Polarimetry with a soft x-ray spectrometer

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ABSTRACT

An approach for measuring linear X-ray polarization over a broad-band using conventional spectroscopic optics is described. A set of multilayer-coated flats reflect the dispersed X-rays to the instrument detectors. The intensity variation as a function of energy and position angle is measured to determine three Stokes parameters: I, Q, and U. By laterally grading the multilayer optics and matching the dispersion of the gratings, one may take advantage of high multilayer reflectivities and achieve modulation factors over 80% over the entire 0.2 to 0.8 keV band. A sample design is shown that could be used with a small orbiting mission.

Keywords: X-ray, polarimeter, astronomy, multilayer, mirror, grating

1. INTRODUCTION

Although polarization is a fundamental property of electromagnetic radiation, there have been no astronomical measurements of polarization in the X-ray band in over 30 yr. There has been no lack of workable concepts, including simple designs such as the Polarimeter for Low Energy X-ray Astrophysical Sources (PLEXAS) that was proposed by Marshall et al. (2003) to use multilayer-coated mirrors tuned to 0.25 keV as Bragg reflectors.1 An excellent review of the history and prospects for astronomical polarimetry in the 0.1-10 keV band is presented by Weisskopf et al. (2006).2 Weisskopf et al. rightly argue that the PLEXAS design had a narrow bandpass, reducing its attractiveness for astrophysical observations because one expects polarization to be energy dependent, so a wide bandpass is desired.

Marshall (2007;3 hereafter, Paper I) described a method to overcome this limitation by using transmission gratings to disperse in the incoming X-rays. Then, a multilayer-coated reflector would be used to modulate the signal in a way depending on the polarization. Two approaches were suggested. The first was a simple modification of a dispersive spectrometer, such as a grating spectrometer proposed for Constellation-X (Con-X). The second approach was intended to provide a means for obtaining polarimetric data by inserting optics forward of the focal plane of a long focal length telescope such as XEUS.

Similar to one of the approaches suggested in Paper I, this paper is limited to the case where the polarization is determined by measuring spectral intensity along different dispersed spectra. In this case, we consider a configuration that would be appropriate for a small orbiting observatory.

2. A SOFT X-RAY POLARIZING SPECTROMETER

2.1 The Spectrometer

As in Paper I, the approach to this polarimeter design was inspired by a new blazed transmission grating design, called the Critical Angle Transmission (CAT) grating,4 and the corresponding application to the Con-X mission in the design of a transmission grating spectrometer.5 For details of the Con-X mission, see the Con-X web site at http://constellation.gsfc.nasa.gov/. This type of grating can provide very high efficiency in first order in the soft X-ray band. For a spectrometer, one places detectors on the Rowland torus, which is slightly ahead of the telescope’s imaging surface.

As in the design for Con-X, using a sector of the primary allows one to take advantage of the asymmetric scattering profile of the mirror surfaces. As noted by Cash (1987,6 and references therein), the scattering profile is much broader in the plane that contains the optical axis (radially away from the mirror surface) than in the azimuthal direction. Thus, the images produced using a small sector of the mirror will be narrow in one dimension

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and broad in the other. By arranging the gratings so that the dispersion direction is along the direction of tight imaging, one obtains better spectral resolution than if the entire aperture was used. We exploit this feature to provide modest spectral resolution in each of many sectors.

There are several factors involved in setting the telescope focal length: the grating period, \( P \); the mirror imaging size (in one dimension), \( \delta \theta \); and the shortest wavelength of interest, \( \lambda_{\text{min}} \). For a given focal length, \( F \), and placing the gratings at, say, 0.9\( F \) from the polarizer, we find that the spectral resolution is given by \( \delta \lambda / P_0 \). For this study, we target a spectral resolution of \( \sim 200 \) at the shortest wavelengths of interest, near 1.5 nm (0.8 keV), so that we may obtain a spectral resolution that is \( > \times 2 \) better than that provided by the multilayer coatings. This criterion gives \( \delta \theta = 14^\circ \) in one dimension for a spectrometer using gratings with \( P = 1000 \text{ Å} \). The mirror half-power diameter can be 4-10\( \times \) larger than this value, due to the larger in-plane mirror scattering. Thus, mirrors with average imaging of order 1-2\( \times \) would be acceptable for this project.

