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X-Ray Polarimetry with the Polarization Spectroscopic Telescope Array (PolSTAR)

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Abstract: This paper describes the Polarization Spectroscopic Telescope Array (PolSTAR), a mission proposed to NASA’s 2014 Small Explorer (SMEX) announcement of opportunity. PolSTAR measures the linear polarization of 3-50 keV (requirement; goal: 2.5-70 keV) X-rays probing the behavior of matter, radiation and the very fabric of spacetime under the extreme conditions close to the event horizons of black holes, as well as in and around magnetars and neutron stars. The PolSTAR design is based on the technology developed for the Nuclear Spectroscopic Telescope Array (NuSTAR) mission launched in June 2012. In particular, it uses the same X-ray optics, extendable telescope boom, optical bench, and CdZnTe detectors as NuSTAR. The mission has the sensitivity to measure $\sim 1\%$ linear polarization fractions for X-ray sources with fluxes down to $\sim 5$ mCrab. This paper describes the PolSTAR design as well as the science drivers and the potential science return.

Keywords: X-Ray Polarimetry; Astronomical Instrumentation; Black Holes; Neutron Stars; Blazars; General Relativity.

1. Introduction

In the following, we describe the Polarization Spectroscopic Telescope Array (PolSTAR), a satellite-borne experiment measuring the linear polarization of X-rays in the energy range from 3-50 keV (requirement; goal: 2.5-70 keV). The mission was proposed to NASA’s 2014 Small Explorer (SMEX) announcement of opportunity (National Aeronautics and Space Administration, 2014). The mission concept builds on the highly successful Nuclear Spectroscopic Telescope Array (NuSTAR) hard X-ray imaging mission (Harrison et al., 2013). The main difference between PolSTAR and NuSTAR is the addition of a scattering element in the focal plane of the X-ray telescope enabling the measurement of the linear polarization properties. PolSTAR measures the polarization fraction and angle, two properties of photon beams characterizing the uniformity and orientation of the electric field carried by the photons, respectively, as a function of photon energy and arrival time. The two fundamentally new observables depend on the emission mechanism, scattering angles, and the geometry and properties of matter, electromagnetic fields and spacetime itself of extreme objects such as black holes and neutron stars. A mission like PolSTAR gives geometric information about objects which are much too small to be imaged directly. For example, consider the Galactic stellar mass black hole GRS 1915+105. At a distance of $\sim 8.6$ kpc (Reid et al., 2014), the gravitational radius $r_g = GM/c^2$ (with gravitational constant $G$, black hole mass $M$, and speed of light $c$) measures 21 km, corresponding to an angle of 4.5 femto-degrees. X-ray polarimetry allows us to measure angles in systems of such small angular extent.

X-ray polarimetry is a largely unexplored field. NASA has so far only launched one dedicated X-ray polarimetry mission, OSO-8, which was in orbit from 1975 to 1978 (Novick, 1975). OSO-8 measured the polarization fraction and angle of the 2.6 keV and 5.2 keV X-ray emission from the Crab Nebula (Weisskopf et al., 1978) and set upper limits on the polarization fraction of the X-ray emission from 14 sources (Silver et al., 1979; Hughes et al., 1984).

Two instruments on the International Gamma-Ray Astrophysics Laboratory (INTEGRAL), the Spectrometer on INTEGRAL (SPI; Vedrenne et al., 2003) and the Imager on Board the INTEGRAL Satellite (IBIS; Ubertini et al., 2003), have revealed tentative evidence for highly polarized $>$100 keV emission from the Crab Nebula (Dean et al., 2008; Forot et al., 2008) and Cyg X-1 (Laurent et al., 2011; Rodriguez et al., 2015), albeit with large systematic errors. Several authors reported the detection of highly polarized X-ray and/or gamma-ray emission from gamma-ray bursts (GRBs; e.g., Willis et al., 2005; McGlynn et al., 2007; Kalenchi et al., 2007; Yonetoku et al., 2011, 2012; Kostelecky and Mewes, 2013, and references therein), but the evidence is not highly significant taking the statistical and systematic errors into account.

