X- & γ-ray Instrumentation
The Dark Ages

Used nuclear physics detectors
  Proportional Counters
  Scintillators

Simple collimators
  HEAO A1 & A2: 2 x 8 degree field of view
  Confusion limit is about 200 sources over whole sky

Or more complex ones
  Modulation collimator, e.g. HEAO A3 – resolution of a few arcmin within a 4 degree field
  Coded masks
Imaging has been revolutionary.

X-ray instruments are strongly affected by the necessity to use grazing incidence reflection.
Wolter Telescopes provide the usual gains we expect from telescopes in the optical, infrared, and radio. They consist of conic sections but operate at grazing incidence. They are hopelessly in violation of the Abbe Sine Condition.
On-axis they provide good images (this is for Chandra).
Corrective optics are not feasible, so the off-axis images degrade quickly as the field angle increases.
**The Basic Chandra Focal Plane Instrument**

**AXAF CCD Imaging Spectrometer (ACIS)**

- Ten 1024 X 1024 CCDs
- Frame transfer readout
- Read out every 41msec
- Quantum yield: 1 electron/3.6eV
CCDs give good results from about 0.6 to 10 keV. 
a = back illuminated, b = front illuminated, 
c = deep depletion, d = pn CCD
The Galactic Center
The CCDs are capable of limited energy resolution.

These pre-launch predictions are a factor of 2 – 3 optimistic because of damage to the CCDs by cosmic rays on orbit.
Bragg diffraction provides better spectral resolution. Uses the structure of a crystal as the diffraction grating.

Constructive interference for \( m\lambda = 2d \sin \theta \)

Therefore, for \( d = 2 \times 10^{-4} \, \mu m \), at 10 kev \( (1 \times 10^{-4} \, \mu m) \), \( m = 1 \)
\[ \theta = 15^\circ \]
The High Energy Transmission Grating (HETG) for Chandra
The grating has a medium energy (outer rings) and a high energy section (inner rings). Each consists of a series of very tiny gold bars. The gold is partially transparent to the x-rays and has a refractive index < 1 so the arrangement induces phase shifts just as other gratings do. For spectroscopy, the grating is moved in front of the detector CCDs to disperse the light onto the ACIS-S array.
Some HETG parameters

Spectral resolution:
up to 1000

Grating period (HEG):
$2 \times 10^{-4}$ μm

Collecting area:
$\sim 30$ cm$^2$, energy dependent
Chandra
$\sim 500$ cm$^2$

Efficiency: $\sim 5 - 10\%$

To left, spectrum of NGC 3783
For reflecting surfaces, Chandra and XMM-Newton used single materials (e.g., platinum, iridium, gold) in grazing incidence. This approach drops rapidly in efficiency (or equivalently works only at more and more grazing incidence) with increased energy and is not effective above about 10 kev.

Higher energy photons can be reflected using the Bragg effect. Two layers alternate in material between high and low density, high and low index of refraction (e.g., tungsten or platinum for high, silicon or carbon for low). The stack (up to 200 layers) acts like a crystal lattice and reflects by constructive interference. With identical layers, the reflection would be over a restricted energy range; by grading the layers, broad ranges are reflected. The top layers have large spacing (d) and reflect the low energies, while lower layers have smaller d for higher energies.

NuStar (launched June 13, 2012) uses this approach to make reflecting optics working up to 79eV. It will use a standard Wolter design with multilayer surfaces deposited on thin glass substrated, slumped to the correct shape. It has 130 reflecting shells, with a focal length of 10 meters. The telescope was deployed after launch so the spacecraft would fit within the launch constraints.
\[ m\lambda = 2d \sin\theta \]

For normal incidence, \( \theta = \pi/2 \), first order (\( m = 1 \)) reflection

\[ \lambda = 2d \]
\[ d = \lambda/2 \]

if the two layers are approximately equal

\[ \Delta t = \lambda/4 \]

a quarter-wave plate coating.
Reflectivity of a graded layer surface.
NuStar on orbit (artist’s concept)
Collecting area comparison:

- **NuSTAR**
- **XMM-Newton/PN**
- **Chandra/ACIS**
NuStar Parameters

**Energy Range:** 6 - 79 keV  
**Angular Resolution:** 46 arcsec (HPD)  
**FOV:** 12 x 12 arcmin  
**Spectral Resolution:** 1.25 KeV at 68 keV  
**Timing Resolution:** 1 ms  
**ToO response:** < 48 hours  
**Launch date:** June 13, 2012  
**Orbit:** 550 km x 600 km, 6 degree inclination
Each of the two NuStar telescopes has four 32 X 32 CdZnTe detector arrays at its focus. These detectors can provide spectral resolution of about 100 through the pulse height from a detected X-ray (similar to CCDs at smaller energies). The high atomic weight materials absorb x-rays effectively and by adjusting the relative amounts of Cd and Zn, the band gap can be tailored to the desired operating temperature.