The system focal length is set only by the requirement that the detector pixels are at least \( \times 4 \) smaller than the spectral resolution element, \( F \delta \theta \). For 25\( \mu \) pixel sizes, then \( F > 1.5 \text{ m} \), so the telescope can be very short. Effective area is a premium in polarimetry, due to the expected low polarization signals, so the mirrors should have the largest diameter possible. For a graze angle of 1\( ^\circ \), needed to reflect 0.8 keV X-rays off Al mirrors at > 90% efficiency, the mirror diameter could be 28 cm for \( F = 2 \text{ m} \). Assuming an inner diameter of 10 cm and an average reflectivity to two reflections of about 70%, the effective area of the mirror would be about 200 cm\(^2\).

### 2.2 The Polarizer

A CAT-based spectrometer becomes a polarimeter by placing multilayer-coated flats on the Rowland circle that redirect and polarize the spectra. The flats are tilted about the spectral dispersion axis by an angle \( \theta \). For this study, the graze angle \( \theta \) is 40\( ^\circ \). The detectors are then oriented toward the mirrors at an angle 90 – 2\( \theta \) = 10\( ^\circ \) to the plane perpendicular to the optical axis of the telescope. Fig. 1 shows how the optics might look. In this case, the entrance aperture is divided into seven sectors, with gratings aligned to each other in each sector and along the average radial direction to the optical axis. This approach generates seven spectra that are reflected by seven polarizing flats to seven detectors.

The multilayer spacing, \( d \), on the polarizing flats would vary laterally (along the dispersion) in order to provide optimal reflection at graze angle \( \theta \). Such optimization is obtained by equating the wavelength from the linearized grating equation, \( m\lambda = P_x / D_R \), to that of a multilayer, \( \lambda = 2d\sin \theta \), giving

\[
d = \frac{P_x}{2mD_R \sin \theta},
\]

where \( x \) is the distance along the dispersion from 0th order, \( D_R \) is the Rowland diameter (the distance between the gratings and the usual detector plane), and \( m \) is the grating order. Thus, the multilayer period varies linearly with \( x \), providing high reflectivity in a narrow bandpass at large graze angles. For a given order, the spectrometer’s gratings direct a narrow bandpass to any given position on the flat, so the bandpass of the multilayer can be similarly narrow. The bandpass of the multilayer decreases approximately as 1/\( N \) for a large number of layers, \( N \), so if the spectrometer has a resolution better than 200, say, then \( N \gtrsim 100 \). Large \( N \) also improves the multilayer reflectivity.

At Brewster’s angle, \( \theta = 45^\circ \), reflectivity is minimized when the \( E \)-vector is in the plane containing the incident ray and the surface normal (\( p \)-polarized) and maximized when the \( E \)-vector is in the surface plane (\( s \)-polarized). The polarization position angle (PA) is the average orientation in sky coordinates of the \( E \)-vector for the incoming X-rays. Sampling at least 3 PAs is required in order to measure three Stokes parameters (I, Q, U) uniquely, so one would require at least three separate detector systems with accompanying multilayer-coated flats. For this study and for the sake of redundancy, seven detector-flat combinations are assumed.

Following Marshall et al.\(^7 \) and Paper I, the intensity \( I_\lambda \) at wavelength \( \lambda \) varies with azimuthal angle \( \phi \) as

\[
I_\lambda (\phi) = I_\lambda^{0} \left\{ \frac{1}{2\pi} + P_0 \cos (2(\phi - \varphi_\lambda)) \right\},
\]

(2)
Figure 1. Left: View from the entrance aperture of a mirror with seven sectors. Gratings are placed behind the mirror with the grating bars oriented along the average radius to the mirror axis. The gratings then disperse X-rays in the directions given for sectors a and e, as shown (lettering proceeding clockwise from the top central sector). The gratings are blazed, so the directions to the orders with highest efficiency are shown for two sectors. Right: The view above the detectors and polarizers. Spectra from the gratings are incident on multilayer-coated flats that are tilted along the dispersion axis which contains the zeroth order (dot in center). The angle of the tilt is the same for all mirrors and always redirects the X-rays to the adjacent detector in a clockwise direction. The mirror assembly would appear something like a pinwheel. The detectors are tilted in the opposite direction – always oriented counterclockwise, to face the corresponding mirror. For a mirror graze angle of 40°, the detector normals would be 80° from the optical axis. Mirrors a and b receive X-rays from the corresponding sector shown in the left side of the figure and all zeroth order light converges to the spot at the center for an on-axis source. For polarized X-rays with an electric vector as shown, the intensity at a given wavelength can vary from detector to detector, as shown schematically here. In this case, long wavelengths at the perimeter are highly modulated with position angle while short wavelengths, closer to the optical axis, are not modulated at all, simulating a wavelength-dependent polarization fraction.

