

# Broad-band Soft X-ray Polarimetry

Herman L. Marshall<sup>a</sup>, Ralf K. Heilmann<sup>a</sup>, Norbert S. Schulz<sup>a</sup>, and Kendrah D. Murphy<sup>a</sup>

<sup>a</sup>MIT Kavli Institute, Cambridge, MA, USA

## ABSTRACT

We developed an instrument design capable of measuring linear X-ray polarization over a broad-band using conventional spectroscopic optics, using a method previously described by Marshall (2008) involving laterally graded, multilayer-coated flat mirrors. We present possible science investigations with such an instrument and two possible configurations. This instrument could be used in a small orbiting mission or scaled up for the International X-ray Observatory. Laboratory work has begun that would demonstrate the capabilities of key components.

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

## 1. INTRODUCTION

There has been considerable work in the last 5 yr on detectors that can measure linearly polarized X-rays in the 2-10 keV band and at higher energies.<sup>1-4</sup> 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).<sup>5</sup> Below 1 keV, however, there have been very few concepts or lab work. Marshall et al. (2003<sup>6</sup>) proposed a design using Bragg reflection from multilayer-coated optics at 0.25 keV in a manner similar to that used in the OSO-8 design that measured the polarization of the Crab Nebula with graphite crystals at 2.6 keV.<sup>7</sup> Weisskopf et al. rightly argued that these Bragg polarimeters have a narrow bandpass, reducing their attractiveness for astrophysical observations because one expects polarization to be energy dependent, so a wide bandpass is desired.

Marshall (2007<sup>8</sup>) described a method to overcome this limitation by using transmission gratings to disperse 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 grating spectrometer. An extension of this approach was suggested by Marshall (2008<sup>9</sup>) that can be used with missions such as the International X-ray Observatory (IXO). A description of the design is given in section 3. Next, we discuss potential scientific investigations that would be possible with a soft X-ray polarimeter.

## 2. SCIENCE WITH SOFT X-RAY POLARIMETRY

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.

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”<sup>10</sup> developed in 1969,<sup>11</sup> critical to modelling pulsars and still widely accepted. Tinbergen (1996<sup>12</sup>) 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.

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Further author information: (Send correspondence to H.L.M.)

H.L.M.: hermanm@space.mit.edu, Telephone: 1 617 253 8573

N.S.S.: nss@space.mit.edu, Telephone: 1 617 258 5767

K.D.M.: kdmurphy@space.mit.edu, Telephone: 1 617 258 6596

Perhaps the most important contribution of optical polarimetry led Antonucci and Miller (1985<sup>13</sup>) 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  $3\sigma$ : the Crab Nebula.<sup>7,14</sup> Even for bright Galactic sources, the polarizations were undetectable or were marginal  $2 - 3\sigma$  results.<sup>15,16</sup> 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 approval of a X-ray polarimetry explorer (the Gravitation and Extreme Magnetism SMEX, or GEMS<sup>17</sup>). 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.

## 2.1 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,<sup>18</sup> while for shocks it should lie perpendicular.<sup>19</sup> McNamara et al. (2009,<sup>20</sup>) 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.

## 2.2 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<sup>21</sup> that could be confirmed using polarimetry. UV observations above the 13.6 eV Lyman edge of 10–20% polarization in active galaxies stand as a challenge to theorists<sup>22,23</sup> and indicate that X-ray polarizations could be higher than observed optically.

Recent theoretical work indicates that AGN accretion disks and jets should be 10-20% polarized<sup>20,24</sup> and that the polarization angle and magnitude should change with energy in a way that depends on the system inclination. Schnittmann & Krolik (2009,<sup>24</sup>) 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  $90^\circ$  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”.<sup>25</sup>

## 2.3 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.<sup>26</sup> 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;