Each pixel is about 605μm, and each 32 X 32 pixel array is about 2 cm on a side. The readout uses a custom integrated circuit (ASIC). Each pixel is attached by flip chip hybridization (similar to the construction of an infrared direct hybrid array).
Energy resolution of a prototype NuStar detector array:
Background particles that do not pass through the telescope will be detected by an active shield of CsI surrounding the focal plane. When it triggers, the output of the focal plane array will be rejected.
Microcalorimeters can provide high resolution X-ray spectra

Microcalorimeters: bolometers can be built to absorb X-rays. If the heat capacity is very low and the response fast, a single absorbed X-ray results in a "pulse" on the output, and the size of the pulse is proportional to the energy of the X-ray (remember, bolometers detect anything they absorb!). Figures below from Wollman et al., NIST:

![Diagram of a microcalorimeter](image)

Microcalorimeter - except for the bismuth absorber (necessary for high efficiency with X-rays), it has all the elements of submm bolometers.
Compared with other imaging detectors (e.g., CCDs), the spectral resolution is fantastic.
Prototype microcalorimeter arrays demonstrate resolution equivalent to $R = 1000 – 3000$. This is achieved without grating inefficiencies and with full imaging information.
The International X-ray Observatory (IXO) was planned to make optimum use of hard X-ray optics and microcalorimeters. It got very ambitious ($$$$$, complexity) and has been cancelled.
This figure shows the gains that are possible.
Prototyped IXO mirror development
# International X-ray Observatory Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tr>
<td>Mirror Effective Area</td>
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<td>0.65 m² @ 6 keV</td>
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<td></td>
<td>150 cm² @ 30 keV</td>
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<td>Spectral Resolution (FWHM), FOV, bandpass</td>
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<td>2 arcmin</td>
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<td>0.3–7 keV</td>
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<td>5 arcmin</td>
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<td>0.3–10 keV</td>
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<td>$\Delta E = 150$ eV</td>
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<td>18 arcmin</td>
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<td>$E/\Delta E = 3000$</td>
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<td>30 arcsec HPD</td>
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<td>7–40 keV</td>
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**Instruments:**

- **XMS**: X-ray Microcalorimeter Spectrometer
- **XPOL**: X-ray Polarimeter
- **XGS**: X-ray Grating Spectrometer
- **WFI/HXI**: Wide Field Imager similar to ACIS, but uses active pixel sensors, similar to CMOS or IR array readout architecture – amplifier for each pixel, so no damage to charge transfer efficiency. HXI is a Hard X-ray Imager based on CdTe detectors.
- **HTRS**: High Time Resolution Spectrometer
ATHENA

• IXO has been resurrected as the Advanced Telescope for High Energy Astrophysics (ATHENA) by ESA. It has been selected as a second large mission of the ESA Cosmic Vision program.
• X-IFU utilizes an array of cryogenically cooled transition edge sensors operating over the range of 0.2-12 keV. The total field of view is 5 arcmin.
• The Wide Field Imager (WFI) utilizes five arrays of p-channel field-effect transistors operating over a range of 0.1-15 keV. The central array has a 256 X 256 pixels and a field of view 7.5 arcmin. Four outer arrays have a format of 448 X 640 pixels and a field of view 40 arcmin.
  • p-channel FETs can be built so ionizing particles in the substrate create free electrons that collect close to the channel and therefore modulate the channel current.
The particles in the shower are highly relativistic and emit Cherenkov light as they penetrate the atmosphere. An optical receiver will detect a burst of light (about 3 nsec in width)
Here is the first such large receiver, on Mount Hopkins
Modern facilities use a number of such telescopes separated by 100m or so. This helps distinguish the gamma ray showers from the nuclear ones.
Two major facilities are in operation: HESS in Namibia (to right) and VERITAS in Arizona (below)
The breakthrough that has made this field successful is to use imaging focal planes and multiple telescopes to isolate the gamma-ray showers. Because the gamma rays are less penetrating, their showers peak higher in the atmosphere than those of protons and other cosmic rays. Their images are therefore more confined, and whereas local single muons also produce confined images they can be screened out because they are seen only by single telescopes. Each VERITAS telescope has an array of 499 photomultipliers to image the showers. Gaps between the PMTs are filled with light cones. Here are some of the light cones shown over the full PMT array.
An example: Tev variability of the Blazar Mrk 421