where $I^0_\lambda$ is directly related to the I Stokes parameter of the source as a function of wavelength $\lambda$, $P^0_\lambda$ is the polarization fraction at this wavelength, $\varphi_\lambda$ is the phase determined by the orientation of average polarization $E$-vector on the sky (i.e., the polarization PA), and $M_\lambda$ is the average system modulation factor. The modulation factor is a function of wavelength, given by $M = \frac{R_s - R_p}{R_s + R_p}$, where $R_s$ and $R_p$ are the reflectivities for the s and p polarizations, respectively. The Stokes Q and U parameters can be derived from $P_0$ and $\varphi$ as a function of wavelength as long as there are three or more position angles that do not differ from each other by 180°.
2.3 System Throughput and Sensitivity

Using the Center for X-ray Optics web page (http://henke.lbl.gov/optical_constants/multi2.html), multilayer efficiencies were computed for a small range of materials for the relevant graze angle. For this work, \( N \) was set to 200 and the interdiffusion thickness was set to 0.3 nm, as has been achieved by several groups.\(^8\)\(^-\)\(^10\) Table 1 gives a sampling of the results, where \( r \) is the peak reflectivity to unpolarized X-rays. The thickness of the first material is 0.4\(d\), while that of the second material is 0.6\(d\) for each calculation. All modulation factors are larger than 85%.

<table>
<thead>
<tr>
<th>( \lambda ) (nm)</th>
<th>( E ) (keV)</th>
<th>( d ) (nm)</th>
<th>( r )</th>
<th>( M )</th>
<th>Materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.61</td>
<td>0.77</td>
<td>1.25</td>
<td>0.013</td>
<td>0.939</td>
<td>W/Si</td>
</tr>
<tr>
<td>1.80</td>
<td>0.69</td>
<td>1.40</td>
<td>0.025</td>
<td>0.939</td>
<td>Ni/Mg</td>
</tr>
<tr>
<td>1.93</td>
<td>0.64</td>
<td>1.50</td>
<td>0.039</td>
<td>0.941</td>
<td>Ni/Mg</td>
</tr>
<tr>
<td>2.06</td>
<td>0.60</td>
<td>1.60</td>
<td>0.081</td>
<td>0.925</td>
<td>Ni/Mg</td>
</tr>
<tr>
<td>2.57</td>
<td>0.48</td>
<td>2.00</td>
<td>0.094</td>
<td>0.915</td>
<td>Ni/Mg</td>
</tr>
<tr>
<td>3.09</td>
<td>0.40</td>
<td>2.40</td>
<td>0.106</td>
<td>0.913</td>
<td>Ni/Mg</td>
</tr>
<tr>
<td>3.15</td>
<td>0.39</td>
<td>2.45</td>
<td>0.258</td>
<td>0.856</td>
<td>Cr/Sc</td>
</tr>
<tr>
<td>3.99</td>
<td>0.31</td>
<td>3.10</td>
<td>0.128</td>
<td>0.990</td>
<td>Cr/Sc</td>
</tr>
<tr>
<td>4.37</td>
<td>0.284</td>
<td>3.40</td>
<td>0.123</td>
<td>0.903</td>
<td>Cr/Sc</td>
</tr>
<tr>
<td>4.63</td>
<td>0.268</td>
<td>3.60</td>
<td>0.232</td>
<td>0.884</td>
<td>C/Cr</td>
</tr>
<tr>
<td>7.71</td>
<td>0.161</td>
<td>6.00</td>
<td>0.123</td>
<td>0.902</td>
<td>C/Cr</td>
</tr>
</tbody>
</table>

For the purposes of this analysis, a CCD detector is assumed to have a thin Al overlayer to act as an optical blocking filter. The resulting effective area is shown in Fig. 2, along with the modulation factor, \( M \).

