Out of the optical Transmission of the atmosphere

Plasma frequency of ionosphere 10-15 Mhz, atmosphere opaque at lower frequencies

Radio band (1cm □ 100m) was the first non-optical band explored
History of Radio Astronomy

Karl Jansky (Bell labs) detected interference at 21 MHz from Milky Way (NY Times May 5, 1933)

Extraterrestrial emission (the Sun) commonly detected during WWII (Hey)

WWII radar development stimulated the field
Radio astronomy potted history

Cyg A: Hey et al. (1946)
Sydney 1948: first interferometer
(8 arcmin using sea reflection)

Cass A: Ryle & Smith (1948)

HI emission: Ewen & Purcell (1951)

M32: Brown & Hazard (1951)

3C 273: Ryle/Hazard/Schmidt 1963

3K CMB: Penzias & Wilson (1964)

Pulsars: Bell & Hewitt (1968)
Simple radio receiver

Superheterodyne detection

\[ ae^{iw_1 t} + be^{iw_2 t} = ae^{iw_1 t} (1 + (a \Box b) e^{i(w_1 - w_2) t}) + be^{iw_2 t} \]

Radio signal from aerial mixed with carrier frequency, signal at beat frequency (Intermediate Frequency) and is filtered and amplified. Tuning = changing the carrier frequency.
Detection of waves

Consider a random phase superposition of $N$ waves at the same frequency

\[ E = \sum_k e^{i\mathbf{k}} \]  
\[ \langle E \star E \rangle = N\hbar^2 \]  
\[ \langle \mathbf{E}^2 \rangle = N^2\hbar^4 \]

(e.g. M. Longair, Theoretical Concepts of Physics, p242-258)

The fluctuations in the field are of the same magnitude as the energy density of the radiation itself

Number of modes in a box:

\[ dN = \frac{8\hbar^3}{c^3} \mathbf{V} d\mathbf{V} \]

\[ u(\mathbf{V}) = \frac{8\hbar^3}{c^3} \mathbf{V}^2 kT \]

\[ u(\mathbf{V}) = \frac{8\hbar^3}{c^3} \frac{\hbar^3}{e^{kT}} \]

Quantum BB formula
Johnson Noise

In 1D transmission line at temperature $T$):

Power delivered: $W = \frac{h\square}{h\square e^{kT} \square 1} \square kT$ ($h\square << kT$)

(Noise signal measured by a receiver in thermal equilibrium)

Radio receiver sensitivity usually characterized by $T_{sys} = W/k$

Knowing $<E^2> = <\square^2>$ in each mode:

The noise power measured by a receiver integrating for a time $t$ with a bandwidth $\square\square$:

$$\square W = \frac{W}{(\square \square t)^{1/2}}$$

Number of independent samples

So for a radio receiver ($h\square << kT$):

$$\square W = \frac{kT_{sys}}{(\square \square t)^{1/2}}$$

Thermal equilibrium + number wave modes
So what happened to photons?

Full quantum treatment (Einstein 1909). Outline:

\[ W = e^{S/k} \]  Boltzmann relation probability \((W)/\text{entropy}\)

Energy fluctuations in cells has normal distribution:

\[
W = \exp\left(\frac{1}{2} \frac{(\square^2)}{\square^2}\right) \quad \text{where} \quad \square^2 = \frac{k}{\partial^2 S / \partial^2 \square}
\]

\[
\frac{1}{T} = \frac{dS}{d\square}
\]

these combine to derive:

\[
\frac{\square^2}{\square^2} = \frac{h\square}{\square} + \frac{c^3}{8\square^2 Vd\square} \quad \text{where} \quad \square = V \ u(\square) \ d\square
\]

\[
= \frac{1}{N_{\text{photons}}} + \frac{1}{N_{\text{modes}}}
\]

optical regime (Wien) \quad \text{radio regime (Rayleigh-Jeans)}
Waves vs photons – Example

