Radio Image of Ionised Hydrogen in Cyg X
CGPS (Penticton)
WHY?

- National Facilities
  - ✔ Easy for non-experts to use
  - ✗ don’t know what you are doing
- Cross fertilization
- Doing the best science
- Value of radio astronomy
Indirect Imaging Applications

- Interferometry
  - radio, optical, IR, space...
- Fourier synthesis
  - measure Fourier components and make images
  - Earth rotation, SAR, X-ray crystallography, ….
- Axial tomography (CAT)
  - NMR, Ultrasound, PET, X-ray tomography
- Seismology
- Fourier filtering, pattern recognition
- Adaptive optics, speckle
Doing the best science

- The telescope as an analytic tool
  - how to use it
  - integrity of results

- Making discoveries
  - Most discoveries are driven by instrumental developments
  - recognising the unexpected phenomenon
  - discriminate against errors

- Instrumental or Astronomical specialization?
HOW?

- Don’t Panic!
  - Many entrance levels

Murray didn’t feel the first pangs of real panic until he pulled the emergency cord.
Basic concepts

- Importance of analogies for physical insight
- Different ways to look at a synthesis telescope
  - Engineers model
    » Telescope beam patterns…
  - Physicist electromagnetic wave model
    » Sampling the spatial coherence function
    » Barry Clark *Synthesis Imaging chapter 1*
    » Born & Wolf *Physical Optics*
  - Quantum model
    » Radhakrishnan *Synthesis Imaging last chapter*
References

• **Essential Radio Astronomy**
  - a complete one semester course, J.J. Condon and S.M. Ransom
  - [www.cv.nrao.edu/course/ast534/ERA.shtml](http://www.cv.nrao.edu/course/ast534/ERA.shtml)
  - David Wilner, ANITA lectures, Swinburne, 2015


• **NRAO Synthesis Imaging workshop proceedings**
  - [www.aoc.nrao.edu/events/synthesis](http://www.aoc.nrao.edu/events/synthesis)

• **IRAM Interferometry School proceedings**

Detecting Signals from Radio Telescopes

Diagram showing the process:
- Antenna
- RF Amplifier + band-pass filter
- Mixer
- I.F. amplifier + B bandpass filter
- Quadratic detector
- Integrator τ₀
- Digitizer 01110010
- Computer

Time domain waveforms:
- s₁(t)
- s₂(t)
- s₃(t)
- s₄(t)
Planck’s Law

Rayleigh-Jeans approximation

The spectral distribution of the radiation of a black body in thermodynamic equilibrium is given by the Planck law:

\[ B_\nu(T) = \frac{2\nu^3}{c^2} \frac{1}{e^{h\nu/kT} - 1} \]

If \( h\nu \ll kT \), the Rayleigh-Jeans Law is obtained:

\[ B_{\nu R}(\nu, T) = \frac{2\nu^2}{c^2} kT \]

In the Rayleigh-Jeans relation, the brightness and the thermodynamic temperatures of black body emitters are strictly proportional (\( \gg 8.3 \)). This feature is useful, so the normal expression of brightness of an extended source is brightness temperature \( T_B \):

\[ T_B = \frac{c^2}{2k} \frac{1}{\nu^2} I_\nu = \frac{\lambda^2}{2k} I_\nu. \quad (8.4) \]

If \( I_\nu \) is emitted by a black body and \( h\nu \ll kT \), then (\( \gg 8.4 \)) gives the thermodynamic temperature of the source, a value that is independent of \( \nu \). If other processes are responsible for the emission of the radiation (e.g., synchrotron, free-free, or broadband dust emission), \( T_B \)
Figure 33–1. Boxcar representation for a stream of radiation. Each boxcar is a sample and corresponds to the reciprocal of the bandwidth, the rate at which new information arrives. A) The high density case where there is an enormous number of photons in each sample and substantial variation from sample to sample. B) The very low density case when the number of photons is minute compared to the number of samples.
## Resolving Power

