Soft X-ray Polarimetry

An instrument concept presented to NASA in response to the Request for Information on "Concepts for the Next NASA X-ray Astronomy Mission"

(Solicitation Number NNH11ZDA018L)

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1 Overview

The NASA Request for Information (RFI) concerning concepts for the next NASA X-ray astronomy mission asks for papers on instrument concepts and enabling technology. Report 3, on "Galaxies Across Cosmic Time," in the NRC's "New Horizons in Astronomy and Astrophysics" study concludes that it is **important** to develop X-ray polarimeters for the study of black hole accretion disks and jets. This paper addresses that need with a development path to incorporate polarimetry as an integral part of future missions at a relatively small additional cost and weight.

Some of the science questions to be addressed by the original IXO design (from table 1 of the RFI) may be addressed with polarization measurements:

- "What happens close to a black hole?" Jet emission is expected to be polarized at a position angle and fraction that depend on how ordered the magnetic field is and whether relativistic shocks drive the emission of X-rays (§2.2).
- "When and how did supermassive black holes grow?" New studies indicate that SMBH mass and spin may be determined using polarization measurements across the 0.1-10 keV band (§2.3).
- "How does matter behave at very high density?" Neutron star atmospheres are expected to be polarized and the amplitude and position angle depends on details of the magnetic field geometry and photon transport through the atmosphere (§2.4).

Dispersive X-ray spectrometers using gratings have been used on the *Einstein*, *Chandra*, and XMM-Newton X-ray observatories to great success, based on technically sound principles. Our approach to provide polarization information relies on Bragg reflection from multilayer-coated flat mirrors added to a dispersive spectrometer with large collecting area. While we have specifically examined a case involving Critical Angle Transmission (CAT) gratings, our design is flexible enough to be used with other designs such as one based on reflection or off-plane gratings. Multilayer coatings have been used in several NASA missions, including TRACE and NuSTAR and are well developed for commercial use. The coatings for a soft X-ray polarimeter would be constructed to reflect the dispersed spectra at large grazing angle (e.g., 35°) where the reflectivity will be sensitive to the polarization of the incident X-rays. The multilayer spacing is varied linearly along the mirror, which is also along the dispersion direction, so that the peak of the coating's reflectivity is matched to the spectrometer's dispersion. With three or more orientations of the dispersion as projected on the sky, three of the four Stokes parameters may be measured as a function of wavelength: I, Q, and U.

Although tens of thousands of X-ray sources are known from the ROSAT all-sky survey, polarization studies were carried out only in the 1970s and were limited to the brightest sources. In over 40 years, the polarization of only one source has been measured to better than 3σ: the Crab Nebula[27,39]. Even for bright Galactic sources, the polarizations were undetectable or were marginal $2-3\sigma$ results[13,14,32]. Furthermore, over the entire history of X-ray astronomy, *there has never been a mission or instrument flown that was designed to measure the polarization of soft X-rays*. Because of the lack of observations, there has been very little theoretical work to predict polarization fractions or position angles but there has been some recent progress with the prospect of a small explorer, the Gravitation and Extreme Magnetism SMEX (GEMS)[34]. GEMS will carry a student experiment designed to operate in a narrow band centered at about 0.5 keV. This experiment employs a multilayer coating deposited on a thin plastic membrane to deflect polarized X-rays to a proportional counter and the signal is modulated as the telescope rotates. While similar to our approach (and based loosely on an earlier design of ours[22]), our proposed design provides a broadband response at several position angles simultaneously, obviating a previous objection to Bragg reflection designs.[38]

2 Science of Soft X-ray Polarimetry

2.1 X-ray Polarimetry as a Growth Field

In X-ray binaries and active galactic nuclei (AGN), accretion onto a compact object (collapsed star or massive black hole) is thought to be the basic mechanism for the release of large amounts of energy in the X-ray band. X-ray radiation is polarized when the production mechanism has an inherent directionality, such as when electrons interact with a magnetic field to make synchrotron emission, which can be up to 65% polarized. The observed degree of polarization can depend on the source geometry, the spacetime through which the X-rays propagate, and the strength of local magnetic fields. Two white papers (co-authored by the PI) were submitted to the 2005 Strategic Roadmap process on how X-ray polarimetry can contribute to NASA's long-term scientific and technical goals in the Universe division and one was submitted for the 2010 decadal review of astronomy by the National Academy of Sciences. X-ray polarimetry is listed as a priority for 21st century space astronomy in the NRC report entitled "Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century".

Polarization studies in the optical and radio bands have been very successful. Radio polarization observations of pulsars provided "probably the most important observational inspiration for the polar-cap emission model"[35] developed in 1969[30], critical to modelling pulsars and still widely accepted[35]. Tinbergen (1996)[36] gives many examples in optical astronomy such as: revealing the geometry and dynamics of stellar winds, jets, and disks; determining binary orbit inclinations to measure stellar masses; discovering strong magnetic fields in white dwarfs and measuring the fields of normal stars; and constraining the composition and structure of interstellar grains. Perhaps the most important contribution of optical polarimetry led Antonucci and Miller (1985)[1] to develop the seminal "unified model" of Seyfert galaxies, a subset of AGN. Their paper has been cited in over 1000 papers in 250 years, over 5% of all papers ever written about AGN. Thus, the extra information from polarimetric observations has provided a fundamental contribution to the understanding of AGN.

Here we describe a few potential scientific studies to be performed with an X-ray polarimetry mission with sensitivity in the 0.1-1.0 keV band.