PolSTAR uses scattering off a lithium hydride (LiH) element to measure the linear polarization of X-rays. In the 2-10 keV energy band, a compet-
| Parameter                                                                 | Requirement | Current Best Estimate |
|--------------------------------------------------------------------------|-------------|-----------------------|
| Telescope bandpass (keV)                                                | 3-50        | 2.5-70                |
| Telescope effective area (effective # of NuSTAR optics)                 | ≥ 0.9       | 1.1                   |
| Energy resolution (FWHM at 6 keV)                                       | ≤ 1 keV     | 0.45 keV              |
| Absolute timing accuracy (msec)                                          | ≤ 15        | 2                     |
| Angular resolution (half power diameter; arcsec)                        | ≤ 80        | 60                    |
| Pointing, during science portion of orbits (99.7% CL)                   | ≤ 62″ from stick center | 17″ from stick center |
| Instrument reconstructed pointing knowledge (99.7% CL)                  | ≤ 15″       | 8″                    |
| Minimum Detectable Polarization (3-15 keV, 25 ks obs’n of 1 Crab source, 99% CL) | ≤1%         | 0.5%                  |
| Polarization fraction systematic error (3-15 keV; 99.7% CL)             | ≤ 1.5%      | 0.25%                 |
| Polarization angle systematic error (≥ 6% polarized source; 99.7% CL)   | ≤ 20°       | 2°                    |
| Bad pixel fraction                                                      | ≤ 2%        | 1%                    |
| Instrument mass (kg)                                                    | ≤ 170       | 131                   |
| Instrument power (W; orbital avg.)                                      | ≤ 45        | 28                    |

Table 1: PolSTAR has significant margin on all primary instrument requirements, largely based on NuSTAR heritage. CL stands for confidence level.

ing approach uses photoelectric effect interactions in a gas chamber read out by gas electron multipliers (GEMs). The proposed Imaging X-ray Polarimetry Explorer (IXPE; Ramsey, 2014) and X-ray Imaging Polarimetry Explorer (XIPE; Soffitta et al., 2013) missions use gas pixel detectors for the readout, enabling spectropolarimetric imaging with an angular resolution of ~25″. The proposed Polarization from Relativistic Astrophysical X-ray Sources (PRAXYS) (former GEMS) mission uses a gas chamber operated as a time projection chamber (TPC; Jahoda et al., 2015; Enoto et al., 2014; Hill et al., 2014; Takeuchi et al., 2014; Kitaguchi et al., 2014; Jahoda et al., 2014). The electron track perpendicular to the beam direction are measured in two dimensions based on strip and drift time measurements. PolSTAR is unique in offering a broad energy range, as that of IXPE, XIPE and PRAXYS is limited to 2-10 keV. PolSTAR does not offer the imaging capabilities of IXPE and XIPE. At the time of writing this paper, NASA selected IXPE and PRAXYS for Phase A studies (The National Aeronautics and Space Administration, 2015), and the European Space Agency (ESA) selected XIPE as one of three M4 candidate missions (The European Space Agency, 2015). The NASA review classified PolSTAR as a Category II proposal defined as a “well-conceived and scientifically or technically sound investigations which are recommended for acceptance, but at a lower priority than Category I” attesting to the soundness of the approach. We are currently considering proposing an enlarged version of PolSTAR to NASA’s upcoming Medium Class Explorer (MIDEX) announcement of opportunity.

The paper is structured as follows. After presenting the PolSTAR design in §2 and the analysis methods and projected performance in §3, we discuss the PolSTAR science program in §4. Section §5 gives a summary.

