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STELLAR X-RAY POLARIMETER POLARIZER DEVELOPMENT AND CALIBRATION AT LEA/LLNL

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ABSTRACT

A large area thin graphite crystal and a lithium scattering block are used as the polarization sensitive elements of the Stellar X-Ray Polarimeter (SXRP). We discuss the construction, selection and characterization of these two polarizing elements. In addition, we describe the plans for calibration of the completed instrument and the facility where it will be conducted.

1. INTRODUCTION

The Stellar X-Ray Polarimeter (SXRP) is a focal plane instrument for one of the SODART telescopes on the Spectrum X-Gamma Mission which is currently scheduled for launch in late 1995. Most aspects of the spacecraft, telescopes and other focal plane instruments are described elsewhere in these proceedings and in previous papers.¹ In this paper we describe the contributions made to SXRP by the Laboratory for Experimental Astrophysics (LEA) of the Lawrence Livermore National Laboratory (LLNL). In particular, construction, selection and characterization of the polarizing elements and plans for calibration of the completed instrument are reviewed.

Figure 1. Schematic representation of the SXRP instrument showing the graphite (A) and lithium (B) polarizers in an x-ray beam with exaggerated divergence. The polarizers are surrounded by four detectors (the fourth detector is rotated out the way for clarity.) The system rotates as shown about the axis of the x-ray beam.

A simplified view of SXRP is shown in Figure 1. The converging x-ray beam from the SODART telescope enters at the top of the instrument and encounters two polarizing elements, a thin graphite crystal mounted above a lithium scattering element. The graphite crystal is mounted at 45 degrees to the incoming beam. It reflects 2.6 keV and 5.2 keV x-rays via first and second order Bragg reflection, into one of four imaging proportional counters. The 50 μm thickness of the crystal allows unreflected, higher energy x-rays to pass through to the lithium scattering element mounted below. In the lithium, x-rays may undergo Thompson scattering and can be detected in one of the four detectors. To measure polarization, the entire detector/polarizer assembly is rotated about the x-ray beam axis.

Both Bragg reflection at 45 degrees and Thompson scattering through 45 degrees occur only if the radiation is polarized normal to the plane defined by the trajectory of the radiation. Thus, as one rotates the assembly, a modulation in counts versus angle is obtained at twice the rotation frequency if the incoming x-ray beam is polarized. The amplitude and phase of the modulation are respectively related to the degree and angle of polarization of the incoming beam. The sensitivity of the instrument is proportional to the square root of the number of x-rays detected and has a design goal minimum detectable polarization of 1% for the strongest sources.

2. GRAPHITE POLARIZER

In a previous paper, we provided detailed selection criteria for the graphite crystal.² The primary considerations are integrated reflectivity and uniformity. A high integrated reflectivity is required to maximize the signal observed from continuum astrophysical sources. Uniform integrated reflectivity is required to avoid spurious modulation of the signal introduced by migration of off-axis sources across the crystal during rotation. Similarly, uniform thickness is required so that spurious modulation is not introduced in the higher energy signal passing through the graphite to the lithium scattering block. A proprietary material, "Supergraphite" from Panasonic Corporation,³ was selected from among several samples which were evaluated based on these criteria. Full-size crystals (5 cm x 7 cm) of the material have been obtained and evaluated for incorporation in the engineering model.

2.1. Graphite Evaluation

The crystals are evaluated by measuring the integrated reflectivity and transmission of a monochromatic, 2.7 keV, polarized, x-ray beam at various locations on the crystal face. The beam is generated by reflecting the $L\alpha$ line of a Rh anode x-ray tube off of two Si (111) crystals (at 43 degrees) oriented in the dispersive geometry (see Figure 2).² The beam is collimated after the last crystal by a 1.5 mm diameter aperture and passes through the axis of rotation of the stage holding the graphite crystal. By measuring the reflection coefficient as a function of angle we obtain a "rocking curve," whose area is the integrated reflectivity (see Figure 3). Transmission through the crystal is measured in the same apparatus, but with the crystal normal to the beam.

SXRP is designed to have a limiting sensitivity of 1%. Therefore, we need to determine the degree of modulation due to systematic effects to better than 1%. Variations in both integrated reflectivity and transmission affect the x-ray count rate which is used to determine the polarization during an observation. We thus desire to measure both values to better than 1%. To avoid statistical errors of this magnitude requires that more than 10,000 counts be collected at each crystal location evaluated. To achieve this precision required several days per scan necessitating the need for automated control of the system.

