γ-ray Detectors

• High-energy γ-rays cannot be reflected or refracted; they interact by the conversion of the γ-ray into an $e^+e^-$ pair
• A major concern is rejecting the much larger number of cosmic rays (need 0.9997 efficiency in rejection)

Full coverage of anti-coincidence detectors
γ-ray Detectors

Fermi energy range from 20 MeV - 300 GeV.

- A layered telescope, with converter layers interleaved with tracking material.
  - The converter is a high Z material (ex. Tungsten in Fermi) providing the target for creating a e+/− pair
- These particles in turn hit another, deeper layer of tungsten, each creating further particles etc
- The direction of the incoming gamma ray is determined by tracking the direction of these cascading particles back to their source using silicon detectors consisting of two planes of silicon one oriented in the "x"-direction, the other plane has strips in the "y"-direction. The position of a particle passing through these two silicon planes can be determined
- By reconstructing the tracks of the charged pair as it passes through the vertical series of trackers, the gamma-ray direction and therefore its origin on the sky are calculated. The absorption of the pair by a scintillator detector or a calorimeter after they exit the spark chamber, determines the total energy of the γ-ray
High Energy Telescopes

- A present can construct 'true' imaging telescopes in the 0.1-70 keV band
- At higher energies one can make 'pseudo-imaging' telescopes using 'coded aperture masks' (shadowgrams)

http://astrophysics.gsfc.nasa.gov/cai/
High Energy Telescopes

- 'true' imaging telescopes
- X-ray can be reflected at 'grazing' incidence (phenomenon of total external reflection at a surface where the index of refraction changes)

X-Ray Optics

1. We must make the X-rays Reflect
   - Total External Reflection
   - Fresnel’s Equations
Chandra

• Focal length = 10 m

• 1 module, 4 shells

• Coating = Iridium

• Angular Resolution = 0.5 arcsec HPD
Images of X-ray Optics

XMM Optics - 58 nested Shells, 0.5mm thick

1.2m diameter, 1 m long Chandra optic
X-Ray Reflection: Zero Order Principles:

Refs:

X-rays reflect at small grazing angles.
An analogy is skipping stones on water.

Scattering of any wave by an ensemble of electrons is coherent only in very special directions; namely, the familiar Angle of Incidence equals Angle of Reflection, $\phi_i = \phi_o$. 
Principle of grazing incidence

Snell's law:

\[
\frac{\cos \theta_1}{\cos \theta_2} = \frac{n_2}{n_1} \quad \Rightarrow \cos \theta_1 = n_2
\]

\[\Rightarrow \text{total reflection for } \theta < \theta_1\]

For X-rays the refractive index can be written as

\[n = 1 - \delta - i\beta\]

\(\delta\) proportional to the atomic number \(Z\)

\[\Rightarrow n \text{ small for heavy materials}\]

From Atwood 1999 http://www.coe.berkeley.edu/AST/sxreuv
The Wolter I mirror profile for X-ray astronomy applications

- it guarantees the minimum focal length for a given aperture
- it allows us to nest together many confocal mirror shells

**Effective Area:** \( 8 \pi F L \theta^2 \text{ Refl.}^2 \)

\[
F = \text{focal length} = \frac{R}{\tan 4\theta} \\
\theta = \text{on-axis incidence angle} \\
R = \text{aperture radius}
\]
X-ray mirrors with parabolic profile

\[ y^2 = 2px \]
\[ p = 2 \times \text{dist. focus-vertex} \]

- perfect on-axis focusing
- off-axis images strongly affected by coma
Reflection of X-rays

The index of refraction or the optical constants can be computed from anomalous dispersion theory. For wavelengths \( \lambda \) or photon energies sufficiently off-set from any electron binding energy a coarse estimate of \( \delta \) can be made:

\[
\delta = \frac{r_e}{2\pi} \frac{N_0 \rho}{A} Z \lambda^2
\]  

(6)

where \( N_0 \) is Avogadro’s number, \( r_e \) is the classical electron radius, \( Z \) and \( A \) are the atomic number and weight, respectively, and \( \rho \) is the mass density. For heavy elements for which \( Z/A \approx 0.5 \), the incidence angle of total reflection for \( \delta \ll 1 \) can be estimated to:

\[
\alpha_t = 5.6 \lambda \sqrt{\rho}
\]  

(7)

with \( \alpha_t \) in arcmin, \( \lambda \) in Å and \( \rho \) in g/cm\(^3\). For X-rays, with \( \lambda \) of a few Å, \( \alpha_t \) is about one degree. Equation (7) suggests the most dense materials as reflective coatings like gold, platinum or iridium.
Can Get Pretty Good Images

- Chandra Images are as good as the best images that can be obtained from the ground.