Unless otherwise noted, all figures and sensitivity estimates assume source fluxes normalized to the observed time-averaged 2-12 keV fluxes measured from 1996-2011 with the All-Sky Monitor (ASM; Levine et al., 1996) on the Rossi X-
### Table 2: Based largely on NuSTAR heritage, the PolSTAR instrument is 82% build-to-print by mass.

| Parameter                  | NuSTAR | PolSTAR |
|----------------------------|--------|---------|
| # telescope modules        | 2      | 1       |
| Effective focal length     | 10.14 m|         |
| Optics                     | Grazing incidence, (conical approx.) | |
| # shells per optics module | 133    |         |
| Multilayer coating         | W/Si and Pt/C | W/Si  |
| Detectors                  | 32 × 32 pix CZT hybrids | |
| # detectors                | 8      | 17      |
| Shielding                  | CsI anti-coincidence | |

PolSTAR measures the flux, polarization fraction, and polarization angle of astrophysical sources as a function of energy. Table 1 summarizes the primary PolSTAR instrument requirements and current best estimate (CBE) of capabilities.

As mentioned above, PolSTAR has high heritage. Largely based on NuSTAR (see Harrison et al., 2013, for a description of the flight hardware and its pre-flight and in-flight performance), PolSTAR uses an identical extendable mast, structures, metrology system, and cadmium zinc telluride (CZT) detectors (Table 2). The optics use the NuSTAR design and assembly with simplified NuSTAR-heritage coatings. There are three main differences from NuSTAR: first, PolSTAR flies only one telescope rather than two. Second, PolSTAR slowly rotates every 10 minutes to minimize systematic errors on the polarization measurements. Third, PolSTAR inserts a passive scattering element into the light path and arrays the CZT detectors around this element, parallel to the incident photon path, to enable the measurement of the photon polarization; NuSTAR uses the same CZT detectors perpendicular to the incident photon path to provide focused images of the high-energy sky. The PolSTAR detection principle is very simple, essentially identical to that of the very first astronomical X-ray polarimeter, an experiment flown on an Aerobee-150 rocket in July 1968 (Figure 1). Fifty years later, PolSTAR can use modern X-ray optics and more capable detectors to provide the first sensitive polarization measurements of a representative sample of high-energy sources across a broad, scientifically compelling energy range.

#### 2. Design of PolSTAR

PolSTAR has a 3-50 keV energy range require-
Table 3: Strong heritage pervades the PolSTAR design.

| Component                  | Heritage |
|----------------------------|----------|
| Optics                     | NuSTAR   |
| Glass substrates           | NuSTAR   |
| Multilayers                | NuSTAR   |
| Mounting/assembly          | NuSTAR   |
| Extendable mast            | NuSTAR   |
| Metrology systems          | NuSTAR   |
| Focal Plane                | NuSTAR   |
| CZT material               | NuSTAR   |
| ASIC                       | NuSTAR   |
| Hybrid sensor              | NuSTAR   |
| CsI shield                 | NuSTAR   |
| Polarimeter                | LiH scatterer | Aerobee-150 |
| Design                     | X-Calibur |