2.1.1. Integrated reflectivity at 2.7 keV

A map of locations scanned and representative rocking curves are shown in Figure 3. The large width of the rocking curves is due to the mosaic nature of the graphite crystals, which consist of many small "perfect" crystallets with crystal plane directions randomly oriented about the peak Bragg angle. This property increases the integrated reflectivity of graphite by increasing the bandwidth of x-rays which can undergo Bragg reflection at a given crystal angle. An x-ray traverses the crystal until it is either absorbed, scattered, or encounters a crystallet at the proper angle to undergo Bragg reflection. Because of the narrow bandwidth of both a single crystallet and the x-ray beam used for the calibration, the rocking curve is a direct measure of the crystallet distribution and is expected to have a Gaussian profile.

Figure 2. Triple axis spectrometer used for evaluation of the graphite crystals. A monochromatic, collimated, polarized x-ray beam is produced with two Si (111) crystals in the dispersive geometry.

Figure 3. Location of measurements on each graphite crystal and representative rocking curves from the indicated locations.

Figure 4. A histogram of integrated reflectivities for one crystal. Values were calculated based on equation (1). Three points falling outside $\pm 3\sigma$ have been omitted.

$\theta_1 = \theta_2$ and $\sigma_1 \neq \sigma_2$.) Others required independent widths and positions (i.e. $\theta_1 \neq \theta_2$ and $\sigma_1 \neq \sigma_2$). The use of equation (1) to fit the crystallet distribution was based on its functional convenience and does not represent any underlying knowledge about the distribution.

In Figure 4 we present a histogram of integrated reflectivities for one crystal. The data does not include three points which fall outside a $\pm 3\sigma$ acceptance window indicating a possible problem in the measurement at those locations. The RMS variation of the remaining 74 points is 3.7%. We believe that a significant fraction of this scatter is due to a correlation in the fit between the background and the peak amplitude and is not inherent to the crystal.

Ideally, one can obtain the integrated reflectivity by numerical integration of the data in the rocking curves so that a fit is not required. Unfortunately, residual scattered radiation contaminated the measurement at the few percent level. The contamination varied as a function of crystal angle and location and could not be removed without data from deep in the wings of each rocking curve. Such data was not collected so that a numerical integration of the peak area could not be used.

Further measurements are planned for the crystals of the flight model. Improvements include additional shielding to reduce scattered radiation reaching the detector and continuing the rocking curve further into the wings to obtain a better background measure. Although a few such curves were collected as a proof of principle, the time pressures of preparing for arrival of the engineering model (which is to be calibrated at LLNL, see Section 4 below) precluded rescanning the crystals for this paper.

2.1.2. Transmission measurements

Transmission measurements for each of the crystals were performed to a statistical accuracy of 1% at the same locations shown in Figure 3. A histogram of the results is presented in Figure 5. The distribution has an average value of 0.2172 with an RMS deviation of 2.1×10^{-3} . These small variations are approximately equal to the statistical precision of the measurement and are evidence of the excellent uniformity of the crystal. They indicate that the graphite will have a minimum effect on the Li polarizer. In particular, the results at 2.7 keV may be scaled to the bottom of the Li energy band at 5 keV using the approximate, small-fluctuation expression:

$$\delta T_{E'} \approx \delta T_E \frac{\lambda'}{\lambda} \quad (2)$$

where the variations in transmission, $\delta T_{E'}$, at a new energy, E' , is related to the variations in transmission, δT_E , at the measured energy, E , by the ratio of the mean free paths λ' to λ . This ratio is 0.15 for 2.7 keV and 5 keV, showing that the variation in absorption at 5 keV is negligible.

To determine the integrated reflectivities, we attempted to fit a Gaussian to the rocking curve at each location using a chi square statistic. The fit results were poor, with an average chi square of 37 for 17 degrees of freedom. A look at the residuals showed that a single Gaussian could not fit both the peak and the wings of the distribution. To improve the fit a double Gaussian of the general form:

$$I = b + i_1 e^{-(\theta - \theta_1)^2 / \sigma_1^2} + i_2 e^{-(\theta - \theta_2)^2 / \sigma_2^2} \quad (1)$$

was tried. This reduced the average value of chi square to 15.2 (15 degrees of freedom) even though all of the additional degrees of freedom of the second Gaussian were not required. The number of free parameters required were different for the individual crystals. In particular, a common amplitude, $i_1 = i_2$, was used for all of the crystals, while a reasonable fit could be obtained by varying only the widths of some (i.e.

$\theta_1 \neq \theta_2$ and $\sigma_1 \neq \sigma_2$).

