A Soft X-ray Polarimeter

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1 Overview – Key Science Goals

The NASA Research Announcement for the supporting technology program says that it will support investigations "that could lead to future advances in instrumentation useful for NASA's space astronomy and astrophysics programs." Our project satisfies this goal by using a soft X-ray polarimetry laboratory to prototype soft X-ray polarimetry measurement techniques and components. Our new designs allow for flexibility to incorporate polarimetry as an integral part of future missions. There are several examples of flight opportunities where our approach can be applied, ranging from a Mission of Opportunity or a stand-alone small explorer to observatory class facilities such as the International X-ray Observatory.

1.1 Scientific Value of Soft X-ray Polarimetry

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" [1] developed in 1969 [2], critical to modelling pulsars and still widely accepted [1]. Tinbergen (1996) [3] 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, [4]) to develop the seminal "unified model" of Seyfert galaxies, a subset of AGN. Their paper has been cited in over 1000 papers in 20 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.

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 [5, 6]. Even for bright Galactic sources, the polarizations were undetectable or were marginal $2-3\sigma$ results [7, 8, 9]. 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, or GEMS). 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 that will not be covered by the primary instrument on GEMS.

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 [10], while for shocks it should lie perpendicular [11]. McNamara et al. (2009, [12]) recently suggested 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.

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 [13] 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 [12, 14] 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 [16, 15] and that the polarization angle and magnitude should change with energy in a way that depends on the system inclination. Schnittmann & Krolik (2009, [15]) 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" [17].

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 [18]. 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

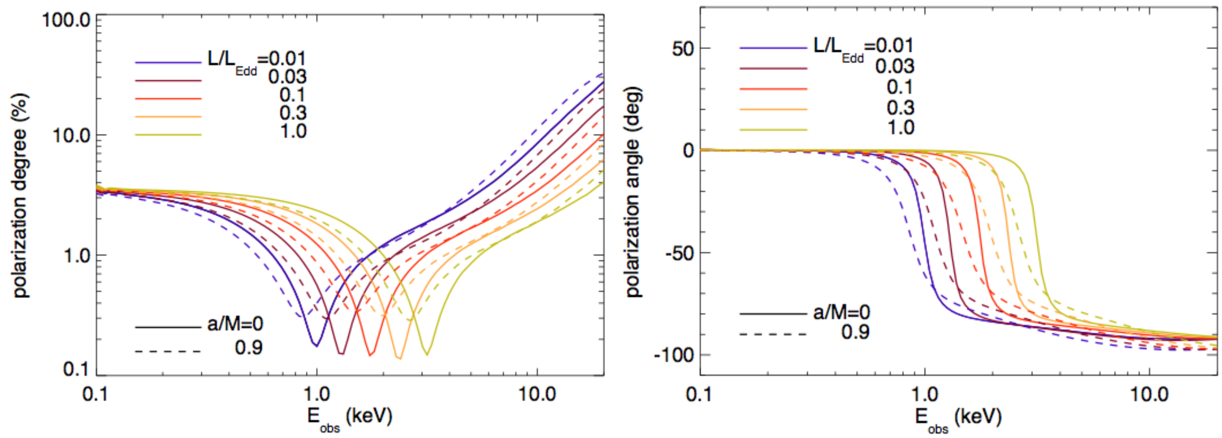

Figure 1: A prediction of the variation of the polarization percentage (left) and its position angle (right) as a function of energy for AGN with varying spin, a/M, and Eddington ratio, L/L_{Edd} [15]. Such studies are just underway due to the prospect of obtaining polarization data at high energies using GEMS. However, the figures also show that predictions depend strongly on energy, warranting observations in the soft X-ray band as well.

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 [19, 20]. 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. The extent of 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, $> 80\%$ [21]. The polarization phase and energy dependence can be used to measure the magnetic field and the star's radius [21].

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 [22]. 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. 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.