It is instructive to compare the design of PolSTAR to that of other scattering polarimeters, i.e. NASA’s balloon-borne X-Calibur hard X-ray polarimeter experiment (Krawczynski et al., 2011; Guo et al., 2013; Beilicke et al., 2014a,b) and the soft gamma-ray telescope (SGT) of JAXA’s ASTRO-H mission (Fukazawa et al., 2014). Whereas PolSTAR uses a passive low-atomic number (low-Z) scattering element, X-Calibur and the SGT use active scattering elements made of heavier elements. PolSTAR’s passive LiH scattering element enables polarimetric measurements in the key 2.5-30 keV energy range. The active scattering elements of X-Calibur and the SGT result in a much higher energy thresholds (~30 keV for X-Calibur and ~50 keV for the SGT), but enable additional background suppression capabilities through the coincident detection of the Compton scattered photon and the Compton electron. In the case of the SGT, the active scattering elements enables furthermore an improved energy resolution by measuring the energy given to the Compton electron. One reason for the higher energy threshold of active scattering elements is the higher Z of active detector elements. X-Calibur uses the scintillator EJ-200 which contains roughly equal amounts of H (Z=1) and C (Z=6), and the SGT uses Si (Z=14) pad detectors. The heavier elements exhibit a much lower scattering efficiency than LiH owing to the prevalence of photoelectric effect absorption over scattering interactions. More quantitatively, the energy at which the scattering cross section starts to dominate above the photoelectric absorption cross section is 9 keV, 20 keV, and 80 keV for LiH, C and Si, respectively. The requirement to trigger the active scattering elements elevate the energy threshold for polarimetric studies even more. Using the standard Compton equations, and assuming a trigger threshold of 2 keV for the X-Calibur scintillator and 5.4 keV for the SGT Si pad detectors, we infer effective energy thresholds of 33 keV and 55 keV for X-Calibur and the SGT, respectively. Note that X-Calibur is optimized for operation on a balloon. As the residual atmosphere at a flight altitude of 125,000 feet anyhow absorbs <30 keV photons, an active scintillator...
scattering element is a good choice for X-Calibur. PolSTAR achieves excellent energy resolutions although it does not measure the energy of the Compton electrons. The main reason is that 2.5-70 keV photons loose only a small fraction of their energy when Compton scattering. For example, a $E_\gamma = 10$ keV photon scattering by $\theta = 90^\circ$ gives only $E_e = (1 - (1 + E_\gamma/m_ec^2)^{-1})E_\gamma \approx 0.2$ keV to the Compton electron (see §3.3 and Fig. 10).

2.2. Instrument Subsystems

Table 3 summarizes the heritage of the PolSTAR instrument components. PolSTAR can reuse a large fraction of the NuSTAR hardware and software. The most significant changes with respect to NuSTAR are the introduction of the passive LiH scattering element and the slow rotation of the satellite. The scattering element has heritage from the Aerobee-150 rocket experiment (Angel, 1969) and the more recent X-Calibur balloon experiment. Below we discuss key instrument subsystems in more detail.

Grazing incidence optics: The PolSTAR optics are a simplified version of the NuSTAR grazing incidence optics, fabricated by the same personnel using the same equipment. The reflecting surface of each glass substrate is coated with a depth-graded multilayer consisting of up to several hundred alternating thin layers of high and low index of refraction material. The small reflections from each layer add in phase, achieving a broad bandpass over a relatively large field-of-view. PolSTAR uses NuSTAR bilayer thickness recipes, deposited using the same custom, high-throughput planar magnetron sputtering facility at DTU-Space (Denmark’s national space institute) as used by NuSTAR. As shown by Sanchez Almeida and Martinez Pillet (1993), grazing incidence optics produce negligible instrumental polarization (< 0.1%). The PolSTAR grazing incidence optics contain 133 nested multilayer-coated shells in a conical approximation to a Wolter-I geometry (Wolter, 1952).

The only change relative to NuSTAR is that NuSTAR used two mirror coating recipes: the inner 89 shells are coated with depth-graded Pt/C multilayers which provide sensitivity up to 79 keV and the outer 44 shells are coated with depth-graded W/Si multilayers which provide sensitivity to 70 keV. PolSTAR only requires an energy
Figure 3: End-to-end Monte Carlo simulations of an unpolarized (left) and polarized (right) source in the 5-15 keV energy range, showing the four unfolded CZT detector modules surrounding the LiH stick, with Detector 17 in the center (see §3 for details about the simulations). The inset black rectangles and circles indicate the LiH stick size and location. Color scale encodes the number of hits, with red indicating the highest flux. Polarized photons preferentially scatter perpendicular to the electric field vector, creating an azimuthally asymmetric photon distribution.

range of 3-50 keV, and therefore uses the less expensive and easier to apply W/Si multilayers on all shells. Eliminating the Pt/C multilayers also provides a 20% larger effective area below 50 keV relative to the NuSTAR optics.

