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Calibration of the Stellar X-Ray Polarimeter

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ABSTRACT

The Stellar X-Ray Polarimeter (SXP) will be more than an order of magnitude more sensitive than any previous x-ray polarimeter in the 2-15 keV energy band. The SXP is a focal plane detector for a Danish-Russian SODART telescope, which will be launched on the Russian Spectrum-X-Gamma (SXG) mission. The SXP exploits the polarization dependence of Bragg reflection from a graphite crystal, and of Thomson scattering from a target of metallic lithium.

The SXP flight model (FM) was calibrated at a facility at Lawrence Livermore National Laboratory (LLNL) equipped with polarized and unpolarized x-ray sources producing x-rays in the band pass for the graphite and the lithium scatterers. By adjusting the orientation of the SXP with respect to the incident x-ray beam, it was possible to simulate the converging beam from a SODART telescope and to measure the SXP response to telescope pointing errors. In this paper, we describe the SXP-FM calibration and present results for the graphite polarimeter.

Keywords: Polarimetry, X-Ray Instrumentation, X-Ray Astronomy

1. INTRODUCTION

The SXP measures x-ray polarization using a graphite crystal and a metallic lithium target as polarization analyzers. X-rays reflected or scattered from these analyzers are detected in four Imaging Proportional Counters (IPCs) surrounding the polarization analyzers, as shown in Figure 1.^{1,2} X-rays reflected from the graphite crystal are focused onto a small region of one of the IPCs. The other three IPCs are used to detect x-rays scattered from the lithium target. The polarization analyzers and x-ray detectors rotate about the optical axis of the SODART telescope.

The graphite crystal, oriented at 45 degrees with respect to the optical axis of the telescope, will reflect only those x-rays with energies satisfying the Bragg condition and with electric field vectors lying in the plane of the crystal. The graphite polarimeter is sensitive in two narrow bands corresponding to the first and second order Bragg diffraction peaks at 2.6 and 5.2 keV. A mosaic graphite crystal is used because of its high integrated reflectivity.³ The graphite crystal is very thin (50 microns), allowing the x-rays which do not satisfy the Bragg condition to pass through the crystal with only moderate attenuation in the 5-15 keV lithium band pass (96% transmission at 10 keV).³ This makes it possible to stack the graphite and the lithium analyzers and obtain data from both simultaneously, greatly improving the observing efficiency of the instrument. For both analyzers, the signature

Figure 1: SXP Concept

Figure 2: SXR orientation parameters

of polarization is a count rate modulated at twice the rotation frequency of the instrument (i.e. a "two-omega" modulation).

Measurements to calibrate the SXR-FM were made at LLNL between July 1996 and September 1996. The purpose of the calibration was to measure the SXR response to a converging x-ray beam in order to simulate the situation that will occur in flight when the SXR is at the focus of a SODART telescope. Below, we describe the calibration setup in section 2. In section 3, we explain the motivation for the measurements made to calibrate the SXR. Section 4 contains calibration results for the graphite polarimeter including the response to polarized and unpolarized x-ray beams.

2. CALIBRATION SETUP

The facility used for the SXR calibration included a 1.5 meter diameter vacuum chamber which housed the SXR, a source chamber, and an evacuated beam about 3 meters in length running between the two chambers. Within the vacuum chamber, the SXR was mounted in a gimbal assembly, which allowed for adjustment of the orientation of the SXR with respect to the incident x-ray beam as indicated in Figure 2. The four allowed degrees of freedom are labeled by the parameters W, X, Y, and Z, and the position $W = X = Y = Z = 0$ corresponds to the orientation where the laser beam used during alignment and the SXR rotation axis are aligned. A separate proportional counter, which could be moved in and out of the beamline was placed in the vacuum chamber with the SXR for source intensity normalizations. The SXR calibration facility has been described in detail previously in Silver et al. (1994)⁴ and Ziocck et al. (1993).⁵ This facility was also used for testing the SXR Engineering Model.⁴