2.2 Probing the Relativistic Jets in BL Lac Objects

Blazars, which include BL Lac objects (e.g. PKS 2155−304), high polarization quasars, and optically violent variables are all believed to contain parsec-scale jets with $\beta \equiv v/c$ approaching 0.995. The X-ray spectrum is much steeper than the optical spectrum, indicating that the X-rays are produced by the highest energy electrons, accelerated closest to the base of the jet or to shock regions in the jet. The jet and shock models make different predictions regarding the directionality of the magnetic field at X-ray energies: for knots in a laminar jet flow it should lie nearly parallel to the jet axis[16], while for shocks it should lie perpendicular[17]. McNamara et al. (2009)[25] determined that X-ray polarization data could be used to deduce the primary emission mechanism at the base, discriminating between synchrotron, self-Compton (SSC), and external Compton models. Their SSC models predict polarizations between 20% and 80%, depending on the uniformity of seed photons and the inclination angle. The X-ray spectra are usually very steep so that a small instrument operating below 1 keV can be quite effective. There is no prediction as of yet regarding the polarization dependence with energy, so any observations below 1 keV would complement those at higher energies in driving theory.

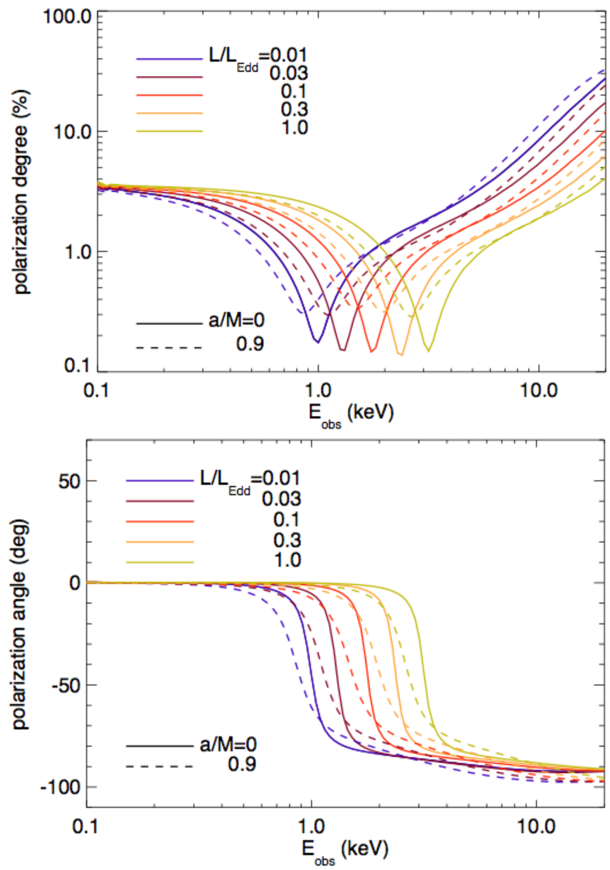

Figure 1: *A prediction of the variation of the polarization percentage (top) and its position angle (bottom) as a function of energy for AGN with varying spin, a/M, and Eddington ratio, L/L_{Edd}[31]. Such studies are just underway due to the prospect of obtaining polarization data at high energies using GEMS. However, the figures show that predictions depend strongly on energy. Observations with a multilayer-based polarimeter working in the 0.1-1.0 keV range would complement those by GEMS.*

2.3 Polarization in Disks and Jets of Active Galactic Nuclei and X-ray Binaries

X-ray emission from accretion onto black holes may arise from Compton scattering of thermal photons in a hot corona or from synchrotron emission or Comptonization by electrons in a highly relativistic pc-scale jet. Jets are frequently observed from quasars and X-ray binaries, so the X-rays should be polarized. In both cases, the origin of the jet is not resolved in the X-ray band, so X-ray polarization measurements can give an indication of the existence and orientation of jets within 1000 gravitational radii. Transients with stellar-mass black holes like XTE J1118+480 can be very soft and jets may contribute most of the X-rays[15] that could be confirmed using polarimetry. UV observations above the 13.6 eV Lyman edge of 10–20% polarizations in active galaxies stand as a challenge to theorists[11,12] and indicate that X-ray polarizations could be higher than observed optically.

Recent theory work indicates that AGN accretion disks and jets should be 10-20% polarized[25,31] and that the polarization angle and magnitude should change with energy in a way that depends on the system inclination. Schnittmann & Krolik (2009)[31] particularly show that the variation of polarization with energy could be used as a probe of the black hole spin and that the polarization position angle would rotate through 90° between 1 and 2 keV in some cases, arguing that X-ray polarization measurements are needed both below and above 2 keV (fig. 1). As Blandford et al. (2002) noted "to understand the inner disk we need ultraviolet and X-ray polarimetry"[2].

2.4 Pulsars and Low Mass X-ray Binaries

Isolated neutron stars should be bright enough for potential soft X-ray polarimeters. Spectral features in the soft X-ray spectrum of RXJ 0720.4-3125 indicate that it may have a magnetic field strong enough that there should be a proton cyclotron line at about 0.3 keV[7]. If so, this neutron star may be a "magnetar". These unusual neutron stars are thought to be powered by the decay of enormous magnetic fields (10^{14}–10^{15} G). These fields are well above the quantum critical magnetic field, where a particle's cyclotron energy equals its rest mass; i.e. $B = m^2c^3/e\hbar$ (=4.4×10^{13} G for electrons). In these ultrastrong magnetic fields, peculiar and hitherto unobserved effects of quantum electrodynamics (QED) are predicted to have a profound effect on the X-ray spectra and polarization that can be tested with soft X-ray polarimetry.