Figure 6. Cross sectional view of the lithium beryllium assembly. The lithium is pressure-molded into a beryllium flange and mounted in vacuum under a 125 μm thick beryllium can.

2.1.3. Integrated Reflectivity at 5.4 keV

A preliminary scan of one of the crystals in second order at 5.4 keV has also been performed using a modified version of the apparatus. The monochromatic, polarized x-ray beam was formed in two steps using the $K\alpha$ line from a chromium anode. The beam is monochromatized by a first order Bragg reflection from a Si (111) crystal. Since this reflection occurs at 21.4 degrees, it does not produce a well polarized beam. However, it must be used because Si (111) does not reflect in second order. To achieve a beam of known polarization ($\sim 100\%$), a graphite crystal reflecting in second order at ~ 45 degrees is used before the Si crystal. The results of this scan were disappointing, showing an average integrated reflectivity of 5.6×10^{-5} radians, with an RMS deviation of 3.8×10^{-6} radians. However, the scan was run with the same set of parameters used at 2.7 keV and the effects in the wings of the rocking curves seen at the lower energy are exacerbated at 5.4 keV. This is indicated by the $\sim$ four-fold improvement in integrated reflectivity ($\Theta = 2.3 \times 10^{-4}$ radians) obtained from a rocking curve run deeper into the wings with more flux collected at each angle. The issue will be reinvestigated when time permits, following calibration of the engineering model.

2.2. Status of graphite polarizer

We have received a total of 5 full-size crystals from Panasonic. One of these has been placed in reserve untouched. Of the remaining crystals, all show acceptable uniformity and values of transmission and integrated reflectivity. One crystal has undergone vibration testing to acceptance levels with no degradation. Thermal and qualification testing will be performed in the coming year.

3. LITHIUM SCATTERING BLOCK

The lithium scattering block is shown schematically in Figure 6. It is held by a beryllium base which has both a ribbed central post and ribbed walls. The lithium is pressure-molded into the base to ensure a solid mount. To protect the lithium from the atmosphere before launch, it is vacuum sealed within a Be can which has walls 125 μm thick. Evacuation is performed without requiring a pump-out access by assembling the can in a vacuum chamber. A helicoflex metal seal forms an all metal seal between the flange attached to the Be can and the one holding the Li.

3.1. Li/Be Transmission Measurements

Characterization of the lithium polarizer was performed in two steps using the apparatus shown in Figure 7. An Fe^{55} source, collimated with a 2.3 mm diameter hole, provides a beam of 5.9 keV x-rays which passes through the test piece and enters a lithium drifted silicon detector (chosen for its long term stability) through a 3.0 mm diameter aperture. The test piece is mounted on rotation and translation stages so that the beam attenuation can be measured at various points on the piece. As with the graphite, data was collected

Figure 7. Schematic diagram of the apparatus used to characterize the beryllium polarimeter. A collimated Fe^{55} source produces a beam of 5.9 keV x-rays which pass through the diameter of the test piece through a second collimator and into a highly stable silicon detector.

Figure 8. Representative transmission measurements of a Be can taken at 5.9 keV. The results at each distance along the can are averaged over all angles. The error bars represent the RMS spread of the measurements at each distance and are commensurate with the errors expected from counting statistics.

represent the RMS scatter of the different rotations at the given linear points and are commensurate with the 0.15% counting statistics of the measurement, i.e. no structure around the circumference of the can was observed to a wall thickness of $\sim 3.5 \mu\text{m}$. To complete the can measurements a modified version of the apparatus was used to scan the domed end of the can. This showed a mean thickness of $160 \mu\text{m}$ with a maximum deviation of $\pm 0.7\%$.

3.1.2. Li measurements

After assembly, the Li/Be polarizer was scanned to determine the uniformity of the lithium cylinder. A histogram of the results from a scan of the engineering model polarizer is shown in Figure 9A. The Li transmission (corrected for the thickness of the Be walls) is 0.219 with an RMS variation of 2.1%. This corresponds to a Li thickness of 2.913 cm with a $40 \mu\text{m}$ variation. Alternatively, one could view the change in transmission as due to a change in the average density along the diameter of the lithium of $7 \times 10^{-3} \text{ gm/cm}^3$ from the nominal value of 0.534 gm/cm^3 . The data show no systematic variations in the transmission when the results at one angle or one distance are averaged with the other values at the same angle or distance. A sample plot of transmissions averaged over all angles at each distance is shown in Figure 9B. The error bars

Figure 9. Transmission measurements of the SXR polarizer engineering model Li scattering block. A is the cumulative histogram of all points through the diameter of the block. B is the average transmission obtained at each distance along the device. The error bars represent the RMS scatter observed at each distance and are much larger than from counting statistics alone.

to achieve a statistical accuracy considerably better than 1%.

