The Use of Laterally Graded Multilayer Mirrors for Soft X-ray Polarimetry

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ABSTRACT

We present continued development of laterally graded multilayer mirrors (LGMLs) for a telescope design capable of measuring linear X-ray polarization over a broad spectral band. The multilayer-coated mirrors are used as Bragg reflectors at the Brewster angle. By matching to the dispersion of a spectrometer, one may take advantage of high multilayer reflectivities and achieve modulation factors near 100%. In Phase II of the polarimetry beam-line development, we demonstrated that the system provides 100% polarized X-rays at 0.525 keV (Marshall et al. 2013). In Phase III of the polarimetry beam-line development, we installed an LGML in the source to polarize a wide range of energies between 0.15 and 0.70 keV (Marshall et al. 2014). Here, we present results from continued development of the LGMLs to improve reflectivity in the band of interest, a blazed reflection grating that is suitable for a small flight instrument, and a new detector with a directly deposited optical blocking filter. We also present updated plans for a suborbital rocket experiment designed to detect a polarization level of better than 10% for an active galactic nucleus.

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

1. INTRODUCTION

We continue our investigation and laboratory work to develop a soft X-ray polarimeter based on Bragg reflection from multilayer-coated optics. Marshall (2007\textsuperscript{1}) described a method using transmission gratings to disperse the incoming X-rays so that the dispersion is matched to laterally graded multilayer (ML) coated reflectors. Some potential scientific investigations that would be possible with a soft X-ray polarimeter were described earlier and include testing the synchrotron nature of quasar jet emission and models of neutron star atmospheres.\textsuperscript{2,3}

Laboratory work was initiated in order to demonstrate polarization measurements using gratings and laterally graded multilayer coated mirrors (LGMLs) for eventual use in a flight design. In Paper I,\textsuperscript{4} we described our first polarization measurements with the MIT Polarimetry Beamline, where we modified an existing grating test facility to polarize X-rays at 0.525 keV and measure the polarization angle. In Paper II,\textsuperscript{5} we reported on the beginning of Phase III, where we replaced the source ML coated mirror with a LGML. With the LGML in place and a linear-drive manipulator, we showed that the source could reflect X-rays at two different energies, 0.451 keV (Ti-\(\kappa\alpha\)) and 0.277 keV (C-\(\kappa\alpha\)) by driving to the location on the LGML. The LGML is set at 45° to the incoming X-rays so that the system can polarize different (selectable) energies and the attached motor drives the source and attached manipulators in order to rotate the polarization angle about the axis of the beamline. Here, we describe continued progress of our development work involving new LGMLs and modifications to the beamline. Further development of a design for a suborbital rocket flight is given in §3, comparable to that described in Papers I and II. The experiment’s minimum detectable polarization (MDP) is expected to be better than 10% when observing a bright blazar such as Mk 421.

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2. POLARIMETRY BEAMLINE DEVELOPMENT

Fig. 1 shows the current polarimetry beamline as viewed from the X-ray source end. Due to the termination of the lease for the floor occupied by the facility for over twenty years, the beamline was moved to a newly leased floor of an adjacent building, designated NE83. In June and July 2014, the parts for the system were disassembled, cataloged, and reassembled by a team of students with professional support. The move required a few weeks to level the beam pipes and chambers and to test electronics and compressed air connections. (Compressed air is used to actuate the gate valves. At one point, the pressure was found to be too low to reliably operate one of the large gate valves, requiring an enhancement of the building supply.)

2.1 Alignment

Most of the time required to verify the new arrangement was spent on alignment. While good results were obtained at a specific rotation angle (Paper II), the system throughput varied significantly with rotation, unsuitable for polarimetry work. To improve the alignment procedure, we made two significant changes to the system. First, we set up a laser on an optical bench at the detector end of the beamline. The laser is attached to several manually operated stages in order to orient the beam very accurately both in pitch and yaw as well as horizontally and vertically.
Figure 2. Improvements to the polarimetry beamline. *Left:* A new backside illuminated CCD detector is added to the system. It is an early example of a CCD with a directly deposited optical blocking filter. *Right:* A student (CR) tests a new counterweight system. The counterweight is an LN$_2$ dewar holding lead shot in order to provide a torque on the 5-way cross to which the X-ray source and mirror manipulators are attached. The counterweight provides a torque that can compensate for that exerted by the 30 kg source in order to avoid misalignments due to twisting.

Next, we found that the LGML manipulators required extra torque from the rotation motor and this torque was not sufficiently aligned with the system axis, so the shaft onto which the LGML was mounted would twist slightly as the source was rotated. A student set up a simple counterweight to provide torque that would substantially nullify the torque caused by the off-axis source mount. The counterweight system (see Fig. 2) works very well to reduce misalignments due to unbalanced torques.