Chandra- fraction of energy inside an inscribed circle on axis
• Depends on mirror diameter, number of shells, focal length and coating of mirror (e.g. which metal coats the substrate)

• XMM mirror - the 'bumps and wiggles' are due to the atomic transitions of gold (the coating material)

• Effect of scattering: ratio of scattered to incident light

\[ \frac{I_s}{I_0} = 1 - \exp\left[-(4\pi \sigma \sin \alpha / \lambda)^2\right] \]

\( \lambda = \) wavelength of x-rays, \( \alpha = \) incident angle for reflection, \( \sigma = 'average roughness' \) - so want \( \sigma \sim \lambda \)

If want <10% scattered at 10\( \text{A} \) with \( \alpha = 1\text{deg} \), \( \sigma < 9\text{A} \)
Some Issues

• The reflecting surfaces have to be very smooth- if they are rougher than the wavelength then the photons hit 'mountains' and scatter (not reflect)

• A 'Wolter type I' optic only focuses 'perfectly' at the center of the field of view- as one goes off axis the angular resolution degrades-while free of spherical aberration, suffer from coma aberration, astigmatism and field curvature. The actual collecting area is much smaller than the polished surface (sin of a small angle)

• Because of the interdependence between f-number, grazing angle, telescope diameter and focal length, large diameter telescopes working at high energies can be constructed only with long focal lengths

Point spread function (PSF)
10' off axis
Manufacturing techniques utilized so far

1. **Classical precision optical polishing and grinding**

   Projects: *Einstein, Rosat, Chandra*

   **Advantages:** superb angular resolution

   **Drawbacks:** high mirror walls ➔ small number of nested mirror shells, high mass, high cost process

2. **Replication**

   Projects: *EXOSAT, SAX, JET-X/Swift, XMM, ABRIXAS* (examples follow hereafter)

   **Advantages:** good angular resolution, high mirror “nesting” the same mandrels for many modules

   **Drawbacks:** relatively high cost process; high mass/geom. area ratio (if Ni is used).

3. **“Thin foil mirrors”**

   Projects: *BBXRT, ASCA, SODART, ASTRO-E*

   **Advantages:** high mirror “nesting” possibility, low mass/geom. area ratio (the foils are made of Al), cheap process

   **Drawbacks:** until now low imaging resolutions (1-3 arcmin)
Present Astronomical optics technologies: HEW Vs Mass/Geometrical area
X-ray optical constants

• complex index of refraction to describe the interaction X-rays /matter:
  \[ \tilde{n} = n + i\beta = 1 - \delta + i\beta \]
  \( \delta \rightarrow \text{changes of phase} \)
  \( \beta \rightarrow \text{absorption} \)
  \( \mu = 4\pi \frac{\beta}{\lambda} \text{ cm}^{-1} \)

• at a boundary between two materials of different refraction index \( n_1 \), \( n_2 \), reverse of the momentum \( P \) in the \( z \) direction:
  \[ p_1 = \frac{h}{2\pi} k_1 \]
  \[ |k_1| = \frac{2\pi}{\lambda} n_1 \]
  \[ 2p_z \propto \frac{4\pi}{\lambda} n_1 \sin \theta_{inc} \]
  \[ r_{12}^s = \frac{n_1 \sin \theta_1 - n_2 \sin \theta_2}{n_1 \sin \theta_1 + n_2 \sin \theta_2} \]
  \[ r_{12}^p = \frac{n_1 \sin \theta_2 - n_2 \sin \theta_1}{n_1 \sin \theta_2 + n_2 \sin \theta_1} \]

• the amplitude of reflection is described by the Fresnel’s equations: