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Soft X-Ray Polarimeter: Potential Instrumentation and Observations

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Abstract

We present an instrument design capable of measuring linear X-ray polarization over a broad-band using conventional spectroscopic optics. A set of multilayer-coated flats reflects the dispersed X-rays to the instrument detectors. The intensity variation with position angle is measured to determine three Stokes parameters: I, Q, and U – all as a function of energy. By laterally grading the multilayer optics and matching the dispersion of the gratings, one may take advantage of high multilayer reflectivities and achieve modulation factors >90% over the entire 0.2 to 0.8 keV band. This instrument could be used in a small suborbital mission or adapted for use in an orbiting satellite to complement measurements at high energies. We present progress on laboratory work to demonstrate the capabilities of key components.

Keywords: polarimetry - X-rays.

1 Introduction

Polarimetry is an inherently multiwavelength phenomenon. In the radio band, the detectors provide linear polarization information but for other bandpasses, special steps are required, so an observer has to choose whether to obtain the additional Stokes parameters.

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" (Taylor & Stinebring1986) developed by Radhakrishnan (1969), critical to modeling pulsars and still widely accepted (Taylor & Stinebring). Tinbergen (1996) 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 & Miller (1985) to develop the seminal "unified model" of Seyfert galaxies, a subset of active galactic nuclei (AGN). Their paper has been cited in over 1000 papers in 30 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 (Novick et al. 1972; Weisskopf et al. 1987). Even for bright Galactic sources, the polarizations were undetectable or were marginal $2-3\sigma$ results (Silver, et al. 1979; Long et al. 1980). 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 in support of the now-cancelled mission, GEMS (the Gravitation and Extreme Magnetism SMEX; see Swank et al. 2010). The X-ray Extreme Universe Satellite (XEUS) and the International X-ray Observatory (IXO) both had been planned to include a polarimeter but their probable successor, ATHENA+, does not, so there is now no mission that is planned to include a polarimeter. 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 would complement observations with an instrument such as GEMS.

2 The Scientific Value of Soft X-Ray Polarimetry

There is significant scientific potential of an X-ray polarimeter operating below 1 keV. Here, we discuss a few types of potential targets; for details see Marshall et al. (2010), Schnittman et al. (2013), Ghosh et al. (2013).

