The Polarization Frontier
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From an observational point of view, X-ray polarimetry starts with a nearly completely blank slate.
Theory predicts that X-ray polarimetry will

• Probe black hole spin and accretion disk geometry
  • direct radiation is polarized parallel to the disk and dominates at lower energies
  • return radiation is polarized perpendicular to the disk
  • polarization magnitude and orientation is diagnostic
• Probe the high magnetic fields near the surface of neutron stars
  • X-rays are highly polarized perpendicular to k-B plane
  • Propagation in high fields probes GR effects
• Characterize the magnetic fields in supernova remnants
Photoelectric X-ray Polarimetry

- **Exploits:** strong correlation between the X-ray electric field vector and the photoelectron emission direction

- **Advantages:** dominates interaction cross section below 100keV

- **Challenge:**
  - Photoelectron range < 1% X-ray absorption depth ($\lambda_x$)
  - Photoelectron scattering mfp < e⁻ range

- **Requirements:**
  - Accurate emission direction measurement
  - Good quantum efficiency

- **Ideal polarimeter:** 2d imager with:
  - resolution elements $\sigma_{x,y} < e^{-}$ mfp
  - Active depth $\sim \lambda_x$
  - $\Rightarrow \sigma_{x,y} < \text{depth}/10^3$
Modulation and sensitivity

In practice, the distribution of estimated track directions, even for purely polarized input, is more complicated than a projection of the $\sin^2 \theta \cos^2 \phi$ probability distribution.

$$N = A + B \cos^2 (\phi - \phi_0)$$

$$\mu = \frac{N_{\text{max}} - N_{\text{min}}}{N_{\text{max}} + N_{\text{min}}}$$

$$\mu = \frac{B}{2A + B}$$
Elihu’s Polarimeter

Electron Optics for X-ray Photon Polarization Measurement

The Basic Scheme:

- Collimator (Cu) for X-rays

- Thin Window (e.g., Si, Al)

- X-rays

- e-

- Venetian Blind Photokly Electromultiplier

\[ \frac{dI}{d\Omega} \propto (k \cdot P)^2 \]
Elihu’s Polarimeter – Physical effects

• Photoelectric absorption
  – Efficiency \( \sim 0.03 \) at 20 keV

• Scattering in the detector
  – Energy loss and angle change via multiple scatters

• Tagging the signal
  • Scintillator tags 9 keV Cu-K photon

• Distribution of tracks
  – Angular resolution provided by an electron collimator

\[
\frac{dI}{d\Omega} \propto (k \cdot \vec{p})^2
\]
Elihu’s sensitivity

Elihu’s estimated detector rate is \(~0.3\) ct/sec for 1 Crab source. (assumes 5 cm aperture)

If

\[ S > B, \]
\[ \mu > 0.1 \]

Polarization of the Crab nebula could have been detected in a few hours
TPC Polarimeter Concept

- Drift direction is perpendicular to X-ray propagation so efficiency is decoupled from other considerations
- One dimensional images using strip readout
- Pixels are formed by time projection, coordinates [arrival time, strip location]
- Drift height determined by collimation of beam
Gravity and Extreme Magnetism Small Explorer Concept

• The Time Projection Polarimeter is the heart of the Gravity and Extreme Magnetism Small Explorer
  • Currently in Phase B
  • Launch in 2014
• Rotation of three-axis stabilized spacecraft for low false modulation due to instrumental systematic error
• Full sky visibility; ~300 sources accessible, each for ~8 weeks every 6 months
• Straightforward operations concept
• 9 month program of 35 targets
• No consumables, lifetime ≥ 2 yr
Benefits of Rotation

- Simulations with $10^6$ photons/run ($\mu \sim 0.5$, MDP < 0.01) show the power of spacecraft rotation
- **PROCEDURE**
  - Generate photons
  - Move photon E-field into detector frame
  - Generate photoelectron direction with $\cos^2(\phi)$ distribution
  - Distort (by stretching) one axis
  - Measure the distorted direction
  - Map the photoelectron direction back onto the sky
- **RESULTS**: Spacecraft rotation removes the effects of detector asymmetries
Black holes bend x-rays and rotate the polarization according to their spin.

How the image of the disk would look if we could resolve the image for a black hole with high spin.
GEMS will open the frontier of X-ray polarimetry

- GEMS will open a brand-new window on the sky.
- Polarization in the X-ray band is essentially unexplored: the polarization of only *one* object outside the solar system has been previously detected.
- GEMS will be ~100x more sensitive than any previous instrument and will be able to study well dozens of objects.
- *Discoveries* are expected from black holes, neutron stars, supernova remnants.

**Targets with known fluxes and polarization estimates**

- Black holes
- Neutron stars
- Supernova remnants

![Graph showing polarization vs. flux](image)