Measuring the polarization of the radiation from magnetars in the X-ray band will not only verify the strength of their magnetic fields, but also can provide an estimate of their radius and distance and provide the first demonstration of vacuum birefringence (also known as vacuum polarization), a predicted but hitherto unobserved QED effect[9,10]. This effect arises from interactions with virtual photons when X-rays propagate in a strong magnetic field. Photons with E-vectors parallel to the magnetic field are impeded more than those with orthogonal E-vectors. The effect is small until the photon propagates through a distance sufficient to rotate the E-vector – $\sim 10^6$ cm. The extent of polarized radiation from the surface of a neutron star increases by up to an order of magnitude when QED propagation effects are included in the calculation. Polarization increases with the strength of the magnetic field and decreases as the radius increases so compact neutron stars are predicted to be highly polarized, $> 80\%$[8]. The polarization phase and energy dependence can be used to measure the magnetic field and the star's radius[8].

Detailed models of less strongly magnetized neutron star atmospheres show that the polarization fraction would be 10-20% at 0.25 keV averaged over the visible surface of the star[29]. Examples in Fig. 2 demonstrate a variety of

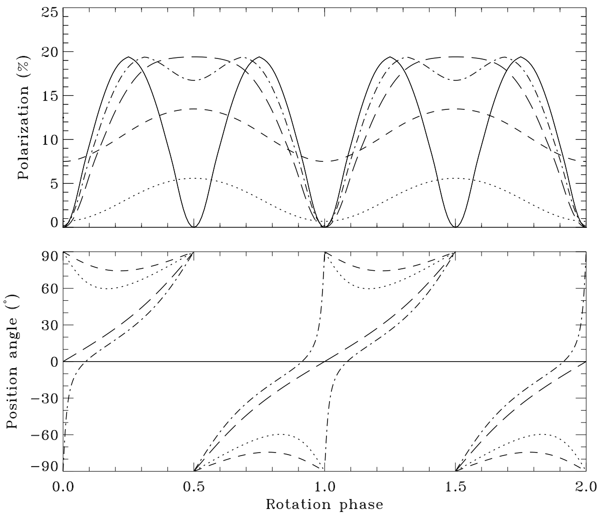

Figure 2: *Predicted phase dependences of the polarization fraction and the position angle for a magnetized neutron star with a temperature of* 10^6 *K*[28]*. The curves correspond to different combinations of the viewing angle* ζ *and magnetic inclination* α*:* 90° *and* 90° *(solid),* 45° *and* 45° *(long dash),* 56° *and* 60° *(dash-dot),* 40° *and* 10° *(short dash),* 16° *and* 8° *(dots). The polarization and position angle depend very sensitively on the orientation of the neutron star spin and the magnetic axis.*

the soft-X-ray polarization patterns. We can constrain not only the orientation of axes, but also the M/R ratio for the thermally emitting neutron stars due to gravitational light bending. With increasing M/R, the gravitational bending of photon trajectories enables us to see a greater fraction of the back hemisphere of the neutron star, which depolarizes the surface-averaged radiation and changes the shape of the polarization pulse profiles. Constraining M/R, impossible from the radio polarization data, is extremely important for elucidating the still poorly known equation of state of the superdense matter in the neutron star interiors. We note that these isolated neutron stars do not produce significant flux above 2 keV, so polarimeters with significant effective area in the 0.1 to 1.0 keV band will be needed to test polarization predictions from neutron star atmospheres.

2.5 Magnetic Cataclysmic Variables

A recent study predicted that the linear polarization of CVs should be as high as 8%[24]. The X-ray emission arises from accretion onto the polar cap and is polarized via Compton scattering in the accretion column; those photons exiting the column near the base are less polarized than those that scatter several times in the column before exiting. Thus, the polarization is sensitive to the density structure in the accretion column and should vary with rotation phase.

2.6 Future of Soft X-ray Polarimetry

The author has been working on soft X-ray polarimetry concepts using multilayer-coated optics for over 15 years, starting with a very simple design[18] emulating an experiment performed using the Extreme Ultraviolet Explorer[23]. Several missions have been proposed to NASA programs based on this approach. One example was the Polarimeter for Low Energy X-ray Astrophysical Sources (PLEXAS) that was proposed to the low cost NASA "University" Explorer program. Marshall et al. (2003)[22] showed that an orbital version of this design can be used to observe over 100 sources per year to detect polarizations of order 5%. The proposal resulted in a category 3 award for technical development funding.

Other proposals have been met with the criticism that a design based on multilayer coatings would have a limited bandpass.[38] We now have a new design that overcomes this weakness that we are working to prototype in the laboratory. Marshall (2007)[19] showed that it is possible to develop a multilayer-coated optic that combines with a dispersive optic to obtain a broad bandpass, when combined with an imaging X-ray mirror assembly. Simple approaches were suggested by Marshall (2008, 2010;[20],[21]) that can be used with large facilities such as those planned to replace IXO carrying dispersive spectrometers. Thus, we now have a potential development path for soft X-ray polarimetry from Explorer-class missions (such as Pharos[6]) up to and including major X-ray astronomical facilities planned by NASA. Potential applications of the technology to be developed under this proposal are discussed in a bit more detail in section 5.

3 Technical Approach

For the past several years we have been working on prototyping our design. We have an X-ray beamline that can produce unpolarized and polarized X-rays in order to test critical components that could be used in a future soft X-ray polarimetric detector. There are three essential elements of the design: 1) a high efficiency transmission grating to disperse X-rays, 2) a laterally graded multilayer-coated mirror, and 3) a soft X-ray imager comprised of charge coupled devices (CCDs). Of these elements, only the multilayer mirror has not yet been flown successfully. Thus, the concept and technology plan is to obtain multilayer-coated mirrors that can be used to produce and analyze polarized X-rays and assemble these into an existing X-ray beamline. This work builds on an existing, approved technology development project funded by the MIT Kavli Institute (MKI) to start up, develop, and test the source of polarized X-rays.