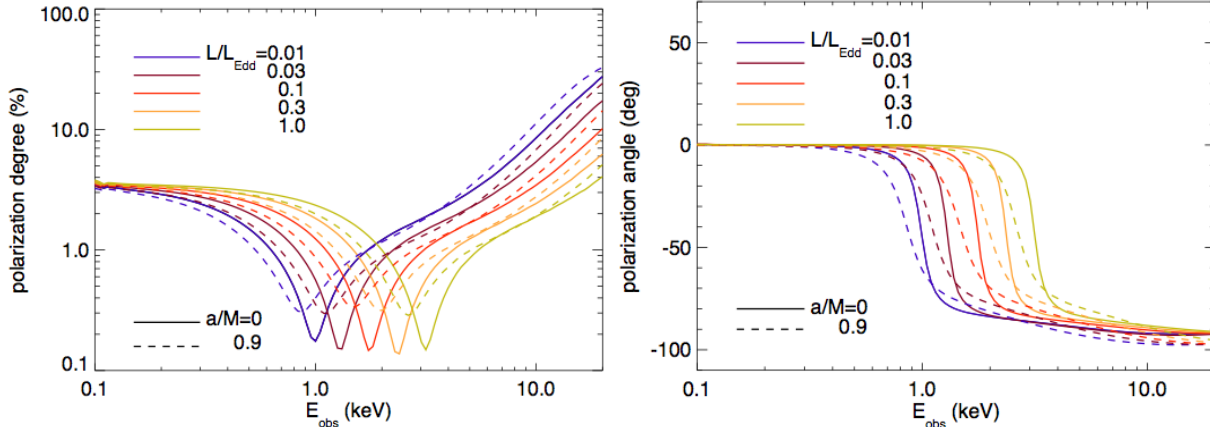


Figure 1. A prediction of the variation of the polarization percentage (left) and its position angle (right) as a function of energy for AGN with varying spin,  $a/M$ , and Eddington ratio,  $L/L_{Edd}$ .<sup>24</sup> Such studies are just underway due to the prospect of obtaining polarization data at energies above 1 keV. However, the figures also show that predictions depend strongly on energy, warranting observations in the soft X-ray band as well.

i.e.  $B = m^2 c^3 / e \hbar$  ( $= 4.4 \times 10^{13}$  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.<sup>27,28</sup> 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,  $> 80\%$ .<sup>29</sup> The polarization phase and energy dependence can be used to measure the magnetic field and the star’s radius.<sup>29</sup>

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.<sup>31</sup> Examples in Fig. 2 demonstrate a variety of 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. 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.

## 2.4 Magnetic Cataclysmic Variables

A recent study predicted that the linear polarization of CVs should be as high as 8%.<sup>32</sup> 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.

## 3. A SOFT X-RAY POLARIZING SPECTROMETER

The basic design was outlined by Marshall (2008<sup>9</sup>). For this paper, we examine the approach that could be applied to a large area grating spectrometer such as what would be included on the International X-ray Observatory.

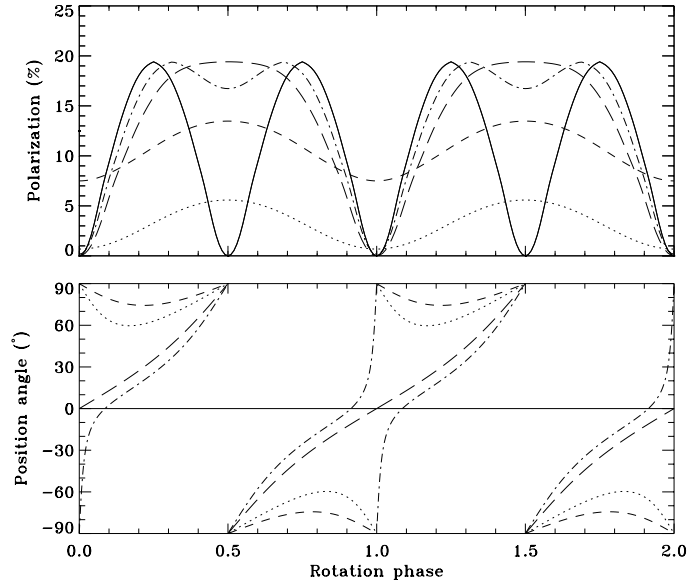


Figure 2. Predicted phase dependences of the polarization fraction and the position angle for a magnetized neutron star with a temperature of  $10^6$  K.<sup>30</sup> The curves correspond to different combinations of the viewing angle  $\zeta$  and magnetic inclination  $\alpha$ :  $90^\circ$  and  $90^\circ$  (solid),  $45^\circ$  and  $45^\circ$  (long dash),  $56^\circ$  and  $60^\circ$  (dash-dot),  $40^\circ$  and  $10^\circ$  (short dash),  $16^\circ$  and  $8^\circ$  (dots). The polarization and position angle depend very sensitively on the orientation of the neutron star spin and the magnetic axis.