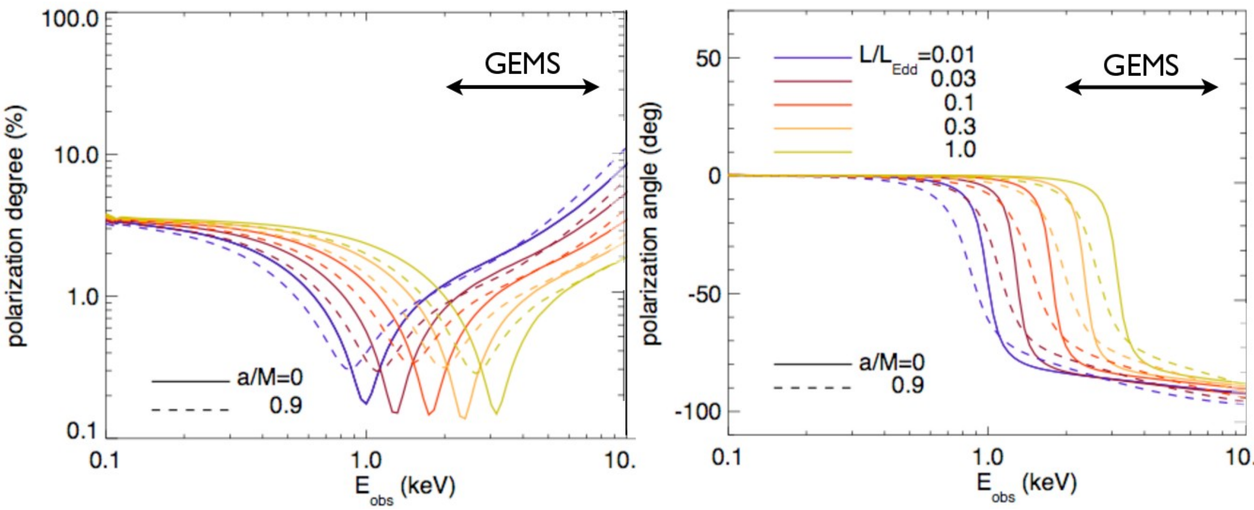

Figure 1: A prediction of the variation of the polarization percentage (left) and its position angle (right) as a function of energy for AGN with varying spin, a/M, and Eddington ratio, L/L_{Edd} (Schnittman & Krolik, 2009). Such studies were initiated with the prospect of obtaining polarization data in the 2-8 keV band using GEMS. The figures show that predictions depend strongly on energy. Observations with a multilayer-based polarimeter would complement those by an instrument such as GEMS.

2.1 Active galactic nuclei

Blazars are believed to contain parsec-scale jets with $\beta \equiv v/c$ approaching 0.995. The X-ray spectra are much steeper than the optical spectra, 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. Brindle (1986) showed that the polarization of blazars increases from the IR to the optical band and can be as high as 25%, indicating that the X-ray polarization should be greater than 30%. 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 (Marscher 1980), while for shocks it should lie perpendicular (Marscher 1985). See also Poutanen (1994). McNamara et al. (2009) 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. Their spectra are very soft, brightest below 1 keV.

Theoretical work indicates that AGN accretion disks and jets should be 10-20% polarized (McNamara et al. 2009; Schnittmann & Krolik 2009, Dovčiak, et al. 2011) and that the polarization angle and magnitude should change with energy in a way that depends on the system inclination. Schnittmann & Krolik (2009) 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 deg between 1 and 2 keV in some cases, arguing that X-ray polarization measurements are needed both below and above 2 keV (fig. 1).

2.2 Isolated neutron stars

Isolated neutron stars (Pavlov & Zavlin 1997) and magnetars (Heyl, Shaviv, & Lloyd 2003, Lai; & Ho 2003) should be bright enough for soft X-ray polarimeters. With temperatures below 0.5 keV, they can only be detected below 1-2 keV. Magnetars 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). 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 radii and distances and provide the first demonstration of vacuum birefringence, a predicted but hitherto unobserved QED effect (Heyl, Shaviv, & Lloyd 2003) . The extent of polarization increases with the strength of magnetic field and decreases as the radius increases so compact neutron stars are predicted to be highly polarized, $> 80\%$ (Heyl et al. 2003) .

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 (Pavlov & Zavlin 2000). 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.