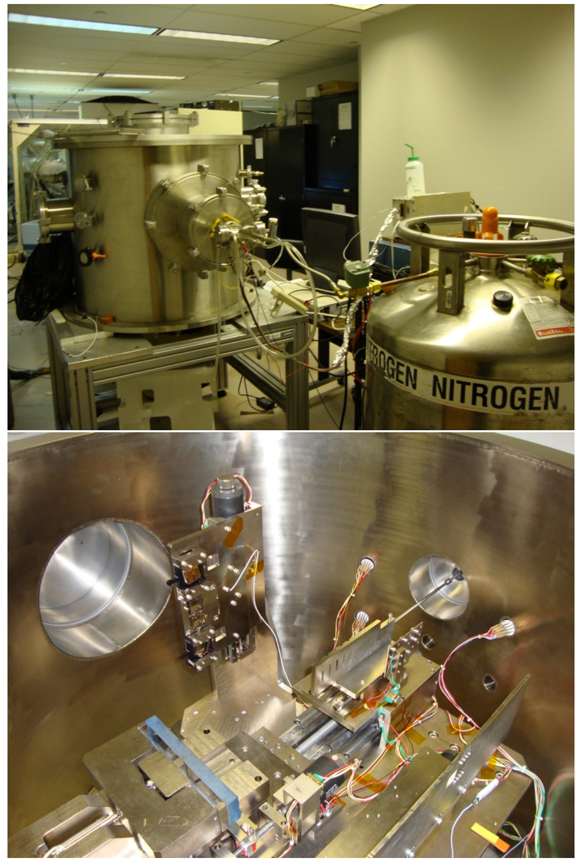

Figure 3: *Pictures of the inside of the grating chamber (right), and the back end of the detector chamber and LN_2 supply tank (left) of the 17 m X-ray beamline in building NE80 at MIT.*

3.1 Existing Facilities, Personnel, and Equipment

We take advantage of decades of experience developing X-ray instruments and laboratory experiments at MIT and existing infrastructure. The foundation of the polarization lab is a 17 m beamline developed for testing transmission gratings fabricated at MIT. Over the past two years, we have purchased, installed, and aligned a polarizing X-ray source that operates at 0.525 keV on funding from an MKI Instrumentation grant. There are flight-like transmission gratings already mounted in the beam-line and many spares that can be used for this project. At the source end of the beamline is one of a matched pair of multilayer optics from Reflective X-ray Optics (RXO) for use in creating polarized X-rays. We have an X-ray sensitive CCD, associated electronics for the detector, and the other multilayer mirror needed to modulate the signal. We have class 1000 clean rooms and electronics assembly areas, clean boxes, and an in-house machine shop. MIT scientists and engineers with decades of lab and flight instrumentation experience have also been involved. In addition, undergraduates from MIT, Colgate, and UNH have worked in the polarimetry lab, so we are providing future

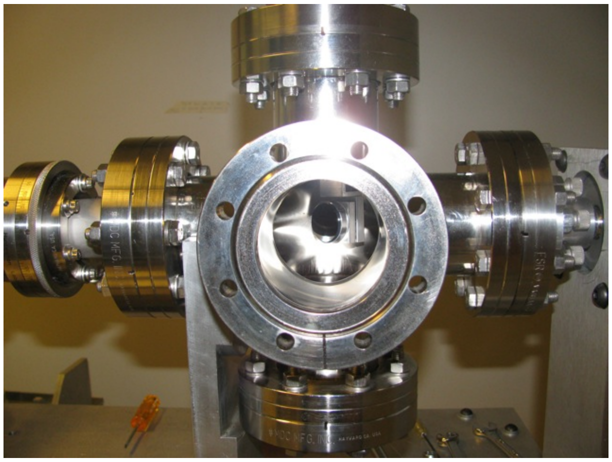

Figure 4: *The polarizing source multilayer mirror. The X-ray source is normally attached to the flange facing the camera.*

engineers and scientists with opportunities for hands-on experience.

3.1.1 The NE80 X-ray Beamline

The construction of the 17 m beamline was funded by the *Chandra* project[37]. The X-ray efficiencies of each grating facet used in the High Energy Transmission Grating (HETG) were measured at the beamline in MIT's building NE80[3]. These gratings were assembled at NE80 into the HETG assembly and flown in 1999 aboard the *Chandra* X-ray Observatory. The calibration of the gratings used in the HETG was described in detail by Dewey et al. (1994)[5].

Pictures of two beamline chambers are shown in Fig. 3. The inside diameter of the main pipe is 28 cm. At 8.7 meters from the source, the X-rays are collimated either by a slit or square aperture to produce a narrow beam. Gratings can be positioned in the beam within a 1m diameter chamber at the midpoint of the beamline. Further along the system 8.67 meters from the grating there were two detectors in another chamber about 0.8 m in diameter that were used to measure the diffracted X-rays from the gratings under test. The original detectors have since been replaced by an X-ray CCD, running ASTRO-E2 (*Suzaku*) breadboard electronics.

3.1.2 A Polarized X-ray Source

The source of X-rays is a Manson Model 5 multi-anode source. A rotating flange allows the source to rotate about the ML mirror (Fig. 4) so as to rotate the direction of polarization about the beam direction. See Fig. 5 for a view of the source at two different rotation angles. The ML mirror coating was designed so that it reflects s-polarization X-rays at 0.525 keV (O-K) when used at Brewster's angle.