The x-ray source could be configured to produce both polarized and unpolarized x-ray beams. Polarized beams were made by reflection of x-rays produced by a modified Henke source from two crystals in a non-dispersive arrangement.^{4,5} The polarized beam, used to calibrate the graphite polarimeter, contained photons in narrow energy bands at 2.6 and 5.2 keV due to two mosaic graphite crystals, which were placed in the source chamber. The (420) crystal plane of LiF was used to produce a polarized 9.7 keV beam for the calibration of the lithium polarimeter. The unpolarized source produced a continuum over the entire SXR band bass (2-15 keV), and allowed for simultaneous graphite and lithium measurements to be made. The beam was formed by collimating the output of a commercial x-ray tube with a toroidal cathode, producing a source with rotational symmetry and hence no polarization ($\leq 1\%$).⁴

3. CALIBRATION MEASUREMENTS

Measurements were made during the SXR calibration to simulate the converging beam of the SODART and also to characterize the effect of pointing errors on the SXR response. We simulated the converging beam of the SODART by rotating the SXR in the W and Z directions. The reflecting surfaces for the SODART telescope are 143 nested thin foil shells. The radius of the inner shell is 82 mm, and the radius of the outer shell is 300 mm. The focal length of the SODART telescope is 8 meters.⁶ Thus, the SXR will receive x-rays from the SODART at angles from 0.587 to 2.148 degrees relative to the rotation axis of the SXR. To characterize the SXR response to the converging SODART beam, we made unpolarized source measurements with the SXR rotation axis at angles of 0.667 degrees, 1.333 degrees, and 2.000 degrees relative to the x-ray beamline. Measurements were also made at these three angles for the lithium polarimeter using the 9.7 keV polarized source. However, for the graphite polarimeter, polarized source measurements were made for 0.667 degrees but not for larger angles since the measured count rate was too low. The low count rate occurs because the polarized source used for the graphite polarimeter only emits photons at discrete energies, and, for large angles, the Bragg resonance condition is not met for these energies. To simulate SODART pointing errors, the SXR is moved in one or both of the two directions perpendicular to the incoming x-ray beam (the X and Y directions marked in Figure 2). The largest pointing error considered was 5 arcminutes, corresponding to a 12 mm displacement. For reference, measurements were also made at $W = X = Y = Z = 0$. In this paper, we focus on the polarized and unpolarized measurements made at $X=Y=0$ for the graphite polarimeter.

Figure 3: Converging beam measurement locations

4. PERFORMANCE OF THE GRAPHITE POLARIMETER

4.1. Polarized source

For the graphite polarimeter, data was acquired using the 2.6 keV polarized source at the seven positions shown in Figure 3. Position 0 corresponds to $W = X = Y = Z = 0$, and Positions 1-6 are equally spaced on a cone with its vertex at $X = Y = 0$ and a half opening angle of 667 millidegrees (mdeg). Modulation curves for each of the seven positions are shown in Figure 4. The azimuth is plotted on the horizontal axis of the modulation curve. The azimuth for a given x-ray detection is determined by the SXR platform azimuth at the time of detection and the position on the IPC where the x-ray is detected. The count rate per bin is plotted on the vertical axis of the modulation curve and is given by the number of x-rays detected in a given azimuthal bin divided by the exposure time for that bin. Background rejection is applied before the azimuthal binning, and a deadtime correction is applied. After background rejection, the background level for the graphite polarimeter is about 0.002 c/s compared to a source count rate of about 10 c/s so background subtraction is not necessary. For the Figure 4 modulation curves, the data is divided into 90 azimuthal bins, and the errors shown are from counting statistics. The two Position 0 modulation curves are from two different acquisitions. During data acquisition, measurements were made with the normalization detector every 190 seconds to characterize any variability in the source flux. These measurements showed that the source count rate was constant to within 1% so no correction has been made for source variation. About 30,000 2.6 keV photons are used for the left hand Position 0 modulation curve, while the right hand Position 0 modulation curve and the curves for Positions 1-6 include about 10,000 2.6 keV photons. The integration time needed to acquire 10,000 2.6 keV photons varies from about 1200 seconds to 2500 seconds depending on the position. The SXR rotation period was set to 120 seconds during data acquisition so each modulation curve is the combination of data from many SXR revolutions.