While this design would work with spectrometer using either off-plane gratings<sup>33</sup> or transmission gratings,<sup>34</sup> we concentrate on the latter design, implemented with critical angle transmission (CAT) gratings.

In order to adapt the spectrometer for polarimetry, we would place laterally graded multilayer-coated flat mirrors alongside the detectors. The mirrors would be as long as the detector but rotated about the long axis in order to deflect the converging beam to the detector at a large graze angle, which then polarizes the output spectrum. The spacing of the multilayer coating would be linearly varied along the mirror's length, tuned so as to maximize the reflectivity at a wide range of wavelengths. 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. 3. The figure also shows how the mirrors' locations may be fixed, used for polarimetry by offset pointing a target to a location that moves the spectra to the multilayer mirrors. There is a corresponding shift in the central wavelength, so the identical mirrors would also be permanently shifted along their lengths. The schematic exaggerates the shifts, which are much smaller than the lengths of the readout arrays.

### 3.1 System Throughput and Sensitivity

Using the Center for X-ray Optics web page ([http://henke.lbl.gov/optical\\_constants/multi2.html](http://henke.lbl.gov/optical_constants/multi2.html)), multilayer efficiencies were computed for a range of materials at a graze angle of  $35^\circ$ . 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.<sup>35-37</sup> The CCD detectors are assumed to have a thin Al overlayer to act as an optical blocking filter. The resulting effective area is shown in Fig. 4, along with the modulation factor,  $M$ . The features in these curves are related to regions where a given pair of materials used in the multilayer coating switches to a new pair as an absorption edge is reached. For example, between 0.30 and 0.40 keV, Cr and Sc are the two materials in the multilayer while Ni and Ti are used in the 0.40 to 0.45 keV range. Fig. 4 also shows how the assumed interfacial roughness can affect the results. If the roughness can be reduced to 0.25 nm, then the effective area above 0.6 keV can increase 30-75%. Changes in the roughness do not have a strong effect on the modulation factor.

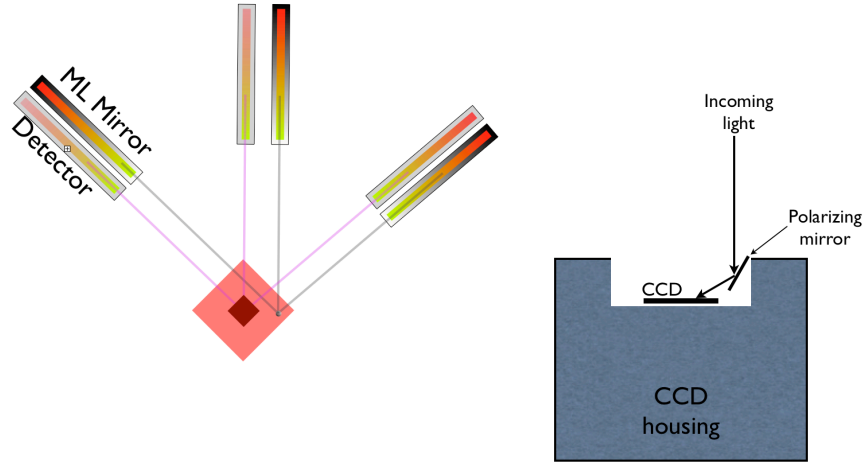


Figure 3. *Left:* Top view of a focal plane layout that could be used for IXO, in the manner suggested by Marshall (2008,<sup>9</sup>). When used as a spectrometer (pink lines), the zeroth order of the spectrometer is centered in the dark red square, representing an IXO wide-field imager. When used as 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  $30^\circ$  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. The schematic exaggerates the offsets, which are much smaller than the lengths of the readout arrays. *Right:* Side view of the CCD housing where the dispersion is perpendicular to the plane of the drawing and the multilayer mirror is oriented  $30^\circ$  to the incoming, dispersed X-rays.

