The brief but long history of X-Ray Polarimetry

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Tuesday May 24, 2016
Outline

- A look to the past
- The present
- A brief view to the future
In the beginning…..

• July 1968 – Lithium-block, Thomson-scattering polarimeter flown on an Aerobee -150 rocket
  – Target was Sco X-1

Fig. 1. (a) Schematic representation of the polarimeter concept. (b) Mounting of the polarimeter and ancillary equipment in the rocket.
Scattering polarimeter

- Thomson cross-section illustrates the angular dependence

$$\frac{d\sigma}{d\Omega} = \left(\frac{e^2}{mc^2}\right)^2 (\cos^2 \theta \cos^2 \varphi + \sin^2 \varphi)$$

- For scattering from bound electrons one must account for both coherent and incoherent scattering and photoelectric absorption
Thompson Approximation

Cos (polar scattering angle)

Azimuthal scattering angle
Advantages

• Inherently broad band device
  – Astrophysical non-thermal spectra are characteristically broad band
  – Astrophysical diagnostics (model discriminators) should benefit from understanding the energy dependence
Considerations

- Scatter as much incident flux as possible
- Avoid multiple scattering
- Collect as many scattered X-Rays as possible
- Minimize the background
- Achieve as large a sensitivity to polarization as possible
  - Optimize the “MDP” at the 99% confidence level

\[
MDP(\%) = (4.29 \times 10^4 / M(\%)) \sqrt{(R_S + R_B)} / \sqrt{R_S^2 t}
\]
Disadvantage: The Polarimeter Conundrum

- The scattering material should be thick (deep) in order to effectively provide for interaction with all the incident photons.
- The scattering material should be thin (narrow) in order to allow the scattered photon to easily escape.
- Similar conundrums apply as well to other approaches to X-ray polarimetry.
In the beginning….

• March 1969 - Lithium-block, Thomson-scattering polarimeter flown on an Aerobee -150 rocket
  – Target was the Crab Nebula

• February 1971 Lithium-block, Thomson-scattering polarimeter and a Bragg crystal polarimeter flown on an Aerobee -350 rocket
  – Target was the Crab Nebula

• Three rockets in 21 months!
Rocket 17.09

- Two instruments in one payload!
  - Lithium scattering polarimeter
  - 4 Bragg crystal polarimeters
Crystal polarimeter
• 1971 Aerobee 350
  • Crab detection!
    • $P = 15\% \pm 5\%$
    • $\varphi = 156 \pm 10^\circ$
On to the satellite experiment

- 1975 OSO-8 crystal polarimeter
  - Precision measurement of integrated Crab Nebula polarization at 2.6 keV
    - \( P = 19\% \pm 1\% \)
    - \( \varphi = 156^\circ \pm 2^\circ \) (NNE)
Compare to modern detailed optical results

• X-ray polarimeter on the original Einstein mission but removed via descoping
  • Polarimeters amongst the first to go
• X-ray polarimeter built for the original SRG mission … which never launched
• Polarimeters don’t get much observatory time
  • 60 days of observation per year (OSO-8)
  • 11 days of observations per year (SXG)
• X-ray polarimeter selected for the last NASA SMEX mission … but was cancelled
Electron-Tracking Polarimeters

• Optical Imaging Chamber
  • Austin & Ramsey 1992

• Pixelated Gas Multiplication
  • Costa et al. 2001

• Time Projection Chamber
  • Black et al. 2007
• The direction of the *initial* K-shell photoelectron is determined by the electric vector and the direction of the incoming photon

\[
\frac{d\sigma}{d\Omega} = f(\zeta)r_0^2 Z^5 \alpha_0^4 \left( \frac{1}{\beta} \right)^{7/2} 4\sqrt{2} \sin^2 \theta \cos^2 \varphi
\]
Electron-Tracking

Site of initial ionization and Auger electron cloud produced by a 54 keV photon
Electron-Tracking

Austin and Ramsey (1992)
We need to remember that X-ray polarimetry is difficult

- One does not expect all astrophysical systems to be strongly polarized
- Instruments typically not fully sensitive to polarization
- Linear polarization is non-negative – i.e. one always measures something, even for an unpolarized source

Looking to the future
Looking to the future

• **X-ray polarimetry can be powerful – especially if accompanied by high-resolution imaging**

• **X-ray polarimetry typically requires longer observing times than imaging, spectroscopy, and timing**

• **Do not rely on an observatory-class mission**
  • Won’t get the needed observing time
  • Early (if not first) candidate for descoping
• Polarimetry is the study of systematic effects
  • End-to-end calibration of the full system with unpolarized beams to the appropriate precision is essential!

Be careful
A look to the future

• So many missions being planned
  • IXPE (NASA SMEX?) 2020
  • Praxys (NASA SMEX? 2020
  • XIPE (ESA M4?) 2025
  • CHINA
  • JAPAN
  • INDIA