1 mJy radio source, $\nu = 1 \text{GHz}$

Telescope = 10 m$^2$, Receiver temperature = 1 K, integration time = $10^4$ sec

$$\frac{h\nu}{kT} = 0.04 \quad \text{negligible}$$

Source: $10^{-28}$ W/Hz

Noise power = $\nu W = \frac{kT}{(\nu t)^{1/2}}$

$$= 3 \times 10^{-30} \text{ W/Hz}$$

$\text{S/N} = 32$

(c.f. photons : $1/N_p = 10^{-9}$)
Photon/wave crossover

\[ h\gamma = kT \]

\[ T = 100\text{K} \]
\[ \gamma = 2000 \text{Ghz} \quad \ell = 144 \text{mm} \]

\[ T = 10\text{K} \]
\[ \gamma = 200 \text{Ghz} \quad \ell = 1.4 \text{mm} \]

\[ T = 1\text{K} \]
\[ \gamma = 20 \text{Ghz} \quad \ell = 1.4 \text{cm} \]
A radio telescope ‘antenna’

Diffraction limit: 305m dish at 21cm $\rightarrow$ 2.4 arcmin

Described by antenna patterns.
Jargon: ‘main beam’ & side lobes (often suppressed by feedhorn)
Brightness

Brightness \( B(\theta, \phi) \) is energy received from a source per \( m^2 \) of collecting area and per steradian on the sky at position \( \theta, \phi \).

For a **BLACKBODY**: 

\[
B = \frac{2}{c^2} \frac{h \theta^3}{\sin \theta} \frac{h \phi}{e^{kT} - 1} = \frac{2kT}{\theta^2} \quad \text{in Rayleigh - Jeans regime}
\]

i.e. pure \( f(T, \theta) \). Hence we can relate all surfaces brightness measurements to the temperature of an *equivalent* blackbody.

Power/unit bandwidth (at frequency \( \theta \)) received by a flat collecting plate of area \( A \):

\[
W = A \int B(\theta, \phi) \cos \theta \, d\theta \quad \text{Units: Watts/Hz}
\]
Antennae Definitions

Normalized antenna pattern $P_n(\theta, \phi)$ (max = 1)

Radio astronomers like to relate everything to temperature!

Received power

$$ W = \frac{1}{2} A_e \int B(\theta, \phi) P_n(\theta, \phi) d\Omega $$

Extended source: Size $\gg$ beam of brightness temperature $T_B$

$$ W = \frac{1}{2} B A_e A_s = kT_B A_e A_s $$

Antenna theorem: $A_e A = \frac{1}{2}$

$$ W = kT_B $$

Turn this round and define antenna temp. $T_A = W / k$

Compact source: write $S_A = \int B(\theta, \phi) P_n(\theta, \phi) d\Omega = \frac{2kT_B}{b} S$ 

$$ W = kT_A = \frac{1}{2} A_e S_A = kT_B A_e S $$

$$ S_A = \frac{2T_A}{A_e} $$

Antenna Temperature, brightness temperate and measured power

$$ T_A = T_B \frac{S}{A_s} $$ (compact source)

$$ T_A = T_B $$ (extended source)
Characterising radio telescopes

Johnson noise: \[ W = \frac{k T_{\text{sys}}}{(t/2)^{1/2}} = k \Delta T_{\text{min}} \]

Write: \[ \Delta S_{\text{min}} = \frac{2k \Delta T_{\text{min}}}{A_e} \]

Let’s us define a sensitivity: \[ \frac{\Delta T_{\text{min}}}{\Delta S_{\text{min}}} = \frac{A_e}{2k} \]

e.g. the Arecibo 1.28-1.50 Ghz receiver has a ‘sensitivity of 12 K/Jy’.
\[ A_e = 33120 \text{ m}^2 \left( \equiv 205 \text{m dish} \right) \]

