction, absorption below ~ 5 MHz

Wave Effects: Rapid phase winding, differential refraction, source distortion, scintillations



Wedge: characterized by
TEC = $\int n_e dl$ ~ 10^{17} m^{-2}

Extra path length adds extra phase
$\Delta L \propto \lambda^2 * TEC$
$\Delta\phi \sim \Delta L/\lambda \sim \lambda * TEC$

Waves: tiny (<1%) fluctuations superimposed on the wedge

- The wedge introduces thousands of turns of phase at 74 MHz
- Interferometers are particularly sensitive to the wave component

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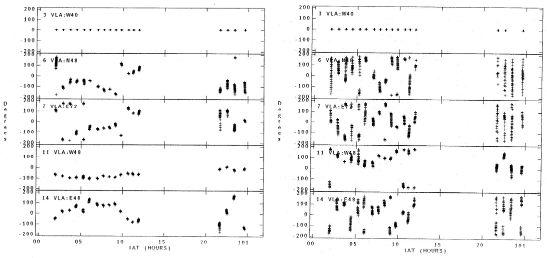
Interferometry Relies on Good Phase Stability:

Dominated & "Corrupted" by the Ionosphere for $\nu \leq$ ~1 GHz

330 MHz A array | 74 MHz – 4 times worse



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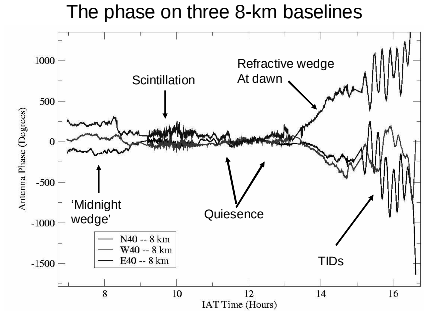
Antenna Phase as a Function of Time

The phase on three 8-km baselines



A wide range of phenomena were observed over the 12-hour observation
=> MYTH: Low freq. observing is better at night.
Often daytime (but not dawn) has the best conditions

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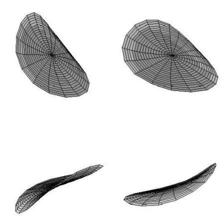
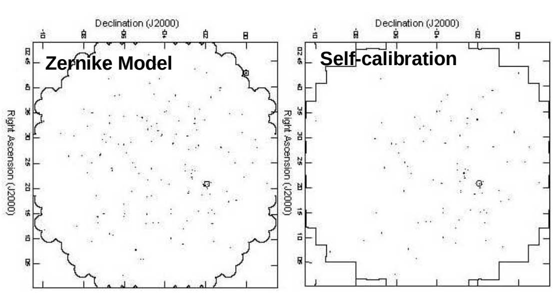
Isoplanatic Patch Assumption

- Standard self-calibration assumes single ionospheric solution across FOV: $\varphi_i(t)$
  - **Problems: differential refraction, image distortion, reduced sensitivity**
  - **Solution: selfcal solutions with angular dependence**
    $\varphi_i(t) \rightarrow \varphi_i(t, \alpha, \delta)$
  - **Problem mainly for 74 MHz A and B arrays**
- Zernike polynomial phase screen
  - **Developed by Bill Cotton (NRAO)**
  - **Delivers astrometrically correct images**
  - **Fits phase delay screen rendered as a plane in 3-D viewed from different angles**

  Key handicaps:
  - **Need high S/N—significant data loss under poor ionospheric conditions**
  - **Total flux should be dominated by point sources**



Breakdown of Infinite Isoplanatic Assumption



Also, average positional error decreased from ~45" to 17"

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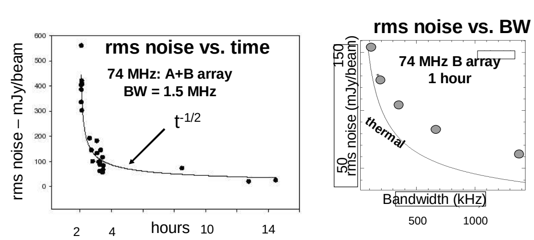
Noise Characteristics



- A+B array noise in 74 MHz maps decreases ~ $t^{-1/2}$
- Slower improvement with BW => confusion limited

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So Why go to all this trouble…?