1.2 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[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, [24]) 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. We now have a new design that overcomes this weakness that we propose to prototype. Marshall (2007, [25]) 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. An simple approach was suggested by Marshall (2008, [26]) that can be used with missions such as the International X-ray Observatory (IXO). Thus, we now have a potential development path for soft X-ray polarimetry from Explorer-class missions up to and including major X-ray astronomical facilities planned by NASA and the European Space Agency. Potential applications of the technology to be developed under this proposal are discussed in a bit more detail in section 2.3.

2 Technical Overview

For this activity, we would use 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.

2.1 The X-ray Polarimetry Prototyping Lab

In this section, we describe the configuration of the laboratory as it will be needed for soft X-ray polarimetric instrument prototyping and testing. Figure 2 shows a schematic of the resultant system.

2.1.1 A Polarized X-ray Source

We plan to operate at a total of 5 energies, so 5 source mirrors are required along with matching detector multilayer mirrors – all to be procured from Reflective X-ray Optics (RXO). The source mirrors would inside the 5-way chamber to which the X-ray source is attached. Each of the coatings will be designed so that they will reflect s-polarization X-rays at one of five energies corresponding to emission lines from one of the five anodes in the source.

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. Five energies from 0.277 to 0.705 keV are planned for the test facility.

Optics will have surface roughness less than 1Å rms. Such smooth surfaces are needed to obtain peak reflectivities of order 20%. Approximately 100 layers should be enough to obtain a bandpass of FWHM $\delta E \sim 0.01E$, where E is the line energy. This bandpass approximately matches the natural line profiles produced by the source. Dr. Windt of RXO has an excellent track record with multilayer coating and was recently awarded APRA funding to continue developing this technology.

2.1.2 Grating subsystem

The transmission grating is considered to be an integral part of the polarimeter optical system. The system is designed to use the MEG gratings, with a 4000 Å period.