- Angular resolution = wavelength/ aperture

<table>
<thead>
<tr>
<th></th>
<th>Light</th>
<th>Radio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td>0.00005cm</td>
<td>21cm</td>
</tr>
<tr>
<td>Aperture</td>
<td>10cm</td>
<td>10km</td>
</tr>
<tr>
<td>Resolution</td>
<td>0.00005/10 rad = 1” arc</td>
<td>21/10^6 rad = 4” arc</td>
</tr>
</tbody>
</table>
Imaging at Radio Wavelengths

- **Bad news**
  - Radio waves are big
  - Need large aperture or an interferometer

- **Good news**
  - Radio frequencies are low
  - Interferometers are easy to build
Greenbank 300' Radio Telescope
Remarks on Units

- $I_\nu = \text{monochromatic intensity} \ [W \ m^{-2} \ sr^{-1} \ Hz^{-1}]$
  - intensity (or brightness)
  - independent of source distance

- $T_b = I_\nu \left(\frac{c^2}{2k\nu^2}\right) = \text{Rayleigh-Jeans Brightness Temperature} \ [K]$
  - for thermal emission $T_b$ is the temperature of the emitting body
  - for other cases, radio astronomers still talk about $T_b$, the equivalent temperature that a blackbody would have to be as bright

- $S_\nu = \text{flux density} = \text{integral of } I_\nu \text{ over solid angle} \ [W \ m^{-2} \ Hz^{-1}]$
  - flux density decreases with source distance squared
Spatial Coherence

The spatial coherence function is the Fourier Transform of the brightness distribution.

van Cittert-Zernike theorem
The spatial coherence function is the Fourier Transform of the brightness distribution.

$P_1$ & $P_2$
spatially incoherent sources

At distant points $Q_1$ & $Q_2$
The field is partially coherent
Analogy with single dish

- Big mirror decomposition
Free space

Guided

\[(\sum V_i)^2\]
Free space
Guided

\((\Sigma V_i)^2\)
Free space
Guided

(Σ Vi)^2
Phased array

Free space

Guided

Mechanical steering

Electronic steering

\[(\Sigma V_i)^2\]
\[(\sum V_i)^2 = \sum (V_i)^2 + \sum (V_i \times V_j)\]
(\sum V_i)^2 = \sum (\vec{V_i})^2 + \sum (V_i \times V_j)
Phased Array

Split signal no S/N loss

Phased array
Tied array
Beam former

I(\(\theta\))

\(\Delta t\)

\(\sum V_i^2\)  \(\sum V_i^2\)
\[ <V_i \times V_j> \]

\[ \Delta t = \Delta \phi / \lambda \]

Correlator

Fourier Transform

van Cittert-Zernike theorem
The Fourier Transform

- Fourier theory states and any well behaved signal (including images) can be expressed as the sum of sinusoids

\[ x(t) = \frac{4}{\pi} \left( \sin(2\pi ft) + \frac{1}{3} \sin(6\pi ft) + \frac{1}{5} \sin(10\pi ft) + \cdots \right) \]

- the Fourier transform is the mathematical tool that decomposes a signal into its sinusoidal components
- the Fourier transform contains all of the information of the original signal
Analogy with single dish

- Big mirror decomposition
- Reverse the process to understand imaging with a mirror
  - Eg understanding non-redundant masks
  - Adaptive optics
- Single dishes and correlation interferometers
  - Darrel Emerson, NRAO
  - [http://www.gb.nrao.edu/sd03/talks/whysd_r1.pdf](http://www.gb.nrao.edu/sd03/talks/whysd_r1.pdf)
Filling the aperture

- Aperture synthesis
  - measure correlations with multiple dishes
  - moving dishes sequentially
  - earth rotation synthesis
  - store all correlations for later use

- Partially unfilled aperture
  - some spacings missing

- Redundant spacings
  - some interferometer spacings occur twice

- Non-redundant aperture
Redundancy

1 unit 5x (source same atmosphere different)
2 units 4x
3 units 3x
4 units 2x
5 units 1x

\[ \frac{n(n-1)}{2} = 15 \]
Non Redundant

1 unit 1x
2 units 1x
3 units 1x
4 units 1x
5 units 0x
6 units 1x
7 units 1x
etc
HERA

Epoch of Reinization Array

- Maximally redundant array to decouple the sky from the instrumental errors
Basic Interferometer
Storing visibilities

A powerful tool to manipulate the coherence function and re-image.