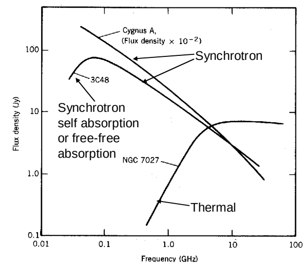
Thermal vs. Synchrotron Emission

Thermal Emission
(Free-Free, Bremsstrahlung):

- Best observed at cm λ ($\nu > 1$ GHz)
- Coulomb force between free electrons and ions
- Depends on temperature of the gas and has a Blackbody spectrum

Synchrotron Emission:

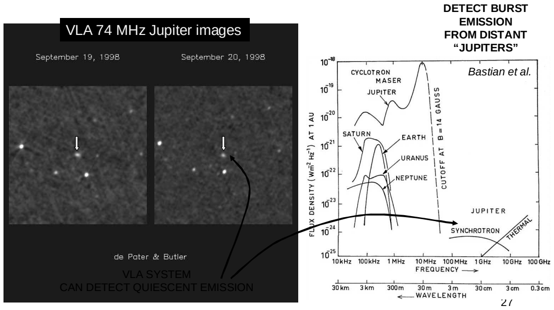
- Best observed at m λ ($\nu < 1$ GHz)
- Relativistic electrons circling around magnetic field lines
- Depends on the energy of the electrons and magnetic field strength
- Emission is polarized
- Can be either coherent or incoherent



Thompson, Moran, & Swenson

Bursts From Extra-solar Planets

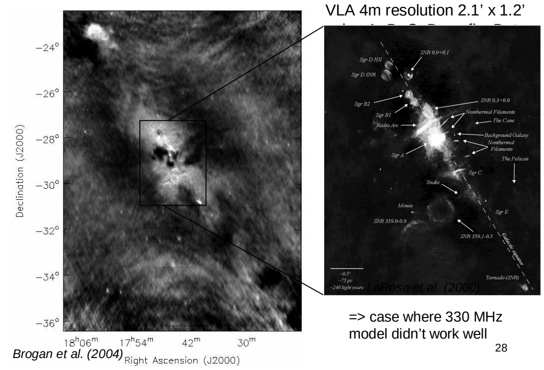
Jupiter's coherent cyclotron emission: complex interaction of Jupiter's magnetsphere with Io torus



Future instruments will resolve Jupiter and may detect extra-solar planets

VLA 74 MHz (4 m) Image

VLA 4m resolution 2.1' x 1.2'



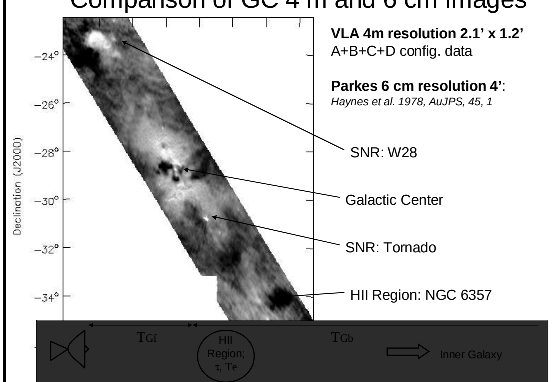
Brogan et al. (2004)

=> case where 330 MHz model didn't work well

Comparison of GC 4 m and 6 cm Images

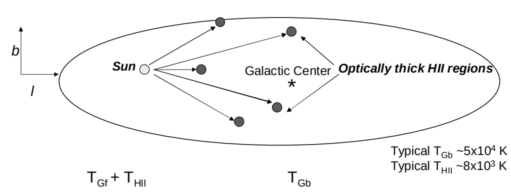
VLA 4m resolution 2.1' x 1.2'
A+B+C+D config. data