The effective area estimate can be used to predict the minimum detectable polarization<sup>5</sup> (MDP) for potential targets. Extragalactic sources such as the BL Lac object PKS 2155–304 are expected to be highly polarized in the soft X-ray band. In a 10,000 s observation of PKS 2155–304, this instrument could detect polarizations of 2-4% in each of four bandpasses 1 nm wide from 2 to 6 nm (0.21 to 0.62 keV). Fig. 5 shows the results graphically. In addition, for isolated neutron stars such as RX J0720.4–3125, it is worthwhile to obtain phase-resolved polarization data. In a 50,000 s observation with this instrument, one could reach MDPs of 8-12% over the 2-6 nm band for each of 10 phase bins.

#### 4. A SOFT X-RAY POLARIMETRY TESTING FACILITY

We have recently recommissioned 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.<sup>38</sup> With MKI technology development funding, we have adapted the source to produce polarized X-rays at the O-K $\alpha$  line (0.525 keV).<sup>39</sup> A new chamber houses a Polarized Source MultiLayer (PSML) mirror, provided by Reflective X-ray Optics (RXO). The source is mounted to this chamber at  $90^\circ$  to the existing beamline. A rotatable flange connects the PSML mirror chamber output port to the vacuum pipe so that the polarization vector can be rotated with respect to the grating and its dispersion direction. This prototyping effort will help us demonstrate the viability of soft X-ray polarimetry and show how a broad-band version can be developed. See Murphy et al. (these proceedings<sup>39</sup>) for more details of the soft X-ray polarization laboratory. A proposal to expand the facility is under consideration by NASA.

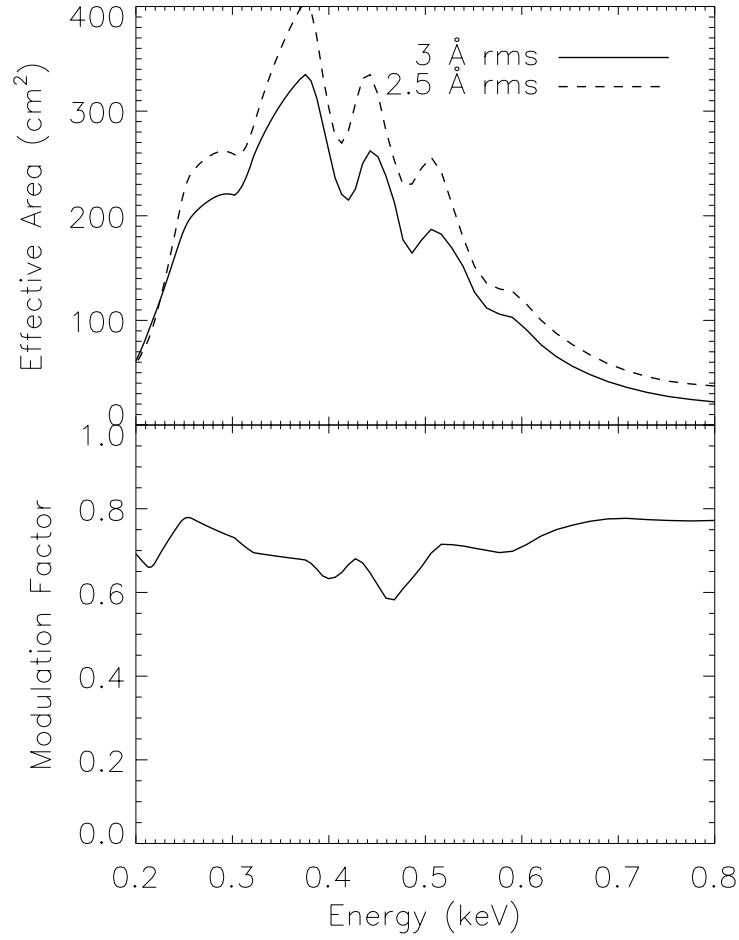


Figure 4. *Top:* The effective area of an instrument that might be on IXO, to unpolarized light. The geometric area of the portion of the mirror tiled with gratings is assumed to be  $3000 \text{ cm}^2$ . Features in the effective area curve are related to reflectivity peaks in specific multilayer compositions, which vary with wavelength. The overall shape is primarily related to the efficiency of the gratings, which depends on the choice of blaze angle. At high energies, the effective area drops due to the performance of realistic multilayer coatings. The dashed line shows how reducing the assumed interfacial roughness can improve the effective area. If the roughness can be reduced to  $0.25 \text{ nm}$ , then the effective area above  $0.6 \text{ keV}$  can increase 30-75%. *Bottom:* Polarization modulation factor as a function of energy across the bandpass of the instrument. For this design, the modulation factor is always above 60%. Changes in the roughness do not have a strong effect on the modulation factor.