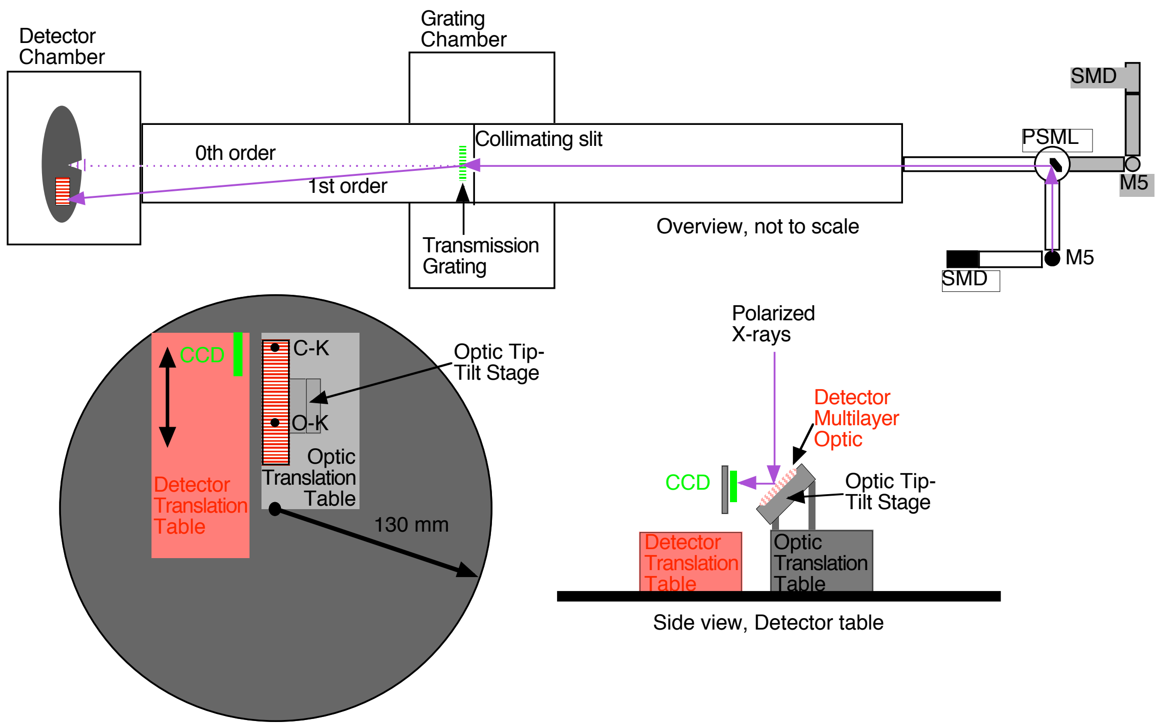

Figure 2: Schematic of the X-GEF beamline after modifications for soft X-ray polarimetry prototyping as proposed here. Items in red are to be added to the system and funded under this proposed program; the rest exist or are to be purchased on separate funding. The SMD is a source monitor detector –a proportional counter that views the Manson Model 5 source (M5). When unpolarized X-rays are needed, the M5 and its SMD are mounted in the original location, shown in gray. X-ray beam is shown in light purple; the source is used with the polarized source multilayer (PSML) to select 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.

2.1.3 Detector subsystem

The dispersed, first order X-rays go to the detector multilayer optic. The optic is mounted on a tip-tilt stage with a $\pm 5°$ motion range in two axes in the plane oriented 45° to the incoming X-rays (see Figure 2). The sensor, a back-side illuminated CCD, faces the multilayer optic on a translation table that moves the CCD to the location appropriate to the dispersion by the grating.

The multilayer optic is the critical component of the detector subsystem. Early testing, will use mirrors with one coating tuned to a specific energy. For a prototype instrument that is like what can be proposed for a flight instrument (see Section 2.3), we will 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. RXO has produced a laterally-graded multilayer coating for a previous project, achieving a linear gradation of 0.2 Å per mm from 35 Å to 55 Å and the spacings were good to 1%, adequate for this project.

2.2 Laboratory Testing

The 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): $MDP = n\frac{\sqrt{2\frac{(R+B)}{T}}}{\mu R}$ where n is 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 $1/\sqrt{(R)}$ 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 placed at 45° to the incoming light but it may well be preferable to choose smaller graze angles for instrumental design purposes. Thus, the primary objective of our program is to verify the predicted performance of flight-like components of a polarimeter.

Rotation about the grating 0th order will provide data to determine the modulation efficiency, given by $\mu = \frac{R_{max}-R_{min}}{R_{max}+R_{min}}$, where R_{max} and R_{min} are the maximum and minimum count rates observed as the source is rotated through $\pm 90°$. The detector assembly's efficiency is determined from the average count rate. Fits to $R(\phi) = R_0(1 + \mu cos[2\phi - \phi_0])$ will give the average count rate and the modulation factor in a simultaneous fit, where ϕ is the rotation angle, and ϕ_0 is a reference angle that is given by the orientation of the detector relative to the rotation defined by the source polarizer.

We would test gratings in unpolarized light to determine the level at which they polarize soft X-rays. We will also check that the source mirrors are aligned by examining the