The ‘system temperature is 30 K’, so in a 100s over the full 0.22 Ghz band we can detect \[ 3 \Delta T_{\text{min}} = 0.2 \text{ mK}, \text{ or} \]
\[ 3 \Delta S_{\text{min}} = 0.02 \text{ mJy} \]
Recall: the Fourier Transform Spectrograph

Difference in distance $x$, phase difference $\phi = 2\pi x / l$

Intensity $I(x) = \mathcal{F}(\phi)[1 + \cos(2\pi x / c)]d\phi$

Is Fourier Transform of Spectrum $f(\phi)$

\Can be be inverted to give the spectrum (at each point on the focal plane!)
Phase difference between two telescopes

\[ I = 2b^2 (1 + \cos \theta) \]
\[ = 2B(\theta)[1 + \cos((2\pi x \theta / c) \sin \theta)] \]

*This time integrate over \( \theta \) (source angular extent)*:  
\[ I(x) = \int 2B(\theta)[1 + \cos((2\pi x \theta / c) \sin \theta)] d\theta \]

Intensity vs separation is FT of the source brightness distribution (all at same fixed observed frequency)

FT pair variables are \( \sin \theta \times \) (c.f. \( \theta \times \) in FTS)
Some Fourier theorems

\[ H(k) = \mathcal{F}\{h(x)\} = \int_{-a/2}^{+a/2} h(x) e^{i2\pi kx} \, dx \]

Basic transforms

\[ h(x) = \text{top hat} \]

\[ h(x) = \begin{cases} 1, & -a/2 \leq x \leq a/2 \\ 0, & \text{otherwise} \end{cases} \]

\[ H(k) = \frac{\sin(\pi a k)}{\pi k} \]

Convolution theorem:

\[ g \ast h \quad G(k)H(k) \]

i.e. \[ \int g(x) h(x - x) \, dx \quad = \quad \int G(k)H(k) e^{i2\pi kx} \, dk \]

\[ G(k)H(k) \ast dk \quad = \quad g(x)h(x) \quad \cdot \quad \int e^{i2\pi kx} \, dx \]

Parseval's Theorem:

\[ \text{Total Power} = \int |h(x)|^2 \, dx = \int |H(k)|^2 \, dk \]
Diffraction limit

Write for simplicity:
\[ \square = \sin \square \quad (\square \text{ small}) \quad & \quad \text{ignore zero offset} \]

\[ I(x) = \left[ B(\square) e^{2\square i\kappa x} \right] \, dk \quad \text{where} \quad k = \frac{\square}{\square} \]

\[ B(\square) = \square (x) e^{2\square i\kappa x} \, dx \]

\text{point source} \quad \square (k \square k_0) \quad \text{gives} \quad I(x) = e^{2\square k_0 x} \]

\text{fringes}

If truncated by finite baseline \( D \):

\[ B(k)_{\text{obs}} = \sum_{-D/2}^{+D/2} e^{2\square i(k \square k_0) x} \, dx \]

\[ = \frac{\sin \left( \square D (k \square k_0) \right)}{\square (k \square k_0)} \]

\( B(k)_{\text{obs}} \) is a sinc function with first zero at \( k = 1/D \), i.e.

\( \square = \square / D \quad \text{Rayleigh criteria} \) for diffraction limit (in 1D)
General array

\[ A(x) = \sum_{m=1}^{N} (x - md) \]

\[ N \text{ antennae, spacing } d \quad \text{by convolution theorem} \]

\[ Nd = D \]

General array:

\[ B(\[]\text{obs} = \sum_{m=1}^{N} (x) A(x) e^{2\pi j k x} dx \]

\[ = FT(I(x)) \quad FT(A(x)) \]

\[ = B(\[]\text{true} \quad \frac{\sin\left(\frac{k N d}{\sin(\frac{k d}{d})}\right)}{k = \frac{\text{baseline}}{\text{d}}} \]

Angular Resolution is set by the maximum baseline.