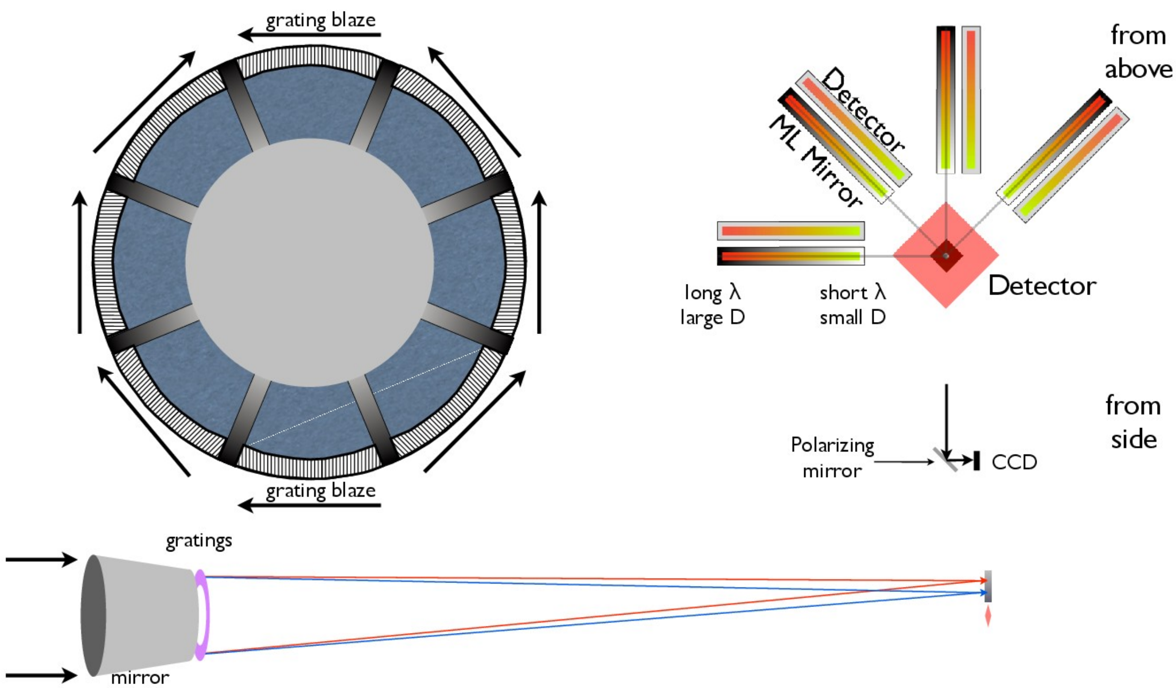

Figure 2: *Bottom:* Overview of a small telescope designed for soft X-ray spectropolarimetry, based on a design suggested by Marshall (2008). A small set of nested mirror shells focusses X-rays through gratings that disperse to an array of detectors about 2 m from the entrance aperture. *Top left:* View from the front aperture. Gratings are placed behind the mirror with the grating bars oriented along the average radius to the mirror axis. The gratings are blazed in the directions shown. *Top right:* The view from above the detectors and polarizers. Spectra from the gratings are incident on multilayer-coated flats that are tilted along the dispersion axis which contains the zeroth order (dot in center). The angle of the tilt is the same for all mirrors and always redirects the X-rays to the adjacent detector in a clockwise direction. The multilayer coating spacing, D, increases linearly outward from zeroth order, just as the wavelength increases, in order to match the first order wavelength to the peak of the multilayer reflectivity. The detectors face the corresponding mirror. Measuring the intensity at a given wavelength as a function of clocking angle then provides $I(\lambda)$, $Q(\lambda)$, and $U(\lambda)$.

3 A Soft X-Ray Polarimeter

We have been working on soft X-ray polarimetry concepts using multilayer-coated optics for almost 20 years, starting with a very simple design (Marshall 1994). Briefly, 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, $\theta = 45\,\mathrm{deg}$, 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.

Designs for flight instruments based on multilayer coated optics generallly have limited bandpasses. We now have a new design that overcomes this weakness that we are prototyping in the lab. Marshall (2007) showed that it is possible to develop a laterally graded multilayer-coated mirror that combines with a dispersive optic to obtain a broad bandpass. We have studied how to develop a multilayer polarimeter as a small mission (Marshall 2008; Marshall et al. 2010). Fig. 2 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 5 min to detect a polarization fraction of 8% for a source like Mk 421 at its current intensity.

4 Conclusions

Soft X-ray polarimetry has excellent prospects for scientific study of AGN, blazars, and isolated neutron stars. We have designed an instrument capable of detecting a polarization fraction as low as 8% in a suborbital mission. We are prototyping components for such a mission in the lab and will have a flight-like configuration within a few months.

Acknowledgement

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DISCUSSION

JIM BEALL: This arrangement sounds like it's pretty delicate. How much of a challenge dos this pose for rocket flight?

HERMAN MARSHALL: All but one of the components have been flown on satellite missions. The remaining component, the laterally graded multilayer coated mirrors, are likely to survive based on experience with other ML coated optics, used primarily for solar astronomy. The remaining challenge is to maintain alignment and pointing, needed to match the dispersed X-rays to the ML coated mirrors. The sensitivity to misalignments will require stiff structures while variations due to pointing jitter will require that the ML coatings have a sufficiently broad response at a target wavelength, which ultimately depends on the dispersion of the gratings used. So, mitigating jitter will depend on a tradeoff between improving pointing stability and the availability of high dispersion gratings.