The final step in fabricating the nested optic is to mount the glass segments. Alternating layers of precision-milled graphite spacers and glass segments are epoxied together using one of the lathe-like assembly machines procured to build the NuSTAR optics (Figure 4). The final optics module produces an azimuthally symmetric point-spread function (PSF) with a tight 18′′ full-width at half maximum (FWHM) core and a 58′′ half-power diameter (HPD) (Harrison et al., 2013). The NuSTAR PSF varies by < 5% as a function of energy (Madsen et al., 2015).

Hailey et al. (2010a) give a detailed description of the NuSTAR optics. Zhang (2009) describes the substrate production, Christensen et al. (2011) summarizes the coatings, and the overall optics fabrication is detailed in Craig et al. (2011).

Extendable mast and structures: PolSTAR uses a build-to-print copy of the canister, deployment mechanism and mast used by NuSTAR to provide the required 10.14-m focal length (Figure 5). These would be fabricated at ATK-Goleta using the same team, facility and processes as used for NuSTAR. The flight-validated design provides the required on-orbit stiffness with a near-zero coefficient of thermal expansion (CTE).

PolSTAR uses identical benches and structures to NuSTAR, as well as a mast adjustment mechanism (MAM) at the optics end of the extendable mast that allows tip-tilt adjustment to the optics unit. The MAM provides for on-orbit refinement to the optical axis (Harrison et al., 2013). The NuSTAR benches were designed for two telescopes (i.e., two optics modules, focusing light on two focal plane modules). In order to maximize heritage with NuSTAR to allow for a build-to-print design, and to reduce costs, PolSTAR uses the same benches, but leaves one of the optical arms empty.

Polarimeter: The polarimeter (Figure 6) consists of a LiH scattering element, CZT detectors, readout electronics, and an active CsI shield. The cylindrical LiH scattering element has a diameter and length of 1 cm and 6 cm, respectively. LiH combines a low mean atomic number (implying a high probability for scatterings relative to photoelectric effect interactions) with a relatively high density of 0.82 g cm$^{-2}$ (implying a high interaction probability for a 6 cm long cylinder). LiH has flight heritage from being used as a shield on the Department of Energy’s Systems Nuclear Auxiliary Power mission. The diameter is driven by the competing desires to have a thin stick to minimize internal absorption, but to have it large compared to the PSF and pointing errors. The current design provides a balance matched to the size of the CZT detector assembly.

LiH reacts with water and oxygen. The stick would therefore be packaged in a thin Be shield,
0.5 mm in thickness along the sides and the rear end, with a 10 µm entrance window at the front (mirror) end. This is sufficient to prevent moisture (on the ground) and atomic oxygen (in orbit) from diffusing into the stick. Launch loads are estimated not to be an issue for the small cylinder. The Be housing, included in the Monte Carlo instrument simulations, has minimal impact on throughput. We are currently evaluating the merits of making the rear end of the scattering slab of Be rather than LiH. Mostly higher energy (>10 keV) photons reach the rear end. The higher density of Be (1.85 g cm\(^{-3}\)) compared to that of LiH (0.82 g cm\(^{-3}\)) leads to an increased fraction of high-energy photons Compton scattering in the rear end of the stick.

*PolSTAR* uses 17 flight-proven 32 × 32 pixel CZT hybrid detectors. Each pixel is attached to a readout circuit on a custom-designed low-noise application-specific integrated circuit (ASIC). *NuSTAR* has two focal plane modules, each constructed of a 2 × 2 array of detectors on wedge-shaped ceramic boards (Figure 7). *PolSTAR* packages the detectors slightly differently, with 16 detectors arranged in four 1 × 4 array modules forming the box that surrounds the LiH stick (Figure 2). The final detector (“Detector 17”) is located behind the LiH stick, perpendicular to the incident photon path as a tail catcher, enabling the imaging of the observed source with photons not interacting in the scattering element. *PolSTAR* uses these images to verify pointing throughout an observation.