Aliasing limits the image size,

Number of resolution elements = \( D/d = N \)

Effective aperture: \( A_e(\text{total}) = N A_e(\text{tel}) \)
How do we fill the 2D plane? (called $u,v$ plane in Fourier space)

Imagine VLA is at North Pole, over 24 hrs will complete 2 cycles, 3 arms only needs 8hrs

3 arm configuration allows full $u,v$ coverage of any object from rise to set. Note integration time smears image!

Max baseline = 36 km
Resolution (1Ghz) = 1.7 arcsec
(43 Ghz) = 0.04 arcsec

$N_{res} = 18$ elements
$u,v$ coverage

Effect of discrete sampling dirty beams (c.f. filled aperture)

Response to a point source of a mulielement array (plotted: log of abs fringe intensity)

$\begin{align*}
N=2 \\
N=4 \\
N=8 \\
N=16
\end{align*}$

Filled aperture (matched resolution), limit $N$
Deconvolution algorithms

Can invert FT but get data convolved with ‘dirty’ PSF (nasty sidelobes)
Can’t divide $I(x)A(x)$ by $A(x)$ (zeroes)

$Deconvolution$ needs non-linear method

CLEAN

Fit bright sources model sidelobes and subtract. More an attempt to clean up dirty sidelobes than full deconvolution.

Extended sources a problem

Lucy-Richardson

Full iterative deconvolution approach based on max. likelihood. Model data $B(\square,\square)_{\text{true}}$ and convolve through aperture data, twiddle $B(\square,\square)_{\text{true}}$ good fit

Maximum Entropy

Similar, but uses an entropic prior, tries to derive smoothest image $B(\square,\square)_{\text{true}}$ which fits the data.

+$others$ …
Aperture synthesis example

Raw \( u,v \) data (3C99 Jodrell Bank)
Iterative CLEAN example

Dirty image

3C99 Jodrell Bank

Cleaned image
Modern receivers

Observe in both polarizations (separate receivers)

Data digitized at the antenna, sent on fast link (e.g. fiber) to correlator

- Multiple baseline correlation (interometer)
- Autocorrelation (FTS mode) – acts as filterbank

Modern correlators are extremely flexible - can operate multiple frequency channels (8-128) (spectral line vs continuum mode)
# VLA receivers sensitivity

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>Band Name approximate wavelength</th>
<th>System Temperature (K)</th>
<th>Antenna Efficiency (%)</th>
<th>Sensitivity (mJy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.073 - 0.0745</td>
<td>400 cm 4</td>
<td>1000-10000</td>
<td>15</td>
<td>150(^{(3)})</td>
</tr>
<tr>
<td>0.3 - 0.34</td>
<td>90 cm P</td>
<td>150-180</td>
<td>40</td>
<td>1.4(^{(3)})</td>
</tr>
<tr>
<td>1.24 - 1.70</td>
<td>20 cm L</td>
<td>35</td>
<td>55</td>
<td>0.056</td>
</tr>
<tr>
<td>4.5 - 5.0</td>
<td>6 cm C</td>
<td>45</td>
<td>69</td>
<td>0.054</td>
</tr>
<tr>
<td>8.1 - 8.8</td>
<td>3.6 cm X</td>
<td>35</td>
<td>63</td>
<td>0.045</td>
</tr>
<tr>
<td>14.6 - 15.3</td>
<td>2 cm U</td>
<td>120</td>
<td>58</td>
<td>0.17</td>
</tr>
<tr>
<td>22.0 - 24.0</td>
<td>1.3 cm K</td>
<td>50 - 80</td>
<td>40</td>
<td>0.22(^{(4)})</td>
</tr>
<tr>
<td>40.0 - 50.0</td>
<td>0.7 cm Q</td>
<td>80</td>
<td>35</td>
<td>0.27(^{(5)})</td>
</tr>
</tbody>
</table>