### 2.2 Detector System Upgrade

As reported in Papers I and II, the detector consisted of a frontside illuminated CCD based on versions used for the *Chandra* ACIS and *Suzaku* XIS detectors. The optical blocking filter was required, similar to that used on the XIS, with 100 nm of polyimide coated with 120 nm of Al. In 5 yr of operation of the polarimetry beamline two filters were damaged due sudden depressurization as pumps failed. In 2014, the second filter merely had a small tear at one end that could be blocked with mylar. However, in July 2014, when the second filter failed catastrophically, we replaced the CCD was replaced with a new backside illuminated CCD with a directly deposited Al filter. This detector is of the same type being used for the REgolith X-ray Imaging Spectrometer (REXIS), an experiment on OSIRIS-REx. Details of the CCDS to be used on REXIS were reported by Ryu et al. (2014$^6$). Briefly, the detector format is similar to the *Chandra* backside illuminated CCDs, with $1024 \times 1024$ pixels that are $24 \mu$ on a side. The Al filter is 220 nm thick. The CCD package was mounted onto the same structure as was used for the previous CCD, retaining the electronics and cooling lines. A picture of the detector is shown in Fig. 2.
Figure 3. Comparison of ALS results for the new (red curves) and old (green curves) W/B₄C LGMLs. The new LGML achieves better reflectivity with fewer layers and significantly improves reflectivities in the 38-45 Å region.

2.3 New LGMLs

With funding from the NASA Astrophysics Research and Analysis (APRA) program, we will soon move to Phase IV, where the goals are 1) to improve the reflectivities of LGMLs by trying new material combinations and 2) show that a grating-LGML combination can measure polarization over wide range of energies, thus prototyping a design that could be used for a flight system. See Paper II for a schematic of the Phase IV configuration.

We have begun work to improve LGML reflectivities using different ML compositions for specific wavelength regions. Figure 3 shows results from testing at the Advanced Light Source in Berkeley, CA. The new W/B₄C LGML significantly improves reflectivity in the 38-45 Å region. New LGMLs of La/B₄C were also made to improve reflectivity longward of 66 Å. Fig. 4 shows the resulting reflectivities measured at the ALS for three different material combinations that provide the best reflectivity for three different wavelength ranges. Note that the ALS beam is polarized at the 70% level in this energy range.

2.4 New Diffraction Gratings

Two new grating development programs were started in order to improve the efficiency of gratings for a small polarimetry mission where the spectral resolution power is not as in high demand as for a large mission. See Fig. 5 for an image of a prototype reflection grating developed at a rather small cost in the MIT Space Nanotechnology Laboratory. This reflection grating has a 15° blaze, designed for high reflectivity at 35 Å, and a 200 nm period, suitable for high dispersion in a small telescope system. The dispersion of a 200 nm period can match the gradient of our existing LGMLs when placed at a distance of 1.6 m, well within the size limitations of a suborbital rocket program. We have designed a mount to place the grating into our system (which was designed for transmission gratings) and it is in the process of fabrication. For our purposes, a spectral resolution power of order 300 is sufficient (to be narrower than that of the LGML Bragg peak) so many aspects of the design can be relaxed.
Simple high resolution etched Si gratings, similar to critical angle transmission (CAT) gratings\(^7\) are also in development. We have one prototype that has been mounted but not yet tested in the beamline. Testing gratings is straightforward with the polarimetry beamline, as we merely move the X-ray source to a downstream portion of the small pipe (left side of Fig. 1) and use it in a direct mode. The grating chamber has motorized and manual slits and the grating mount is a vertically oriented X-Y stage with rotation about the vertical axis, so these are used in combination to move slits and gratings to obtain specific wavelengths in dispersion on the immobile detector. This approach was demonstrated to be feasible with spare gratings from the *Chandra* project.

### 3. A SOFT X-RAY POLARIZING SPECTROMETER

The basic design of a polarizing spectrometer was outlined by Marshall (2008\(^8\)). For this paper, we examine the approach using CAT gratings\(^7\) that could be applied to a suborbital rocket experiment. Figure 6 shows a possible schematic and some solid body models of the detector vacuum box. Sampling at least 3 position angles is required in order to measure three Stokes parameters (I, Q, U) uniquely, so one would require at least three separate detector systems (one of which could be just for 0th order) with accompanying multilayer-coated flats or that the rocket rotate during the observations (which is expected anyway, to take out systematic effects).

The system design consists of a mirror system with an assumed effective area of 500 cm\(^2\) below 1 keV, backside-illuminated CCD detectors with thin directly deposited optical blocking filters, and CAT gratings blazed to maximize efficiency at 300 eV. For multilayer coating reflectivities, we used values for LGMLs that we have tested. The effective area estimate can be used to predict the minimum detectable polarization (MDP) for a potential target. Extragalactic sources such as the BL Lac object Mk 421 are expected to be highly polarized in the soft X-ray band. We use the same expected spectrum as assumed in Paper I. In a 300 s observation of Mk 421, the MDP would be 4.9%.
Figure 5. Scanning electron microscope image of a prototype reflection grating. The grating period is 200 nm, the groove angle is 15°, blazed for highest efficiency at about 35 Å. The groove profile has a short flat section at top but is otherwise smooth.

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Figure 6. Top: Schematic of a suborbital soft X-ray polarimeter using critical angle transmission (CAT) gratings. Top left: View of the grating mount, where blazed gratings are oriented approximately azimuthally and in sectors. One sector is vacant for illustrative purposes. Top right: Top and side views of a focal plane layout that could be used for a suborbital rocket experiment, in the manner suggested by Marshall (2008). The prime detector receives X-rays that do not intercept the grating modules. The zeroth order is placed at the location of the dot so that the dispersed spectrum first intercepts the laterally graded multilayer mirror that is angled at 45° to the incoming X-rays. In the side view, the dispersion is perpendicular to the plane of the drawing and the multilayer mirror is oriented 45° to the incoming, dispersed X-rays. Bottom: Two views of the detector vacuum box, without the door.