Not possible in most other domains

But will this be part of our pipeline future?
Why have a dish at all?

- Sample the whole wavefront
- \( n \propto \frac{\text{Area}}{(\lambda/2)^2} \)
- For 100m aperture and \( \lambda = 20\text{cm}, \ n = 10^4 \)
  » Electronics costs too high!
Radio Telescope Imaging

image v aperture plane

Dishes act as concentrators
Reduces FoV
Reduces active elements
Cooling possible

Increase FoV
Increases active elements

Active elements \( \sim \lambda/\lambda^2 \)
Radio Telescopes

- MWA
- Meerkat
- ASKAP

Aperture plane
Image plane
Fourier Transform and Resolution

- Large spacings
  - high resolution

- Small spacings
  - low resolution
Fourier Transform Properties
from Kevin Cowtan's Book of Fourier

http://www.ysbl.york.ac.uk/~cowtan/fourier/fourier.html
Fourier Transform Properties

10% data omitted in rings
Fourier Transform Properties

Amplitude of duck
Phase of cat

FT
Fourier Transform Properties

Amplitude of cat
Phase of duck

\[ \text{FT} \]
In practice...

1. Use many antennas (VLA has 27)
2. Amplify signals
3. Sample and digitize
4. Send to central location
5. Perform cross-correlation
6. Earth rotation fills the “aperture”
7. Inverse Fourier Transform gets image
8. Correct for limited number of antennas
9. Correct for imperfections in the “telescope” e.g. calibration errors
10. Make a beautiful image…
## Terminology

### RADIO
- **Antenna, dish**
- **Sidelobes**
- **Near sidelobes**
- **Feed legs**
- **Aperture blockage**
- **Dirty beam**
- **Primary beam** (single pixel receivers)

### OPTICAL
- **Telescope, element**
- **Diffraction pattern**
- **Airy rings**
- **Spider**
- **Vignetting**
- **Point Spread Function (PSF)**
- **Field of View**
## Terminology

<table>
<thead>
<tr>
<th>RADIO</th>
<th>OPTICAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Map</td>
<td>⇔ Image</td>
</tr>
<tr>
<td>Source</td>
<td>⇔ Object</td>
</tr>
<tr>
<td>Image plane</td>
<td>⇔ Image plane</td>
</tr>
<tr>
<td>Aperture plane</td>
<td>⇔ Pupil plane</td>
</tr>
<tr>
<td>UV plane</td>
<td>⇔ Fourier plan</td>
</tr>
<tr>
<td>Aperture</td>
<td>⇔ Entrance pupil</td>
</tr>
<tr>
<td>UV coverage</td>
<td>⇔ Modulation transfer function</td>
</tr>
</tbody>
</table>
### Terminology

<table>
<thead>
<tr>
<th>RADIO</th>
<th>OPTICAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dynamic range</td>
<td>⇔ Contrast</td>
</tr>
<tr>
<td>Phased array</td>
<td>⇔ Beam combiner</td>
</tr>
<tr>
<td>Correlator</td>
<td>⇔ <em>no analog</em></td>
</tr>
<tr>
<td><em>no analog</em></td>
<td>⇔ Correlator</td>
</tr>
<tr>
<td>Receiver</td>
<td>⇔ Detector</td>
</tr>
<tr>
<td>Taper</td>
<td>⇔ Apodise</td>
</tr>
<tr>
<td>Self calibration</td>
<td>⇔ Wavefront sensing (Adaptive optics)</td>
</tr>
</tbody>
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