**Frequency RMS Point-Source Sensitivity (12 hours)**

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>(mJy)</th>
<th>(mK)</th>
<th>(\theta_{PB})</th>
<th>Peak</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.073 - 0.0745</td>
<td>15(^{(3)})</td>
<td>300</td>
<td>700'</td>
<td>20</td>
<td>350</td>
</tr>
<tr>
<td>0.3 - 0.34</td>
<td>0.17(^{(3)})</td>
<td>52.0</td>
<td>150'</td>
<td>1.8</td>
<td>15</td>
</tr>
<tr>
<td>1.24 - 1.70</td>
<td>0.0066</td>
<td>1.9</td>
<td>30'</td>
<td>0.11</td>
<td>0.35</td>
</tr>
<tr>
<td>4.5 - 5.0</td>
<td>0.0064</td>
<td>1.9</td>
<td>9'</td>
<td>0.002</td>
<td>0.02</td>
</tr>
<tr>
<td>8.1 - 8.8</td>
<td>0.0053</td>
<td>1.5</td>
<td>5.4'</td>
<td>0.001</td>
<td>--</td>
</tr>
<tr>
<td>14.6 - 15.3</td>
<td>0.020</td>
<td>6.0</td>
<td>3'</td>
<td>0.0001</td>
<td>--</td>
</tr>
<tr>
<td>22.0 - 24.0</td>
<td>0.025(^{(4)})</td>
<td>10.0</td>
<td>2'</td>
<td>0.0001</td>
<td>--</td>
</tr>
<tr>
<td>40.0 - 50.0</td>
<td>0.030(^{(6)})</td>
<td>20.0</td>
<td>1'</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>

Most \(\square\) = 43Mhz See [http://zia.aoc.nrao.edu/vla/obstatus/vlas/](http://zia.aoc.nrao.edu/vla/obstatus/vlas/)
## VLA Spectral Line Modes

<table>
<thead>
<tr>
<th>BW Code</th>
<th>Bandwidth (MHz)</th>
<th>Single IF Mode</th>
<th>Two IF Mode</th>
<th>Four IF Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No. Channels</td>
<td>Freq. kHz</td>
<td>No. Channels</td>
<td>Freq. kHz</td>
</tr>
<tr>
<td></td>
<td>Separ. kHz per IF</td>
<td></td>
<td>Separ. kHz per IF</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>16</td>
<td>3125</td>
<td>8</td>
<td>6250</td>
</tr>
<tr>
<td>1</td>
<td>32</td>
<td>781.25</td>
<td>16</td>
<td>1562.5</td>
</tr>
<tr>
<td>2</td>
<td>64</td>
<td>195.313</td>
<td>32</td>
<td>390.625</td>
</tr>
<tr>
<td>3</td>
<td>128</td>
<td>48.828</td>
<td>64</td>
<td>97.656</td>
</tr>
<tr>
<td>4</td>
<td>256</td>
<td>12.207</td>
<td>128</td>
<td>24.414</td>
</tr>
<tr>
<td>5</td>
<td>512</td>
<td>3.052</td>
<td>256</td>
<td>6.104</td>
</tr>
<tr>
<td>6</td>
<td>512</td>
<td>1.526</td>
<td>256</td>
<td>3.052</td>
</tr>
<tr>
<td>8</td>
<td>256</td>
<td>0.763</td>
<td>128</td>
<td>1.526</td>
</tr>
<tr>
<td>9</td>
<td>512</td>
<td>0.381</td>
<td>256</td>
<td>0.763</td>
</tr>
</tbody>
</table>
Radio astronomers get pixels!

Parkes multibeam

21cm (HI line) system with 13 simultaneous beams!

14 arcmin resolution per beam, 7 beams on sky. $T_{\text{sys}} \sim 20K$

HI Parkes All Sky Survey

ZOA survey

Juraszeck et al.

example galaxy
Radio: types of object

Radio galaxies. Radio QSOs.