Figure 4: Polarized source graphite polarimeter modulation curves for Positions 0-6

The function used to fit the modulation curves shown in Figure 4 accounts for the two-omega component from the polarized source and for the fact that the measured count rate depends on whether the Bragg resonance condition is met. This function has the form,⁷

$$f(\phi) = A(1 + \mu \cos 2(\phi - \phi_2)) \exp(-(\theta - \theta_b)^2/2\sigma^2) \quad (1)$$

where A is the scale factor for the fit, μ is the Bragg crystal modulation factor, ϕ_2 is the azimuthal offset for the two omega component, θ_b is the Bragg angle (45 degrees), and θ is the angle between the incoming beam and the normal to the plane of the Bragg crystal. σ is a measure of the width of the Bragg resonance. θ is given by,

$$\theta = \arccos(\cos\alpha \cos\beta + \sin\alpha \sin\beta \cos(\phi - \phi_0 - \delta)) \quad (2)$$

where α is the angle between the SXR rotation axis (Ω in Figure 5) and the normal to the plane of the Bragg crystal (n) and β is the angle between the SXR rotation axis and the incoming x-ray beam (s). ϕ_0 specifies the direction of the offset between the SXR rotation axis and the incoming x-ray beam referenced to the $-Z$ rotation axis so that ϕ_0 and β are related to W and Z according to the equations, $\sin W \cos Z = \cos\phi_0 \sin\beta$, $\sin Z = -\sin\phi_0 \sin\beta$, and $\cos W \cos Z = \cos\beta$. In our case, β , W , and Z are small angles, so these equations can be approximated as,

$$W = \beta \cos\phi_0 \quad \text{and} \quad Z = -\beta \sin\phi_0 \quad (3)$$

Figure 5 clarifies the parameter definitions. In equation 2, δ is a constant phase factor, defined so that the quantity $\phi - \phi_0 - \delta$ is the difference between the azimuthal angles for s and n . It should be noted that if $\beta = 0$, indicating that there is no misalignment between the SXR rotation axis and the incoming x-ray beam, then $\theta = \alpha$, and the exponential term in equation 1 contributes to $f(\phi)$ only as a constant factor. In this case, the shape of the modulation curve is unaffected by the exponential term. This fact is illustrated in the Figure 4 modulation curves since the exponential term does not noticeably distort the two-omega term for the Position 0 modulation curves (where $\beta \sim 0$). However, significant distortion is observed for the other positions where β is far from zero.

Figure 5: Calibration geometry

The parameters σ and δ are determined from measurements made during the calibration. σ is found to be 0.448 ± 0.003 degrees, and δ is 96 ± 2 degrees. The modulation curves shown in Figure 4 were first fit via χ^2 minimization leaving α , β , and ϕ_0 as free parameters. The average of the values of α found from the fits for the seven positions is found to be 44.9527 ± 0.0018 degrees. Since α describes the orientation of the graphite crystal relative to the SXRP rotation axis it must be the same for each position; thus, in the modulation curve fits described below, α is fixed to 44.9527 degrees. It should be noted that the specification for the graphite alignment is 45.000 ± 0.083 degrees so that the value of α found here is well within the specification. After values for β and ϕ_0 were found for each of the modulation curve fits (with α fixed), W and Z were calculated according to equation 3. The W and Z settings used during data acquisition were then subtracted from each of the calculated W and Z values giving ΔW and ΔZ for each modulation curve. The averages of the ΔW and ΔZ values are found to be $\Delta W = 27.1 \pm 4.1$ mdeg and $\Delta Z = 206.7 \pm 4.6$ mdeg, and these values are used when fixing β and ϕ_0 in the modulation curve fits described below. While the value found for ΔW represents a small misalignment, the value for ΔZ is large enough to noticeably affect the modulation curves shown in Figure 4. The relatively large value of ΔZ is probably due to misalignment of the crystals in the source chamber and an offset between the position of the polarized source and the position of the laser used for alignment.