Multilayer coatings consist of thin layers of contrasting materials - usually one with a high index of refraction and the other with a low value. The input wave is divided at each layer into transmitted and reflected components. When many layers are placed on a surface, then the reflected components may constructively interfere, enhancing the overall reflectivity of the optic. The Bragg condition must be satisfied: $\lambda = 2D\sin\theta$, where $D = d_a + d_b$ is the thickness of the bilayer consisting of one layer of material A with thickness d_a, and one layer of material B with thickness d_b; λ is the wavelength of the incident radiation; and θ is the graze angle. When used at Brewster's angle, $\theta = 45°$, the reflectivity of p-polarization is reduced by orders of magnitude, so that nearly 100% of the exiting beam is polarized with the $E-$vector perpendicular to the plane defined by the incoming and outgoing beams. Fused silica substrates for the source optics have have surface roughness less than 1Å rms.

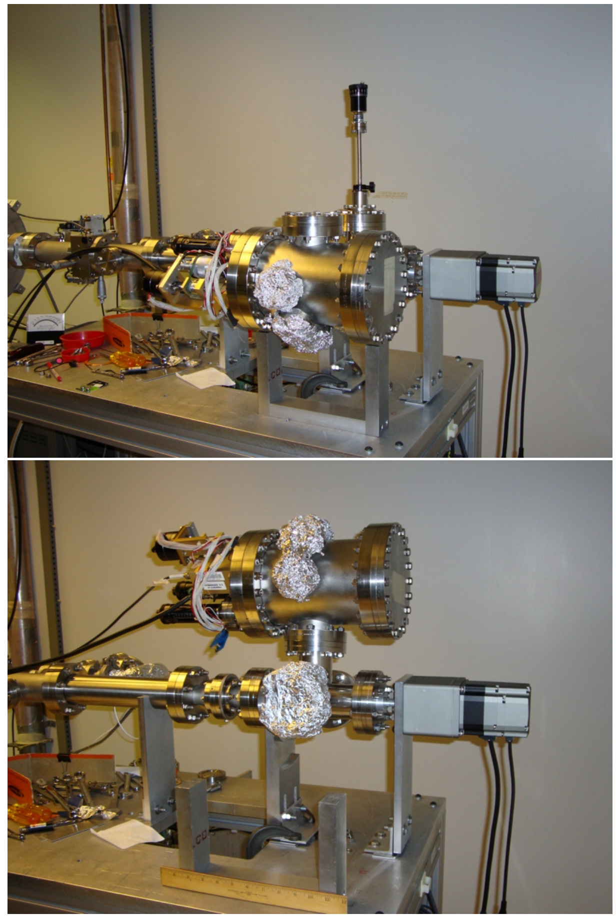

Figure 5: *The source of polarized X-rays in two orientations. In the top picture, the X-ray source is positioned above a safety stand and the manual mirror alignment knob is visible at top. In this orientation, the X-rays reflected down the beamline to the left are polarized in a direction parallel to gravity. In the bottom picture, the source has been rotated by 90° to orient the polarization direction parallel to the table top. Foil covers the viewports to eliminate optical light leaks. The motor at right drives and holds the source at commanded orientations*

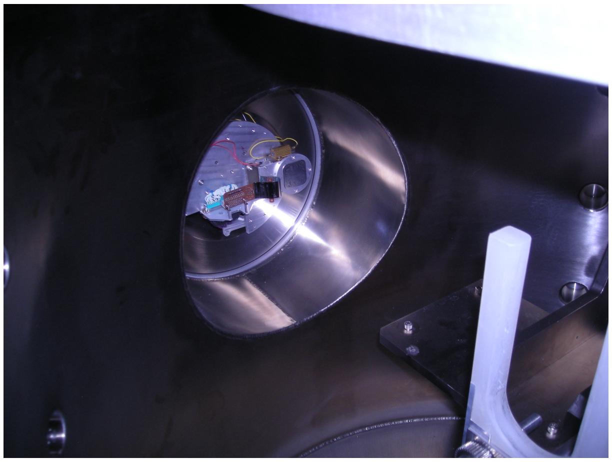

Figure 6: *The CCD detector inside the detector chamber. In this configuration, the CCD faces the incoming beam and will not be sensitive to polarization.*

3.1.3 Detector subsystem

The dispersed, first order X-rays go to the detector multilayer optic. The sensor, a front-side illuminated CCD (Fig. 6), faces the multilayer optic. The optic is mounted on a rotational stage that can adjust the graze angle of the detector ML coated mirror relative to the incoming X-rays (see Figure 7).

The multilayer optic is the critical component of the detector subsystem. For a prototype instrument that is more like what can be proposed for a flight instrument (see Section 5), we would have to obtain a flat, polished substrate about 75 mm by 25 mm. For this mirror, the multilayer D spacing will be constant along the short direction but will vary linearly along the long dimension, in order to match the dispersion of the grating, when given the distance from the mirror to the grating. For use at 45° and a distance of 8.6 m, the D spacing will change by 0.46 Å/mm. Such a coating is feasible for RXO and Rigaku's optics group. RXO has produced a laterally-graded multilayer coating for a previous project.

3.2 The X-ray Polarimetry Lab

In this section, we describe the configuration of the laboratory as it will be needed for further soft X-ray polarimetric instrument prototyping and testing. Figure 7 shows a schematic of the resultant system.