The effective area estimate can be used to predict the minimum detectable polarization\(^2\) (MDP) for potential targets. As described by Marshall et al.,\(^1\) extragalactic sources such as the BL Lac object PKS 2155−304 are expected to be highly polarized in the X-ray band. In a 100,000 s observation of PKS 2155−304, this instrument could detect polarizations of 3−7% in each of four bandpasses 1 nm wide from 2 to 6 nm (0.21 to 0.62 keV). Fig. 3 shows the results graphically. In addition, isolated neutron stars such as RX J0720.4−3125 are expected to polarized due to effects of photon propagation in strong magnetic fields.\(^2\) In this case, it is worthwhile to obtain phase-resolved polarization data. In a 200,000 s observation with this instrument, one could reach MDPs of 5−8% over the 2−5 nm band (in 1 nm wide bands) for each of 10 phase bins.

There are many combinations of elements and multilayer coating parameters that were not investigated for this preliminary study, so one might expect to improve upon the multilayer-coating reflectivities. It may be possible to superpolish the substrates to obtain 0.1 nm roughness,\(^1^1\) which would increase reflectivities significantly.

3. A TEST AND CALIBRATION FACILITY

Drs. R. Heilmann and N. Schulz are currently working to fully recommission the X-ray grating evaluation facility (X-GEF), a 17 m beamline that was developed for testing transmission gratings fabricated at MIT for the Chandra project.\(^1^2\) In addition to plans to test CAT and other types of gratings, we have proposed to add equipment to the facility so that it may be used for testing and calibrating components that could be used in a soft X-ray polarimeter. Fig. 4 shows how it might appear when operational.

Equipment to be added to X-GEF would include a new X-ray source with multilayer coated optics to produce highly polarized X-rays at each of five X-ray emission lines (see Table 2), a grating rotation stage to simulate telescope rotation, and a multilayer mirror and CCD combination acting as the polarimeter. The detector and its associated mirror would be mounted on a rotation stage to match the rotation of the grating so that the polarization modulation factor can be measured. The detector’s multilayer-coated mirror is challenging to fabricate but two vendors have provided quotes.
Figure 2. Top: The effective area of a small mission, to unpolarized light. The effective area of the broad-band mirror is assumed to be 200 cm$^2$. Bottom: Polarization modulation factor as a function of energy across the bandpass of the instrument. For this design, the modulation factor is always above 85%.

Table 2. Polarization Source Emission Lines

<table>
<thead>
<tr>
<th>Emission Line</th>
<th>Energy (keV)</th>
<th>Multilayer Spacing (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C-K</td>
<td>0.277</td>
<td>3.165</td>
</tr>
<tr>
<td>Ti-L</td>
<td>0.452</td>
<td>1.940</td>
</tr>
<tr>
<td>O-K</td>
<td>0.525</td>
<td>1.670</td>
</tr>
<tr>
<td>Cr-L</td>
<td>0.573</td>
<td>1.530</td>
</tr>
<tr>
<td>Fe-L</td>
<td>0.705</td>
<td>1.244</td>
</tr>
</tbody>
</table>
Figure 3. Minimum detectable polarization as a function of energy across the bandpass of the instrument for two different possible observations. The solid line shows how we could detect linear polarization at a level of 15-20% across the entire energy band from 0.2 to 0.8 keV for PKS 2155-304 in 100 ks. For RX J0720-31, spectroscopy allows one to obtain the polarization below, in, and above absorption features.
Figure 4. Schematic of the MIT 17 m beamline after proposed modifications for soft X-ray polarimetry prototyping. Items in red would be added to the system. The SMDs are source monitor detectors – proportional counters that view the associated Manson Model 5 source (M5). The X-ray beam is shown in light purple; a new source would be used with the polarized source multilayer (PSML) angled at 45° to pass polarized X-rays. The bottom two views are subject to detailed mechanical design and stage dimensions. The dispersed, first order X-rays go to the detector multilayer optic, angled at 45° to the incoming X-rays. The CCD faces the multilayer optic on a translation table that moves the CCD to the location appropriate to the dispersion by the grating (Table 2). The CCD stage and its associated multilayer optic are mounted on a platform and can be rotated ±180°.
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