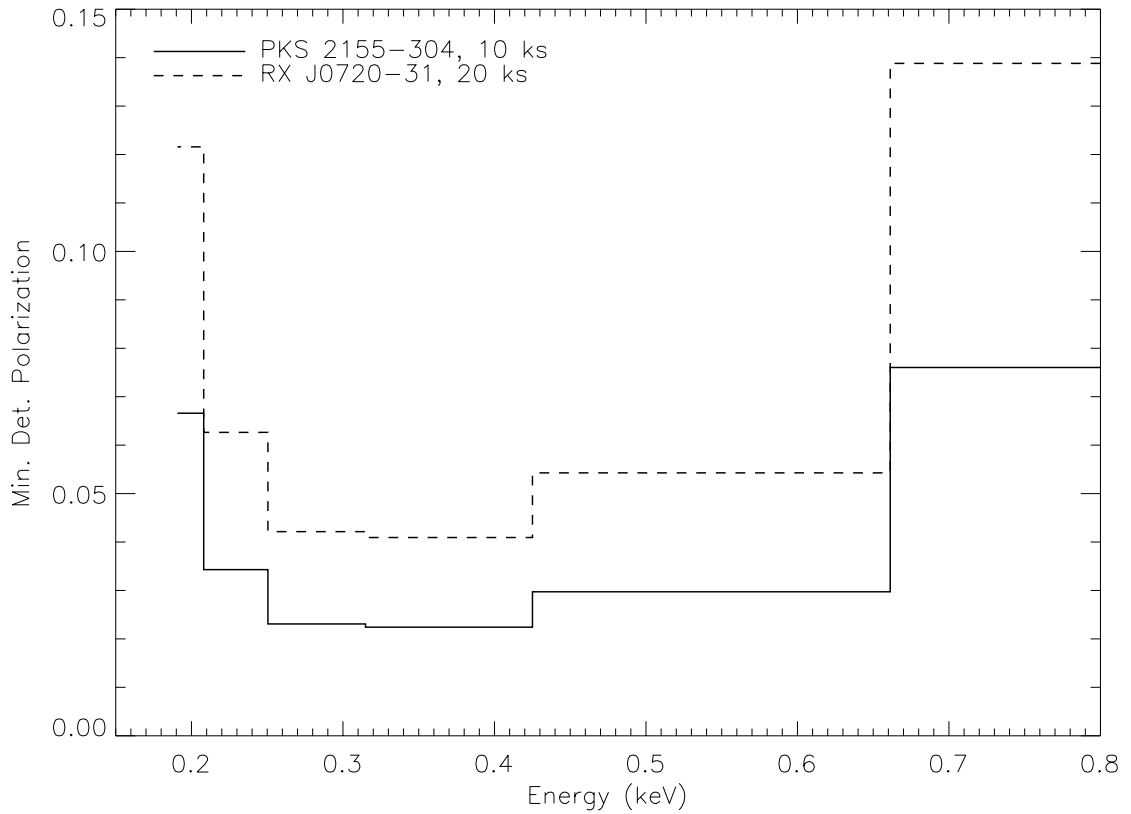


Figure 5. Minimum detectable polarization as a function of energy across the bandpass of the instrument for two different possible observations. The solid line shows how we could detect linear polarization at a level of 8% across the entire energy band from 0.15 to 0.8 keV for PKS 2155-304 in 10 ks and to better than 3.5% over the 0.20 to 0.65 keV range. For RX J0720-31 (dashed line), spectroscopy allows one to obtain the polarization below, in, and above absorption features to a level of a few percent in 20 ks.

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