Parkes 6 cm resolution 4':
Haynes et al. 1978, AuJPS, 45, 1



Galactic Cosmic Ray 3-D distribution

- CR energy ~ energy in starlight, gas pressure, and Galactic magnetic field



Typical T_{Gb} ~5x10^4 K
Typical T_{HII} ~8x10^3 K

$T_{Gf} + T_{HII}$ T_{Gb}

$\Rightarrow T_{Gf} = T_{Gt} + T_{obs\_i} - T_{HII}$

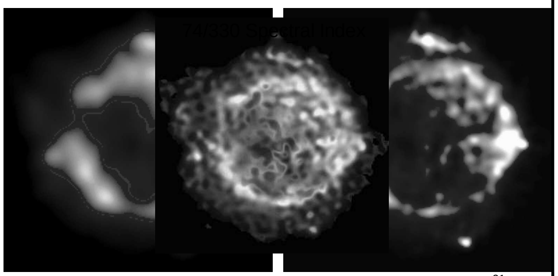
$\Rightarrow$**Emissivity=** T_{Gf}/D

- Galactic cosmic ray origin
- Galactic magnetic field morphology

SNRs: Shock Acceleration vs.Thermal Absorption Cas A

A array

A array + Pie Town



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(*T. Delaney – thesis with L. Rudnick*)

Pulsars

- Detecting fast (steep-spectrum) pulsars
  - highly dispersed, distant PSRs
  - tight binaries
  - submsec?
- Probe PSR emission mechanism
  - explore faint end of luminosity function
  - spectral turnovers near 100 MHz
- New SNR/pulsars associations
  - Deep, high surface brightness imaging of young pulsars

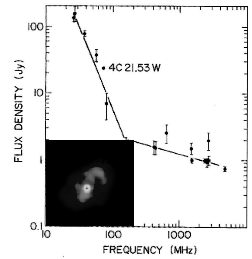

FIG. 2.—The radio spectrum of 4C 21.53W. Data are listed in Table 2. The solid lines correspond to spectral indices of −0.26 (ν > 150 MHz) and −2.44 (ν > 150 MHz).

Spectrum of 4C21.53: 1st (& still fastest known) msec pulsar

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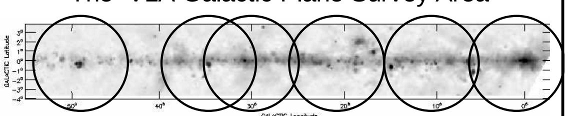
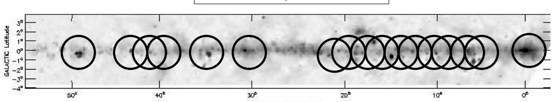
The VLA Galactic Plane Survey Area



* 74 MHz (4 m)
* A, B, C, & D configurations
* final resolution ~45"
* rms ~50 mJy/beam



* 330 MHz (90cm)
* B, C, & D configurations
* final resolution ~20"
* rms ~5 mJy/beam

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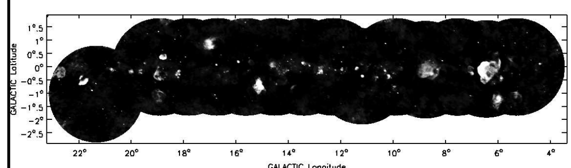
Greyscale Bonn 21cm (1465 MHz) Survey with 9.4' resolution

330 MHz Survey of Inner Galactic Plane



- VLA 330 MHz mosaic composed of C+D configuration data
- The resolution is 2.2' x 1.4' and the rms noise is ~15 mJy/beam
- The mosaic is made up of 14 pointings, 3 from the VLA archive
- Superior to any previous survey for ν < 2 GHz.