Early days of radio astronomy – led the way to high-z universe. Now routinely observed to z=4

Normal galaxies

Local: HI gas masses/rotation curves. Hot gas (e.g. E galaxy haloes, clusters)

High-z: can see emission from SF to z~0.5 (deepest VLA) – emission from SNe remnants

Pulsars, SNe, etc

Gas lines: HI, HII, OH, CN, etc.
sub-mm astronomy

In this nasty piece of spectrum:

Atmospheric emission dominant source of noise. Rapid beamswitching removes systematics. Water vapour column varies hour-hour and limits what can be observed

Mixture of heterodyne (radio) and bolometer techniques. Shot noise and wave noise both important
e.g. JCMT

Heterodyne receivers: 200-800 Ghz
Spectral line observing, ~ 3Jy in 2000s
($T_{\text{sys}} \sim 10^4 K$)

SCUBA bolometers (cuum): 100-900 Ghz
91 pixels, 7 arcsec ‘beam’
20 mJy in 2000 secs
Sub-mm & far-IR

Predominant cuum emission: cool dust blackbody emission
Star-forming regions in local galaxies
Starburst galaxies
Circumstellar emission (rings etc.)
Redshifted IR emission in high-redshift galaxies ($z>1$ R-J tail negative $K$-correction)

SCUBA HDF images
7 arcsec resolution
Hughes et al.

What next? Large sub-mm arrays (e.g. ALMA, 64 12m dishes baseline = 10 km)
2002 launch

- 3 – 180 μm

imaging to 0.001 mJy
spectroscopy to 0.01 mJy

Photoelectric array detectors (back in single photon regime!)

Cool science:
Brown dwarfs
Warm dust & gas
Molecular lines
  - Star-formation regions
  - Starburst/active galaxies
High-redshift galaxies

What distinguishes a far-IR telescope from an optical/near-IR/UV telescope?

Detectors – mentioned already
Optics – purely reflective (lack of IR transmissive glasses), see earlier lectures
Cryogenics – keep everything cold!!
(Telescope, instruments, detectors)
Near-IR bands

3-5 μm – thermal windows open on ground, but non-cosmological (except South Pole)

1-2.5 μm – J, H & K bands. Domain of optical instruments, albeit cooled and with IR detectors & wavelength optimization (coatings, glasses etc). Sky background mostly airglow lines, non-thermal

Detectors – already mentioned
Optical astronomy

Been there, done that!

Still the domain where the deepest, highest redshift observations have been made (CCD age). \( z=3,4 \) galaxies, \( z=5,6+ \) QSOs. \( z>7 \) might require IR!

\( T \) range for thermal emission: few 100 – few 10,000 K.
UV astronomy

Scattering loses in all transparent media (air, glass etc.)

Also absorption bands (O\textsubscript{2}, O\textsubscript{3}, etc.)

Mirrors stop reflecting well, UV easily absorbed

FUV designs minimise reflections – e.g. the FUSE Rowland circle design, COS mission

Detectors: Microchannel plate (also for X-ray). CCD: can use fluorescent coating but need visible filter! DQE as low as 1-3%
Microchannel plate

DQE ~ 40%, RN=0,
instantaneous photon response

UV or X-rays

Anodes: MAMAs (wire grid), Phosphor+CCD, electron bound CCDs etc.
UV regions

Near ‘NUV’
2000Å \(\rightarrow\) optical

Far ‘FUV’
912Å \(\rightarrow\) 2000Å

Extreme ‘EUV’
6Å (200eV) \(\rightarrow\) 912Å

solar mass populations, ISM, AGN

Ly\(\beta\) forest, AGN, young OB stars, UVX ellipticals (HB/AGB)

Active stars, white dwarfs, HI blocks extragalactic

Young stars

Evolution of a starburst

HB + AGB in pop II
1300 – 3000Å all-sky imaging survey at AB=21.7, ~ 10⁷ galaxies

Note previous all-sky UV survey was TD-1 (1974) – 9th mag! Massive potential for serendipity.