We are about 80% through our first phase, funded from an MKI Instrumentation grant. We have a matched pair ML coated mirrors to polarize the O-K lines from the X-ray source. The coatings consist of 200 layers, each with 5.04 Å of W and 11.76 Å of B_4C, achieving a peak reflectivity to polarized X-rays of 5.0%. The reflectivity of the band is narrow, approximately matching the O-K natural line width. Our most recent tests verified that the alignment of the aperture and grating stages is accurate

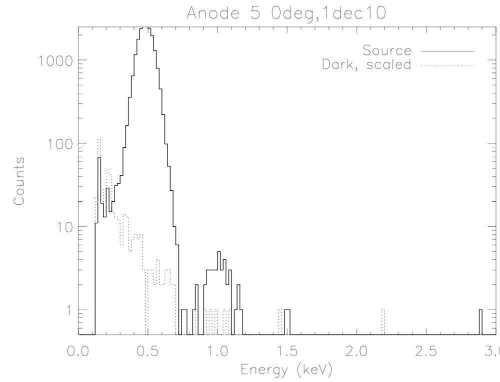

Figure 8: *Data from a 160 s run of the beamline. The source was run at a voltage of 5 kV and a current of 0.1 mA. The PSML mirror properly passes only O-K photons, found here at a peak energy of 0.50 keV, before correction for gain drift. The background is very low and one can see a weak pileup peak at 1.0 keV. An Al-K line from fluorescence of Al in the system is observed at 1.5 keV. The detector is imaging the PSML directly without gratings or detector ML mirror; about 130 count/s were observed in this test.*

and stable. We operated the CCD detector in direct view of the source and with the ML mirror. We verified that the ML mirror passes O-K line photons with the expected efficiency; see Fig. 8, which shows results from one of our experiment runs. We have solved certain problems of alignment and repeatability that were reported at the 2010 SPIE meeting[26].

3.2.1 Development Plans

The most important change to the lab would be to procure and mount a laterally graded multilayer coated mirrors in the detector chamber and remount the CCD on a translation stage. We would then begin a series of component tests.

The primary tests that a prototype polarimeter should satisfy relate to its sensitivity and modulation factor. For a flight polarimeter the figure of merit is the minimum detectable polarization MDP (as a fraction): MDP $= n\sqrt{2(R+B)/T}/(\mu R)$ where n is (approximately) the number of sigmas of significance desired; R is the source count rate; B is the background count rate in a region that is the size of a typical image; T is the observation time; and μ is the modulation factor of the signal relative to the average signal for a source that is 100% polarized. As usual, it is important to have low background, which necessitates focussing optics and low noise sensors in order to study faint targets. Sensitivity of the system figures into the computation of the count rate, so MDP drops as $R^{-1/2}$ for low B. More important, however, is that the MDP varies inversely with the modulation factor, μ, so a polarimeter must discriminate well between photons of the perpendicular polarizations. Our multilayer-based approach gives $\mu = 1$ if the detector multilayer optic is

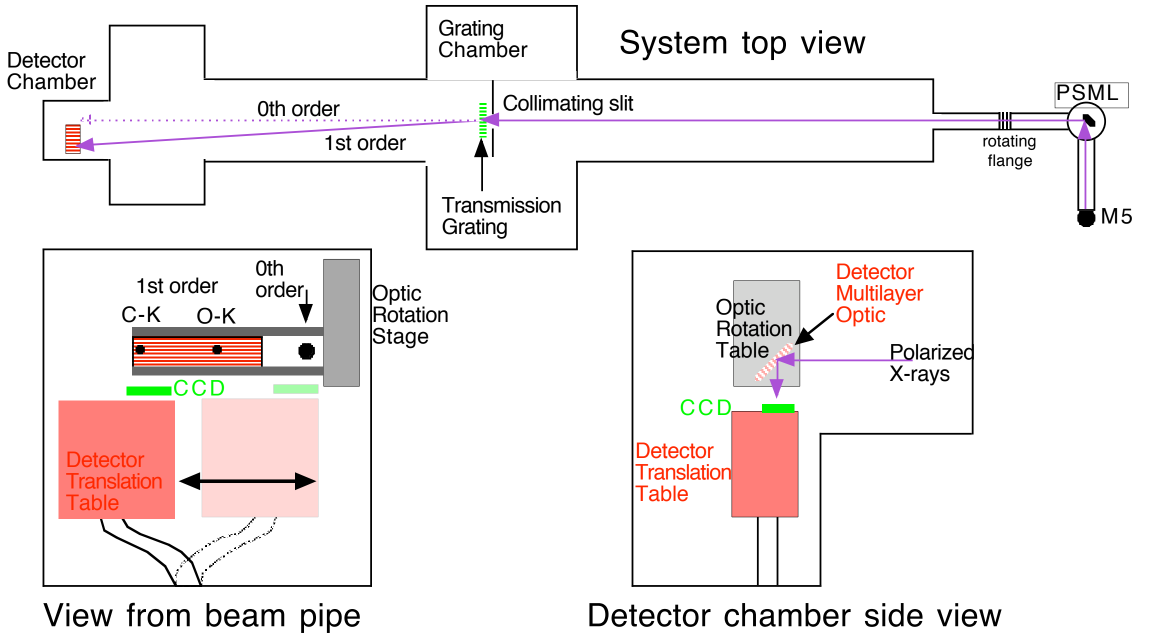

Figure 7: *Schematic of the polarized X-ray beamline after modifications for soft further instrument prototyping under development. The X-ray source is a Manson Model 5 source (M5, see Fig. 5). X-rays are polarized by the polarized source multilayer (PSML) upon reflecting down the beamline. The dispersed, first order X-rays go to the detector multilayer optic, angled at 45° to the incoming X-rays, rotated about the dispersion direction. The CCD faces the multilayer optic on a translation table that moves the CCD to the location appropriate to the dispersion by the grating). All components are in hand except those in red (the translation table and detector ML optic).*

placed at 45° to the incoming light but it may well be preferable to choose smaller graze angles for instrumental design purposes.