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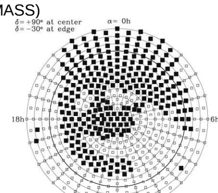
Brogan et al. (2004)

VLA Low Frequency Sky Survey: VLSS

(formerly known as 4MASS)



- Survey Parameters
  - 74 MHz
  - Dec. > -30 degrees
  - 80" resolution
  - rms ~100 mJy/beam
- Deepest & largest LF survey
  - N ~ 10^5 sources in ~ 80% of sky
  - Statistically useful samples of rare sources => fast pulsars, distant radio galaxies, radio clusters and relics
  - Unbiased view of parent populations for unification models
- Important calibration grid for VLA, GMRT, & future LF instruments
- Data online at: **http://lwa.nrl.navy.mil/VLSS**
- *Condon, Perley, Lane, Cohen, et al*

Progress:
~50% of survey complete
~40,000 sources detected

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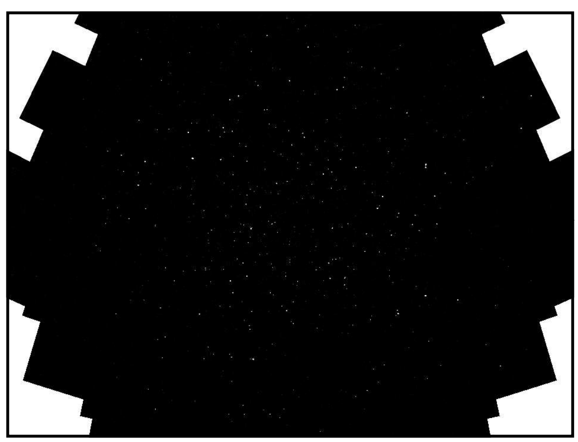
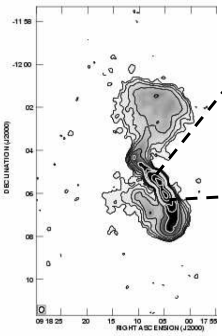
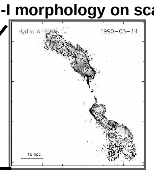


FR-I's at Low Frequency





- **Hydra A at 4500 MHz (inset) shows an FR-I morphology on scales of <1.5 arcmin**
- **New 74 and 330 MHz data show Hydra A is > 8 arcmin in extent with large outer lobes surrounding the high frequency source**
- **The outer lobes have important implications for the radio source lifecycle and energy budget**

Lane et al. (2004)

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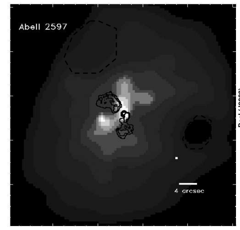
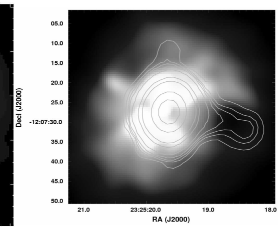
Abell 2597 : Radio/X-ray Interaction





- **Chandra image with 8 GHz radio contours (*McNamara et al. 2000*)**
- **dashed areas show ghost holes in the thermal X-ray gas at radii larger than currently active central radio source**
- **330 MHz radio data show an extension to the western X-ray hole (*Clarke et al. 2004*)**
- **Holes are where the emission from a previous radio outburst has displaced the surrounding thermal gas creating the holes**

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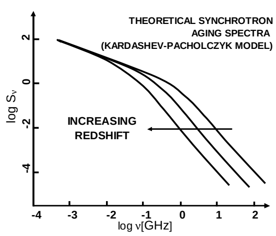
High Redshift Galaxies: Natural Steep Spectrum Sources



- Synchrotron losses steepen the spectrum of radio galaxies
- At high z the already steep spectrum is also redshifted to lower frequencies so that the entire *observed* spectrum is steep.
- Inverse Compton losses act similarly to steepen the spectrum, especially at high z since IC losses scale as z^4.