3.1.1. Be can measurements

Using the setup described above, the Be can was scanned through its diameter at 5 mm intervals along its length at each 20 degree interval. A total of three cans were obtained and all show similar properties. In Figure 8, the average transmitted beam (for all angles) is plotted versus position along the can. As can be seen, a maximum variation of $\sim 1\%$ in transmission occurred for the combined two wall thickness. Using a Be density of 1.848 gm/cm^3 , we obtain a single wall thickness of $\sim 156 \mu\text{m}$ which varies by $12 \mu\text{m}$ along the can length. The thickest portion of the can is at the flange end. (This variation in wall thickness agrees with micrometer measurements taken before the x-ray scans.) The error bars

represent the actual RMS scatter of the points at the plotted distance and are much larger than the $\sim 0.5\%$ statistics achieved at each location. A similar scan performed on a Li cylinder as obtained from the vendor before pressure molding, showed RMS variations of only 1.1%. The cause of the increased variation of the pressure-molded sample is uncertain at this time.

3.2. Status of the lithium polarizer

A total of 3 Be cans have been obtained and tested. They all show acceptable properties. A polarizer for the engineering model has been assembled and evaluated as shown above. It is awaiting incorporation into the SXP engineering model. Both thermal and vibration tests are planned on additional models to be made in the near future. In an effort to improve the uniformity of the polarizer, we will look at annealing procedures and modifications to the pressure-molding process currently conducted at room temperature.

4. CALIBRATION OF SXP

Calibration of the SXP engineering model has three primary goals. The first goal is operation of the calibration system in conjunction with the engineering model. By performing a complete calibration on the engineering model, we will reduce the risks associated with and time required to calibrate the flight model. The second goal is measurement of the response of SXP to on-axis polarized and unpolarized x-ray beams, optimized for both the Li and graphite polarizing elements. Measurement with a polarized beam will provide the depth and phase of the modulation curve for each polarizer. The expected strength of the signal from the polarized beam will be useful in verifying system performance. Response of SXP to an unpolarized beam will provide critical information on systematic spurious polarization effects. The third goal of calibration is to provide a detailed map of the instrument response to the converging beam of the SODART telescope. This is accomplished by orienting the rotation-axis of SXP relative to the incoming x-ray beam both in angle and in position.

4.1. Calibration Facility

Calibration of SXP will be conducted at LEA in a facility specially constructed for this purpose. The system is shown schematically in Figure 10, it comprises a 1.5 m diameter vacuum chamber for housing SXP, a beam line and an x-ray source chamber. A particularly desirable feature of this system is that a valve at the main chamber allows the x-ray source to be changed without venting the main chamber and unnecessarily cycling the detector windows of the polarimeter.

X-rays will be generated from either of two locations on the source chamber depending on the polarization properties required. For polarized beams the output of an x-ray tube will be sent through a double crystal spectrometer, which can be configured in either a dispersive (shown) or non-dispersive geometry. The second crystal will be oriented such that the beam passes through an aperture (collimator) to the beam line, with a second aperture at the entrance of the main chamber. The unpolarized x-rays will be provided by commercially manufactured x-ray tubes with toroidal cathode symmetry.⁵ The beam from the tube will pass through the location of the second polarizing crystal, overlapping the geometry of the polarized beam. The

Figure 10 Schematic of the calibration facility. Both polarized and unpolarized x-ray beams can be generated.

Figure 11. Schematic of the gimbal assembly allowing positioning of SXRP relative to the incoming calibration beam.

second crystal is mounted on a kinematic mount and will be removed for unpolarized operation. The particulars for each of the polarized and unpolarized configurations are given in Table I. To monitor the strength of the x-ray beam entering SXRP, a small proportional counter (normalization detector in Figure 10) mounted behind the last beam defining aperture can be remotely moved into the beam.

Throughout the duration of the calibration, SXRP will be mounted in a gimbal assembly shown schematically in Figure 11. This structure allows orientation of SXRP relative to the incoming x-ray beam as shown. The x-y motion will be used to obtain modulation curves with the beam at different locations in the entrance aperture. The angular motions will be used to simulate the converging beam obtained off of the SODART mirrors. To ensure proper thermal conditions for the instrument while it is mounted in the gimbal, thermal conductors will be attached between the mounting surfaces of SXRP and the vacuum chamber.