In the fits to the modulation curves shown in Figure 4, there are three free parameters: A , μ , and ϕ_2 , which depend on the flux from the source, the level of source polarization, and the orientation of the source polarization angle, respectively. Since the source is nearly 100% polarized, μ is a measurement of the modulation factor, which is defined as the instrument response to a 100% polarized beam. The values of μ and ϕ_2 found from the fits to the modulation curves are given in Table 1 along with the reduced χ^2 values for the fits. The values of χ^2 range from 0.982 to 1.422 for 87 degrees of freedom (dof) indicating that the fitting function provides reasonably good fits to the data. The average of the values found for μ is $100.0 \pm 0.1\%$, indicating that the modulation factor is near 100%, and the average ϕ_2 value is 94.6 ± 0.1 degrees, which is consistent with the polarization direction.

Table 1: Fit parameters for the fits to the modulation curves shown in Figure 4

Position	μ (Modulation Factor in %)	ϕ_2 (degrees)	χ^2 for 87 dof
0 (left)	100.04 ± 0.15	94.10 ± 0.16	1.203
0 (right)	100.47 ± 0.32	94.87 ± 0.28	1.055
1	100.07 ± 0.23	95.25 ± 0.22	1.422
2	100.02 ± 0.98	94.24 ± 0.50	1.198
3	98.62 ± 0.74	95.27 ± 0.36	0.982
4	99.83 ± 0.21	94.56 ± 0.24	1.170
5	100.51 ± 0.37	94.43 ± 0.31	1.069
6	100.15 ± 0.46	94.49 ± 0.33	1.248

The graphite polarimeter response to a converging beam is measured by adding the count rates for Positions 1-6, and this combined modulation curve is shown in Figure 6. The fitting function accounts for the fact that the modulation curve is a combination of six positions, and can be written as,

$$f(\phi) = A(1 + \mu \cos 2(\phi - \phi_2)) \sum_{i=1}^6 \exp(-(\theta^{(i)} - \theta_B)^2 / 2\sigma^2) \quad (4)$$

where $\theta^{(i)}$ depends on the values of β and ϕ_0 for the i^{th} position according to equation 2. This function gives a reasonably good fit to the data ($\chi^2 = 1.217$ for 87 dof), and the modulation factor is found to be $99.75 \pm 0.11\%$. The Figure 6 modulation curve is similar to the Position 0 modulation curves shown in Figure 4 in that the exponential term does not noticeably distort the two-omega term.

Figure 6: Polarized source graphite polarimeter modulation curve for a converging beam

4.2. Unpolarized source

Data was acquired using the unpolarized source at the seven positions shown in Figure 3. The modulation curve for Position 0 is shown in Figure 7, and the modulation curves for Positions 1-6 are shown in Figure 8. The data is processed as described for the polarized source including background rejection and a deadtime correction. During data acquisition, measurements were made with the normalization detector every 65 seconds to characterize any variability in the source flux. These measurements showed that the source count rate was constant to within 0.35% so no correction has been made for source variation. About 22,000 2.6 keV photons are collected in 1100 seconds for the Position 0 curve, and about 11,000 2.6 keV photons are collected in 550 seconds for each of the other six curves. The SXRP rotation period was set to 80 seconds during data acquisition so each modulation curve is the combination of data from many SXRP revolutions.

Figure 7: Unpolarized source graphite polarimeter modulation curve for Position 0

Figure 8: Unpolarized source graphite polarimeter modulation curves for Positions 1-6

For the unpolarized modulation curves, the fitting function used is the sum of a constant term and the two lowest order harmonic terms ($f(\phi) = a_0 + a_1 \cos(\phi - \phi_1) + a_2 \cos 2(\phi - \phi_2)$). No exponential term representing the Bragg resonance condition (cf. equation 1) is included since the unpolarized source produces an energy continuum. In Figures 7 and 8, the solid lines show the fits to the curves, and the dashed lines are shown at a_0 for comparison. Since the beam is unpolarized, we expect the two-omega level, measured by the parameter a_2 , to be small. The values of the fit parameters obtained are given in Table 2 along with the values of χ^2_ν for the fits. The values of χ^2_ν range from 1.045 to 1.590 for 85 dof. At Position 0, the one-omega level is low, while a significant one-omega level is measured for Positions 1-6. The two-omega levels are consistent with zero for all positions except for Position 2, where the two-omega level is significant at a level of 2.7σ .