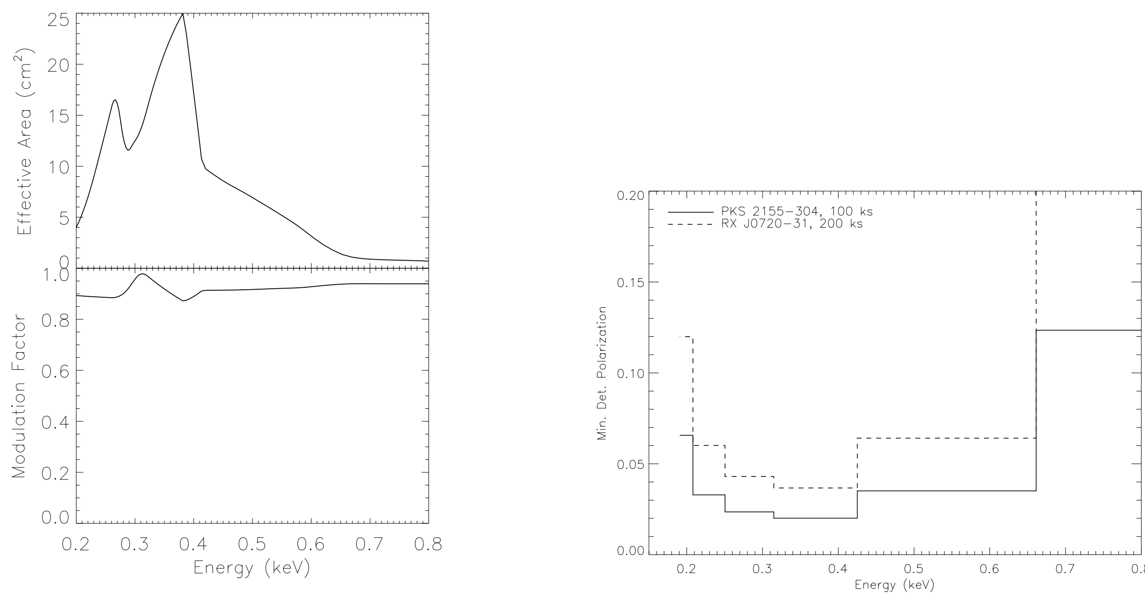

Figure 3: *Left:* The effective area of a small mission, to unpolarized light. The effective area of the broad-band mirror is assumed to be 200 cm^2. For details, see Marshall (2008, [26]). *Right:* Minimum detectable polarization as a function of energy across the bandpass of the instrument for two 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.

dependence of ϕ_0 on the source selection. We would validate the process by which such multilayer coated optics are fabricated. Laterally graded multilayer coated mirrors are used at different graze angles in order to examine the tradeoff between loss of system modulation and improved reflectivity as the graze angles decrease.

2.3 Potential Flight Opportunities

Although transmission gratings such as those built for Chandra can be used in our design, Critical Angle Transmission (CAT) gratings[30] are preferred. They have excellent prospects for high efficiency in first order, up to 50% over a wide band. This efficiency is significantly better than the MEG efficiencies, which average about 2-3% in the soft band, partly because of the 0.5 μm thick polyimide film on which the gratings are fabricated. The CAT gratings are free-standing (so no support membrane is needed) and have higher intrinsic efficiency than the gratings used on the *Chandra* program, making them excellent candidates for use in X-ray spectrometers as well as a possible X-ray polarimeter.

Marshall (2008, [26]) showed how a grating spectrometer could be adapted to enable it