4.2. Calibration Details

4.2.1. General Considerations

The stated goal of 1% minimum detectable polarization for SXRP requires that systematic modulation errors be known to better than this accuracy. This implies that a minimum of 10,000 counts be acquired at each calibration position, with a preferred value of 100,000 counts. In addition, to avoid systematic errors, it is desirable to obtain several revolutions of the rotating platform during each measurement. The beam size will be set to ~ 2 mm diameter through the choice of apertures which may be changed with a corresponding change in beam flux. Since the point response of the SODART optics will produce an ~ 5 mm diameter spot, this choice of beam size will allow us to sample the response at twice the position resolution of the telescope.

4.2.2. On-axis Beam

Each of the targets will be calibrated with an on-axis beam of polarized and unpolarized x-rays (see Table I). These measurements are straightforward for the Li polarizer but measurement of the graphite is complicated by its narrow energy response. At 45° , the first order Bragg reflection from graphite occurs at 2.610 keV while the 0.5° mosaic spread of the crystal implies a ~ 28 eV bandpass. The Rh $L\alpha_{1,2}$ lines at 2.697 and 2.692 keV fall well outside this band meaning no x-rays will be reflected. To take advantage of the 3000:1 line-to-continuum ratio obtained from the x-ray tube and avoid development of an even weaker broadband polarized x-ray source, we have opted to install a 1.66° shim under the graphite crystal. This is sufficient to satisfy the Bragg condition for the Rh x-rays. However, wobble of the graphite during rotation can take the system out of alignment during portions of the rotation curve, introducing a modulation as the reflectivity of the line varies. The maximum expected wobble is 0.033° which gives a 0.6% spurious modulation (based on a 2 eV width to

Table 1. Source Properties

Polarizer	Source type	Anode	Line	Energy	Crystal	Crystal angle
Lithium	Polarized	Au	$L\alpha$	9.7 keV	LiF (420)	45
	Unpolarized	W	--	4-15 keV		
Graphite	Polarized	Rh	$L\alpha$	2.7 keV	Si (111)	43
	Unpolarized	W	-	2.5-5.6 keV

Figure 12. A shows the relative size and location of the scan location points. The large circle corresponds to the 1.5 cm scan area and the small circles, the location of the 2 mm diameter beam at each of the measurement locations. B shows the planned angular positions (not to scale) for each of the locations in A.

the Rh $L\alpha_1$ line). For the unpolarized measurements we will use a tungsten tube which provides continuum radiation in this energy region (2-6 keV). Since this tube does not have a strong line in this energy band, we avoid the difficulties of spurious modulation due to wobble. This is particularly important in the unpolarized source measurements since we are specifically looking for small spurious modulation factors introduced by the instrument.

4.2.3. Complete scan

In order to fully calibrate the instrument, one must map the response to both off-axis sources and to the converging beam of the SODART telescope. Off-axis sources represent a translation of the source spot on the focal plane. Estimates for the nominal pointing accuracy of the spacecraft range between 1' and 2'. To completely bracket these estimates we will measure the response over an x-y grid of 1.5 cm representing a 3' pointing error. To properly map the response to the ~ 5 mm blur circle of the telescope we sample at half this interval or in 2.5 mm

steps. The proposed map of beams on this circle is shown in Figure 12.

To map the response to the converging beam of the telescope, we will perform multiple measurements at each of the locations indicated in Figure 12. Specifically, the SODART beam converges with a 2° half-angle. We will measure at eight equally spaced locations on cones with half angles increasing by $2/3^\circ$, as shown in Figure 12. To obtain the instrument response at each location, the data from all angles at that location must be combined to simulate the SODART beam. Measurement of the Li target to both the polarized and unpolarized sources of Table I is straightforward.

Measurement of the graphite with the monoenergetic polarized beam is once again complicated by its narrow energy response. Even for the $2/3^\circ$ half angle cone, the beam will fall outside the $1/2^\circ$ acceptance angle of the graphite. This will result in a strong 1ω modulation of the 2ω polarization response curve. It should be noted that the averaged result from all angles should remove this spurious modulation to obtain the true instrument response.

This mode of operation was selected for two reasons. First, as mentioned above, the intensity of continuum sources as currently configured in the calibration facility is reduced by a factor of ~ 3000 below that of line sources. Thus, use of the line source reduces the time required for a complete calibration. Second, this effect is always present, even though it is washed out by the broadband nature of astronomical sources. Therefore, we maintain that this data will be very valuable to properly understand the instrument response, verify that the modeling is accurate, and completely test the data analysis. For calibration of the flight model we will develop a broadband polarized source based on Thompson scattering which will remove these complications.

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