Scatter Angle Distribution in the Hard X-ray Polarimeter XL-Calibur

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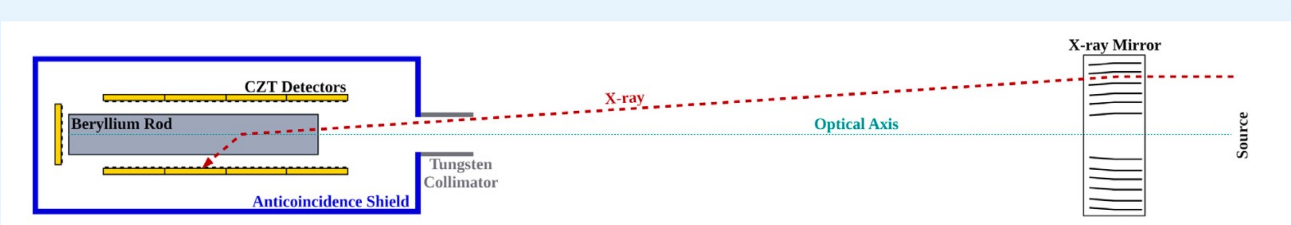
Introduction

XL-Calibur is an X-ray telescope which will analyze black hole and neutron star systems using polarization data, which has information about the geometry (see Fig. 1).

- The polarization of light refers to the amount that oscillating electric and magnetic fields of light waves are aligned with each other. Within a single wave, the electric and magnetic fields are perpendicular. Polarization degree refers to the amount of light which is polarized, while polarization angle is the angle 90˚ from the scattering angle.
- The angle at which the light scattered is perpendicular to the polarization angle.

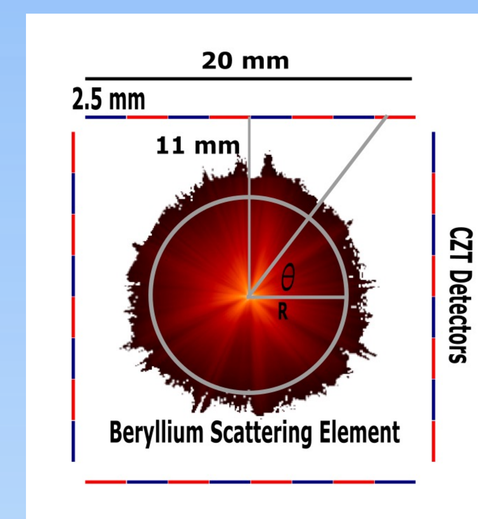
[Figure 1]: XL-Calibur, highlighting the X-ray mirror, polarimeter, and shield. [1]

- XL-Calibur has a detector that measures polarization at the focus of an X-ray mirror. The telescope utilizes:
  - A WASP pointing system mounted on a gondola.
  - A 12 m truss attached to the x-ray mirror.
  - A 12 m x-ray mirror which focuses light on the polarimeter.
  - A polarimeter and anticoincidence shield which measure scattering angle (See Fig. 2).

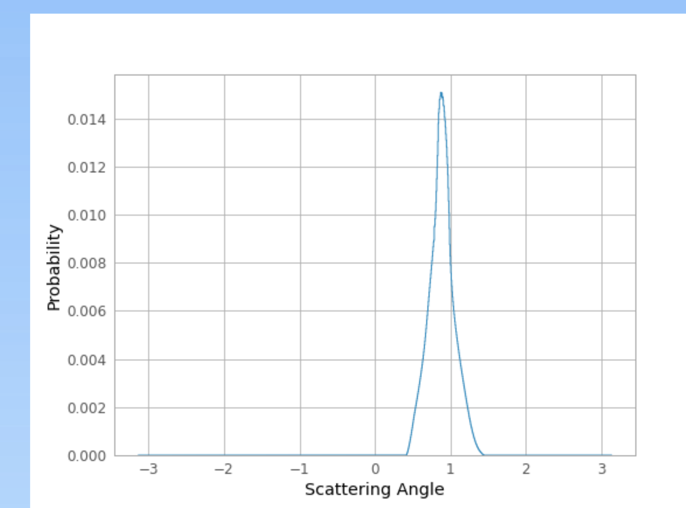


[Figure 2]: Side view of polarimeter and X-ray mirror [2]

- The polarimeter consists of a beryllium scattering rod that is 12 mm in diameter.
- The rod is surrounded with CZT (cadmium-zinc-telluride) detectors containing pixels which detect the photons. There are 8 pixels on each side of the scattering rod.
- When light strikes the beryllium rod (see Fig. 3) it scatters and hits the pixels which detect the light.
- The image overlaid over the geometry is a point spread function (PSF) of where the light hits the rod. The brighter color corresponds to more photons hitting a location (see Fig. 3).
- Based on what pixel is struck, the angle that the light scattered can be calculated.
- This measurement determines the polarization of the light, giving insights into the source.



[Figure 3]: A sketch of the polarimeter facing the beryllium rod (radius 6 mm), with the point spread function overlaid on it. There are 8 pixels on each side of the rod which detect photons.



[Figure 4]: The probability distribution for pixel 1 with a rotation of 0. As expected due to the geometry, the peak is at a little less than 1 radian and is sloped because of the PSF.