3 reflections – aluminum coatings would have ~ 50% reflectivity at that wavelength. However 3 mirrors allow aberration correction and give a 1° FOV with a 2.4 arcsec spot size.

Note archive will be at JHU (merged with SDSS)
Blueward! Grazing incidence optics

EUV and X-ray bands

Wölter, 1952

Remember: \[ n \square 1 = \frac{N_e e}{2 \hbar m_e (\square^2 - \square^2)} \]

At high \( \square \) then \( n \square l \) is negative

X-rays are refracted in solid media – \( n \sim 1 \square 10^{-3} \)

\( \square \) Will be totally ‘externally’ reflected \( \square < 2 \square 3^\circ \)

\( \square \) which gives 50% reflectivity in silver
The high energy universe

AGN
QSOs

Interesting fact: for a ‘normal’ gas/dust ratio a 2keV photon has the same optical depth as a 2\,mm photon

IGM – gas haloes in clusters of galaxies
(Coma: $T \sim 7$ keV $\sim 8 \times 10^7$ K $\sim \frac{m_p}{m_e} v^2 \sim 1100$ km/s, $M \sim 10^{15} M_\odot$, $L \sim 10^{13} L_\odot$)

Small haloes: X-ray haloes of massive ellipticals

Stellar accretion (X-ray binaries) – Neutron stars, Black holes
X-ray detectors

Microchannel plates
Common for imagers

CCDs!

X-ray photons – create 100-1000s of electrons (e.g. \( N = \text{Energy}/3.6 \text{eV} \))
Counting the electrons \[ \text{energy resolution. i.e. spectroscopy} \]
Read fast (~ few secs)
Block optical/UV light with some material (e.g. Al/Polyimide/Al in Chandra ACIS), keep as thin is possible (e.g. ACIS can see \( V=8 \))
CHANDRA

0.5 arcsec resolution!

Chandra Science Instruments

- **Advanced CCD Imaging Spectrometer (ACIS)**
  - CCD array with 16’x16’ field of view (ACIS-I)
  - high energy grating readout array (ACIS-S)
- **High Resolution Camera (HRC)**
  - microchannel plate imager with 31’x31’ field of view (HRC-I)
  - low energy grating readout array (HRC-S)
- **High Energy Transmission Grating Spectrometer (HETG)**
  - transmission grating pairs for medium and high energy
- **Low Energy Transmission Grating Spectrometer (LETG)**
  - transmission grating for low energy

Dispersive spectrometers using gratings
Chandra grating spectroscopy

Capella X-ray spectrum (energy color coded)

Grating assembly (gold facets)
The inner two rings are high-energy grating, HEG, facets, and the outer two rings are medium-energy grating, MEG, facets.

Facets made of individual bars
γ-rays

> 30 keV (0.4 Å)

No mirrors! Detectors themselves are as large as possible

Scintillation detectors, spark chambers. Angular resolutions low ~ few degrees
Resolution ~ 12 arcmin via coded mask

Pinhole will image γ-rays – but not very efficient!
A general mask will cast a shadow, offset by the angular position of the source. Can find by cross-correlation. Multiple sources become more difficult.

Random mask (50% black) – reconstructed image predicts mask pattern. 50% correct if wrong, 100% correct if right.

Hadamard cyclic difference sets provide exact autocorrelation functions (0%→ 100% for correct shift)

Image reconstruction: deconvolution like methods (Wiener, max Entropy etc.)
VHE $\gamma$-rays – back to ground based optical astronomy!

$>10$ GeV – $10$ TeV

very few photons

Cherenkov telescopes observe air showers.

Efficiency improves with zenith angle!

Elliptic image points back towards source on the sky

HESS Stereoscopic 16 telescope array (Namibia) – 6 arcmin resolution!
"Mr. Osborne, may I be excused? My brain is full."

Thank you for your attention!