4 Technology Drivers

The main technologies that should be developed for a flight mission are the laterally graded multilayer mirrors and CAT gratings. The multilayer coatings have been constructed at RXO for ground-based use but have not been flown on a NASA mission. Furthermore, it is important to test the fabrication accuracies in laboratory tests. The testing described here would take at least two years to completely validate these mirrors for flight use.

The CAT gratings are needed for a high efficiency system but a backup approach would use gratings such as those flown in the Chandra High Energy Transmission Grating Spectrometer. The status and technology development plan for the CAT gratings is addressed in a separate response to the RFI.

5 Application to Future NASA missions

For our paper study of potential applications, we assume that CAT gratings will be available and that the reflectivity of the laterally graded multilayer coating can be improved by optimizing materials. The materials used for the ML coated mirrors now in the lab were chosen by RXO for convenience and low price, not high reflectivity, which peaks at 2.5% for unpolarized 0.525 keV photons (5% for s-polarized keV photons). For example, a Ni/Mg multilayer for flight use would achieve a reflectivity for unpolarized light of 10%, $\times 4$ higher than for the B_4C/W multilayer that was provided by RXO at cost for our prototyping effort.

We have studied how to develop a multilayer polarimeter as a small mission[20]. Fig. 9 shows the results from a design suitable for a Mission of Opportunity or a small Explorer, using one mirror assembly of a size planned for GEMS but with a 2 m focal length. This telescope would take a day to measure the polarization of a source like PKS 2155-304 in several bandpasses. For an old pulsar such as RX J0720-3125, the polarization fraction may be measured around and in spectral features as a function of pulse phase (see Fig. 9). The soft channel currently planned for GEMS as a student experiment would be very

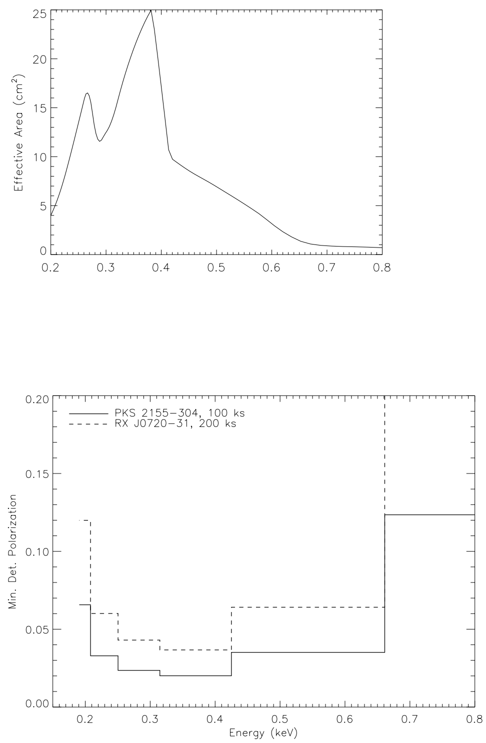

Figure 9: Top: *The effective area of a small multilayer polarimeter, to unpolarized light. The broad-band mirror is assumed to be only 30 cm in diameter. For details, see Marshall (2008,[20]). The modulation factor is indistinguishable from 1 over the bandpass.* **Bottom:** *Minimum detectable polarization for this small mission 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 the pulsar RX J0720-3125, one may detect polarization levels of 10% in each of ten phase bins.*