- A function that describes the number of photons detected for a given scattering angle is:

$$f(\psi) = \left(\frac{1}{2\pi}\right)\left(1 + p_0\mu\cos\left(2\left(\psi - \psi_0 - \frac{\pi}{2}\right)\right)\right) \text{ [3]}$$

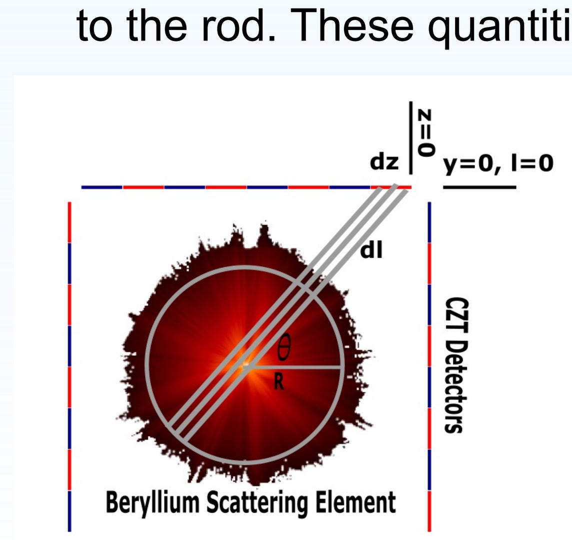
- p_0 is the true polarization fraction, μ is the modulation factor, ψ is the angle orthogonal to the scatter angle, and ψ_0 is the phase constant
- To determine the scattering angle of a photon, one calculates the angle as shown from the center of the scattering element to the pixel which detected the photon.
- When the probability distributions of multiple rotation angle-pixel pairs are shown on the same graph, they form a sinusoidal curve. The angle at which the function is at a minimum is the polarization angle (Fig. 4).

Methods

- This project takes into account that:
  - The light does not always hit the center of the rod.
  - The light does not always hit the middle of a pixel.
  - The telescope rotates while in flight.

Using the coding language Python, a set of possible scattering angles were calculated for every location on the rod, for every pixel, and for every rotation angle.

- The probability of a given scattering angle given a pixel is $p(\phi) = \iint P(x(l,z), y(l,z))\Theta(R^2 - (x(l,z))^2 - (y(l,z)^2) dl dz$ where $x(l,z) = z - l\cos(\phi)$, and $y = y_0 - l\sin(\phi)$
- P is the point spread function, and z is the position on an individual pixel, and l is the distance from that point on the pixel to the rod. These quantities are illustrated in Fig. 5.

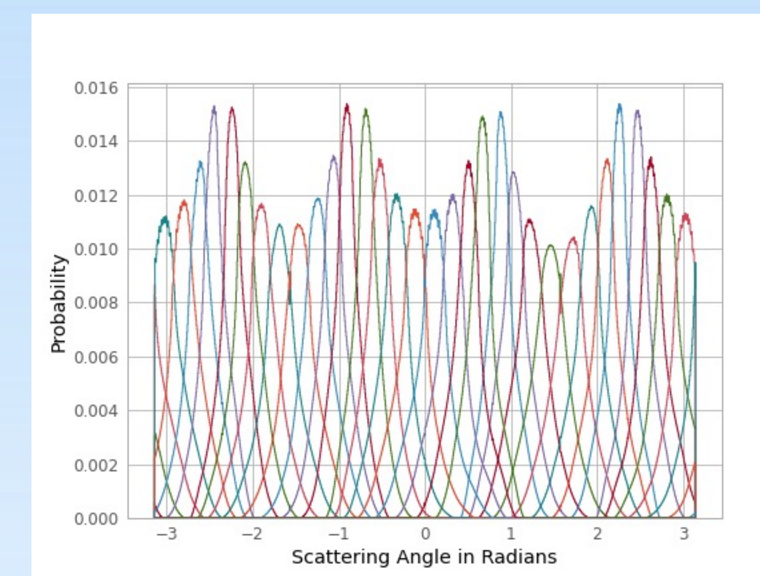


[Figure 5]: A diagram showing the Integration process. z and l are measurements along the pixel and along the path of integration, respectively.

- This is achieved by calculating the scattering angle between the horizontal of the location struck by the light and a given location on a pixel.
- Each angle was multiplied by a weight from the PSF.
- These data were put into a matrix where the scattering angle probability distribution can be found for any pixel and rotation angle combination.

Results

Figure 5 is a histogram showing the probabilities of scattering angle for all pixels and rotation angles.



[Figure 5]: A histogram showing the scattering angle probabilities for all pixels at a rotation of 0˚.

Discussion

- The XL-Calibur will be ready to launch on May 8th, 2024, and will actually be launched in the time window between then and early July.
- The Python program developed will allow more accurate analysis of polarization data collected from the XL-Calibur during its flight because it accounts for the factors stated in the methods section.
- Given a pixel and rotation angle, data can be extracted that shows the probability distribution for that pixel and rotation angle.
- Next steps include running simulations to test the improvement in polarization analysis with these results.

References

[1] M. Aoyagi et al. "Systematic effects on a Compton polarimeter at the focus of an X-ray mirror", Astropart. Phys. 158 (2024) 102944.
[2] Q. Abarr et al. "XL-Calibur – a second-generation balloon-borne hard X-ray polarimetry mission," Astropart. Phys. 126 (2021) 102529.
[3] F. Kislat et al. "Analyzing the data from X-ray polarimeters with Stokes parameters", Astropart. Phys. 68 (2015() 44-51.

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