Table 2: Fit parameters for the fits to the modulation curves shown in Figures 7 and 8

Position	a_1/a_0 (%)	ϕ_1 (degrees)	a_2/a_0 (%)	ϕ_2 (degrees)	χ^2_ν for 85 dof
0	1.45 ± 0.95	146 ± 37	0.37 ± 0.94	150 ± 79	1.137
1	7.31 ± 1.33	252 ± 10	1.51 ± 1.30	42 ± 26	1.045
2	10.07 ± 1.43	186 ± 8	3.90 ± 1.42	4 ± 10	1.542
3	6.71 ± 1.32	163 ± 11	1.71 ± 1.31	142 ± 22	1.333
4	7.82 ± 1.34	111 ± 10	1.04 ± 1.34	89 ± 37	1.393
5	7.70 ± 1.39	28 ± 11	1.21 ± 1.40	92 ± 33	1.590
6	6.33 ± 1.41	322 ± 13	0.92 ± 1.42	21 ± 43	1.489

Fits have also been calculated to the modulation curves for data taken at Positions 1-6 on cones with a half opening angles of 1333 mdeg and 2000 mdeg. As above, the fitting function used is the sum of a constant term and the two lowest order harmonic terms. The two-omega levels for the 1333 mdeg and 2000 mdeg curves are similar in size to those observed for the 667 mdeg curves with the highest two-omega levels being significant at level of 1.3σ (1.79 ± 1.36) and 2.2σ (2.86 ± 1.31), respectively. However, the one-omega levels for the 1333 mdeg and 2000 mdeg curves are about 14% and 20%, respectively in contrast to the 8% level observed for the 667 mdeg curves.

The one-omega component observed for the unpolarized modulation curves would be produced if the source intensity varies with energy near 2.6 keV. A spectrum which is not flat near 2.6 keV produces count rate modulations since the Bragg energy depends on θ (cf. Figure 5). A modulation produced by spectral variations is expected to be dominated by the one-omega component. However, higher-order components could be significant and will depend on the shape of the energy spectrum. This probably explains why the values of χ^2_ν shown in Table 2 are relatively high. We are presently preparing to make a high resolution energy spectrum of the source used for the calibration in order to improve our understanding of the unpolarized modulation curves.

We combine the count rates from Positions 1-6 to measure the graphite polarimeter response to a converging beam. Figure 9 shows the combined modulation curves for converging beams with half opening angles of 667 mdeg and 2000 mdeg. The function used to fit the modulation curves shown in Figure 9 is the sum of a constant term and the two lowest order harmonic terms. The solid lines show the functional fit to the modulation curves, and the dashed lines show the best fit horizontal line for comparison. The one-omega levels are $1.50 \pm 0.56\%$ and $1.85 \pm 0.54\%$ for the 667 and 2000 mdeg modulation curves, respectively. These levels are similar to the one-omega level for the Position 0 modulation curve shown in Figure 7 ($1.45 \pm 0.95\%$). The one-omega levels are probably different from zero because of small alignment errors (e.g. ~ 100 mdeg) between the beamline and the SXRP rotation axis (s and Ω in Figure 5).

The two-omega levels are $0.55 \pm 0.56\%$ and $0.56 \pm 0.53\%$ for the combined 667 mdeg and 2000 mdeg modulation curves, respectively, while the two-omega level for the Position 0 modulation curve shown in Figure 7 is $0.38 \pm 0.94\%$. Since the sensitivity of the graphite polarimeter is limited by any spurious two-omega level, these two-omega levels indicate that the graphite polarimeter should be sensitive to polarization at the 1% level.

Figure 9: Unpolarized source modulation curves for converging beams with half opening angles of 667 mdeg and 2000 mdeg

4.3. Summary of graphite polarimeter results

The results presented here indicate that the graphite polarimeter functions correctly. Measurements using a polarized x-ray source give a modulation factor of $99.75 \pm 0.11\%$, and measurements using an unpolarized x-ray source indicate that the graphite polarimeter systematic errors should be at or below the 1% level. Comparing the graphite polarimeter response to a converging beam with the response to a single on-axis beam indicates that the response is not significantly affected when the SXR is illuminated by a converging beam.

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