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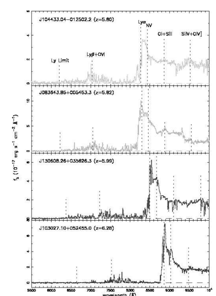
Epoch of Reionization: $z \approx 6$ (H I at 200 MHz)

Universe made rapid transition from largely neutral to largely ionized

- Appears as optical Gunn-Peterson trough in high-z quasars
- Also detectable by highly-redshifted 21 cm H I line in absorption against first quasars?
- WMAP Update: "first" of two re-ionization epochs near z~20 (HI at 70 MHz)??



SDSS: Becker et al. (2001)

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Low Freqs and the EVLA

- The 74 and 330 MHz receiver systems are not slated for upgrade in the EVLA
- However, there will be benefits:
  - New correlator will allow much wider bandwidths with sufficient channels to prevent bandwidth smearing at 1420 and 330 MHz
    - 1420 MHz from 50 MHz to 1 GHz
    - 330 MHz from 12 MHz to 40 MHz (limited by front-end filter)
    - 74 MHz will still be limited by front end filter (and confusion)
  - The 100 kHz oscillators that cause the "comb" will be eliminated

Significant improvement requires a system designed for low frequencies => LWA (10-100 MHz) and LOFAR (100-300 MHz)

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For the future: the Long Wavelength Array (LWA)

- 74 MHz VLA demonstrates major breakthrough in sensitivity & angular resolution
  - =>10^2 less collecting area than UTR-2, but 10^2 better sensitivity
  - – Opens door for sub-mJy, arc-sec resolution LWA of greater size, collecting area, and frequency coverage
- Consortium of universities, the Naval Research Laboratory, and Los Alamos National Laboratory
  - – Prototyping already underway
- LWA to explore the region of the EM spectrum below the FM bands
  - – LWA intended to explore region of the spectrum below 100 MHz
  - – 74 MHz VLA and past experience (e.g. Clark Lake) show that technology is in hand to do this at modest cost and with low technical or scientific risk

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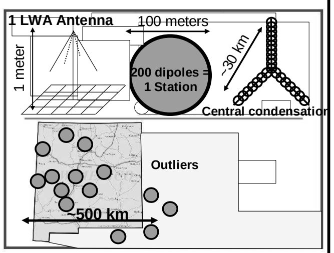
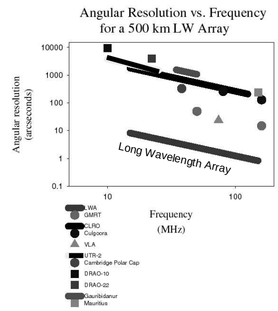
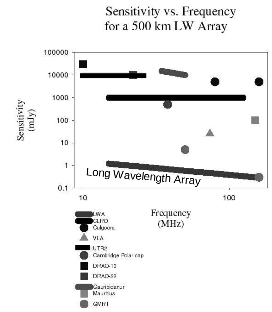
LWA Concept

- Fully electronic, broad-band antenna array
  - Frequency range: ≤ 90 MHz, no ionospheric limit on baseline length
- Large collecting area:
  - ≥ 1×10^6 m^2
- Baselines ≥ 100 km
- 2-3 orders of magnitude improvement in resolution & sensitivity:
  - [4", 1.6"] @ [30, 74] MHz; ≤ 1 mJy sensitivity
- Low Cost: < $50M



LWA: Opening a New Window on the Universe





Also, LOFAR coming in Netherlands to cover 100 to 300 MHz band

For more information:

Further reading:

White Book: Chapters 12.2, 15, 17, 18, 19, & 29

Data Reduction:

http://www.vla.nrao.edu/astro/guides/p-band/

http://www.vla.nrao.edu/astro/guides/4-band/

Future Instruments:

http://lwa.nrl.navy.mil/

http://www.lofar.org/

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