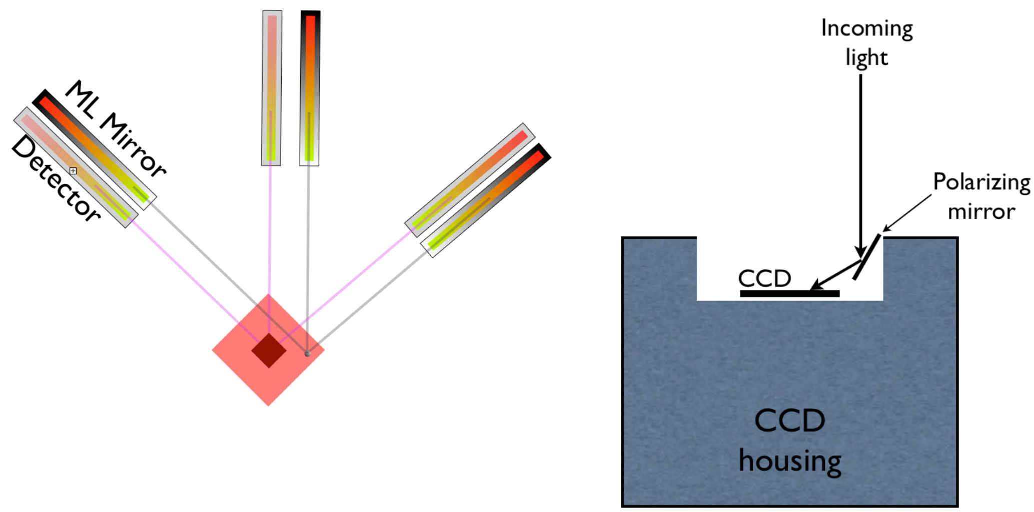

Figure 4: *Left:* Top view of a focal plane layout that could be used for IXO, as suggested by Marshall (2008, [26]). When used as a spectrometer (pink lines), the zeroth order of the spectrometer is centered in the dark red square, representing an IXO wide-field imager. When used as a polarimeter (gray lines), the zeroth order is placed at the location of the gray dot so that the dispersed spectrum first intercepts the laterally graded multilayer mirror that is angled at 30° to the incoming X-rays. The lines leading to zeroth order are all the same length, showing that specific wavelengths appear at different distances from the near end of the mirror but are at the same distances when used as a spectrometer. *Right:* Side view of the CCD housing where the dispersion is perpendicular to the plane of the drawing and the multilayer mirror is oriented 30° to the incoming, dispersed X-rays.

to measure polarization. Such a spectrometer could be designed as a small mission and be outfitted for polarimetry [26]. Fig. 3 shows the results from a design of a small telescope, suitable for a Mission of Opportunity or a Small Explorer, using one mirror assembly such as those proposed for GEMS (0.33 m in diameter, 2 m focal length). Such a mission would take a day to measure the polarization in several bandpasses in a source like PKS 2155-304.

In addition, a CAT grating spectrometer has been proposed as one of two approaches to use on the IXO, so there is a development path for the type of soft X-ray polarimeter that will be prototyped under this program [26]. 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 with accompanying multilayer-coated flats, as shown in fig. 4.

3 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. It could take several years for current CAT grating research to demonstrate that a high efficiency grating can be fabricated reliably.

4 Partnerships, Current Status, and Activity Schedule

The main activity described here is to develop soft X-ray polarimeter components to a level needed for a flight project. We will take advantage of decades of experience developing X-ray instruments and laboratory experiments at MIT and existing infrastructure. We will build on the current effort of the co-Investigators who are recommissioning a 17 m beamline, with its unpolarized X-ray source as well as the MKI-funded development project. There are test and flight-like transmission gratings already mounted in the beam-line that can be used for this project and plans are underway to purchase multilayer optics from Reflective X-ray Optics (RXO) for use in creating and measuring polarized X-rays. We will use an existing X-ray sensitive CCD for the sensor and MKI-supplied CCD electronics.

The CCD lab is extensively equipped with two vacuum chambers currently in use for CCD testing. The lab has been developed with funding from several flight projects, including the *Suzaku*, *HETE*, and *Chandra* projects as well as new development programs funded by NASA through the ROSS or ROSES program. The lab has many spare parts, including working flight-like CCDs and associated electronics that are available for use on this project.

The source of unpolarized X-rays is a Manson Model 5 multi-anode source. Operating at up to 10 kV and 0.2 mA, the source can select from six installed anodes without breaking the vacuum in the 17 m pipe. A translational grating mount is about 8.7 m downstream of the X-ray source in a chamber about 1m in diameter that can be isolated via gate valves from the rest of the beamline. The grating mount still contains reference gratings, one each of the high- and medium-energy type grating facets (HEGs and MEGs). There are also two MEGs in the "test" positions on the grating mount (as the facility was used to test two gratings in one day without breaking vacuum).

Over the upcoming year, we will finish recommissioning the X-GEF facility. We have funding from a Kavli instrumentation grant to develop a source of polarized soft X-rays and for minimal testing. Critical Angle Transmission (CAT) gratings are currently being developed under funding by the NASA Astrophysics Research and Analysis (APRA) technology development program. If successful, these gratings will be used in subsequent design and development of soft X-ray polarimetry experiments, both for testing the the laboratory and for flight missions. We have informal interest from several groups in the U.S. and other countries who would be willing to collaborate on a mission by supplying primary optics for a flight mission. X-ray sensitive CCD detectors have been developed for flight at MIT that would be sufficient for any application.

This technology development would take place over several years in a phased testing approach. By mid-2011, laterally graded multilayer mirrors can be tested to sufficient levels to use as the basis of a small explorer or mission of opportunity proposal. Such a mission could then be launched by 2015.

5 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 $\times 10$ larger scale than would be tested in the lab and (probably) an added detector readout array.

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