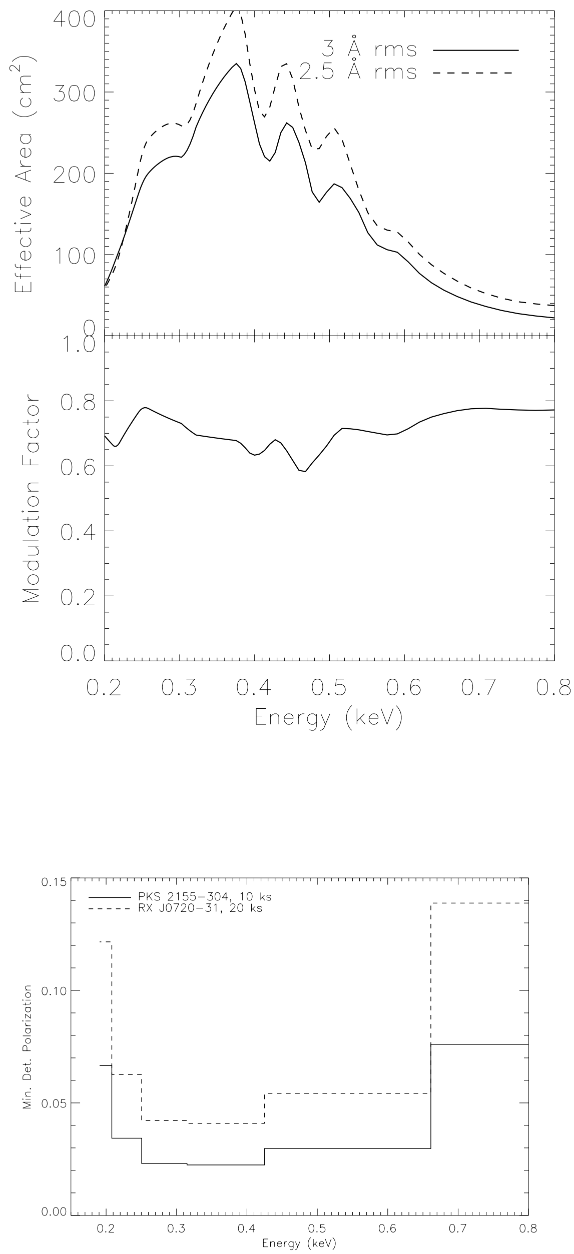

Figure 10: Top: *The effective area of an IXO-like spectrometer with 1000 cm^2 of effective area outfitted with polarizing ML coated mirrors. Depending on the layer interface roughness (3 Å roughness is currently achievable), the effective area can reach 300-400 cm^2.* **Middle:** *Modulation factor for this design. The mirrors are 35° to the incident beam, limiting the modulation factor to less than 80% but is still better than 60% across the entire band.* **Bottom:** *Same as fig. 9 but for an IXO-like mission. The solid line shows how we could detect linear polarization at a level of 2-4% across the energy band from 0.2 to 0.65 keV for PKS 2155-304 in only 10 ks. For the pulsar RX J0720-3125, spectropolarimetry allows one to obtain the polarization below, in, and above absorption features in several bands at the 5% level in a rather short exposure.*

limited in comparison, providing a measurement for only a few sources over its mission lifetime and only in a narrow bandpass at 0.5 keV.

Pharos (originally named the Cosmic Web Explorer,[6]) is a design for a high resolution spectrometer that would address the "missing baryon" problem by slewing rapidly to γ-ray bursts in order to find absorption by O VII and O VIII in the intergalactic medium. As an explorer mission dedicated to observing a transient phenomenon, it would also observe more persistent targets between bursts. Marshall (2008,[20]) showed how an X-ray spectrometer such as Pharos could be adapted to enable it to measure polarization.

In addition, grating spectrometers were baselined for the IXO. We have published an arrangement that enables an IXO grating spectrometer to double as a multilayer polarimeter[21], so there is a development path for the type of instrument that will be prototyped under this program. 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, as shown in fig. 11. If our approach were applied to the IXO grating spectrometer, the same observational results on PKS 2155-304 as shown in fig. 10 could be achieved in less than 10 ks. The peak effective area of the polarimeter would be about 300-400 cm^2. The modulation factor of the system was predicted to exceed 60% over the entire 0.2 to 0.8 keV energy range. Such an instrument would complement any high energy photoelectron-tracking polarimeter such as proposed by Soffitta et al. (2010) for NHXM[33] or Costa et al. (2008) for IXO[4].

6 Cost Estimate

The main activity described here is to develop soft X-ray polarimeter components to a level needed for a flight project. This development has been estimated at about $ 250,000 per year for three years and has been submitted to NASA's APRA technology development program. A dedicated flight mission of the scale of a small explorer can be designed based on the technology suggested here. Adding a soft X-ray polarimetry capability to a mission such as IXO would require the development of multilayer mirrors on a ×10 larger scale than would be tested in the lab and extra engineering work to integrate the ML coated mirrors into the detector housing. A study is needed to determine whether the ML gratings should be movable or merely fixed.

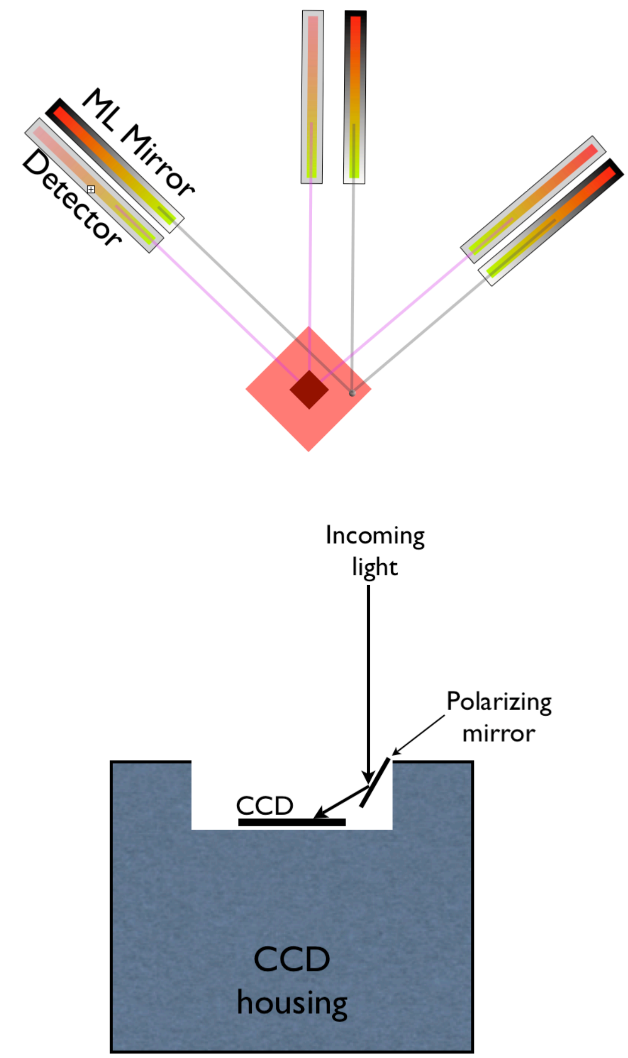

Figure 11: *Top: Top view of a focal plane layout that could be used for IXO, as suggested by Marshall (2010,[21]). When used as a spectrometer (pink lines), the zeroth order of the spectrometer is centered in the dark red square, representing an IXO imager – perhaps an imaging, high energy polarimeter. When used as a polarimeter (gray lines), the telescope pointing direction is offset so that the zeroth order is placed at the location of the gray dot. The dispersed spectrum then intercepts the laterally graded multilayer mirror that is angled at 35° to the incoming X-rays. Bottom: Side view of the CCD housing where the dispersion is perpendicular to the plane of the drawing and the multilayer mirror is oriented 35° to the incoming, dispersed X-rays.*

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