Each pixel in the CZT detector has an independent discriminator, and individual X-ray photons trigger the readout process. On-board processors, one for each detector module, identify the row and column with the largest pulse height and read out pulse height information from this pixel as well as its eight neighbors, as on *NuSTAR*. Unlike CCDs, CZT detectors are non-integrating and self-triggering: for each incident photon the charge deposited in the detectors is collected within ≤1/2 µs and is subsequently read out with an electronic processing time of 2.5 ms per event. The event time is recorded to an accuracy of 2 µs relative to the on-board clock and with an absolute timing accuracy of ≤ 2 ms limited by the stability of the spacecraft clock. The design replicates the timing capabilities of *NuSTAR* which surpass those of X-ray telescopes with CCD detectors and have led to numerous discoveries (e.g. [Mori et al., 2013](#) [Bachetti et al., 2014](#)).
Metrology system: PolSTAR uses the NuSTAR build-to-print metrology system, consisting of two infrared lasers mounted on the optics bench that focus beams on two corresponding detectors on the focal plane bench. The lasers spots are measured to an accuracy of 10 µm (0.1″) and, combined with the instrument star camera data, track the thermal mast motions and enable accurate knowledge of the X-ray focal point position. The metrology system can be used to track the movement of the focal spot during the observations (Figure 8). Liebe et al. (2012) gives a detailed description of the system.

Shield module: PolSTAR’s equatorial orbit, identical to that of NuSTAR, provides a low cosmic-ray flux and minimizes South Atlantic Anomaly (SAA) passage, thereby enabling re-use of the NuSTAR’s low mass, cost-effective shield configuration. The polarimeter is contained inside a CsI active anti-coincidence shield with a photomultiplier tube, essentially identical to the one used on NuSTAR, but with an elongated geometry to accommodate the polarimeter. The rear portion of the CsI shield is 1.5 cm thick, and the side walls are 1.2 cm thick adjacent to the CZT detectors. The front (collimator) portion of the active shield has a wall thickness of 0.9 cm close to the CZT detectors tapering to 0.4 cm at the front side.

Calibration source: PolSTAR uses the same radioactive $^{155}$Eu calibration source and deployable mounting as NuSTAR. The 10 µCi source is mounted on the side of the shield and can be moved into the field-of-view to monitor the gain and functionality of the detectors. When not deployed, the detectors are shielded from the source. As was done with NuSTAR, PolSTAR would use the calibration unit extensively during integration and testing, but only rarely on orbit.

2.3. Mission and Mission Operations

PolSTAR would be in a similar low-Earth (~530 km), 6° inclination, near-circular orbit to NuSTAR. On orbit, PolSTAR has two operational modes. During solar-eclipse portions of orbits, PolSTAR would point at science targets and slowly rotate along the optical axis as a systematic error mitigation strategy. During the Sun-illuminated portions of orbits, the spacecraft would maintain the same pointing with respect to the science target, but would stop rotation. The solar panel array can have a fixed attitude with respect to the Sun and charge the batteries. The
typical eclipse rotation rate would be once per 10 min, or three full rotations per eclipse; for observing efficiency, the rotation rate would be tuned on a per-target basis to maintain an integer number of rotations per science observation. The settle time as the observatory goes in and out of eclipse is <15 sec. Note that this is a conservative approach, providing significant power margins for charging the batteries. *NuSTAR* nominally observes during both solar-illuminated and eclipse portions of orbits. We plan for a baseline mission with 18 months of science observations.

2.4. Returned Data

As per *NuSTAR*, for each event *PolSTAR* records the pulse height measured in the triggered CZT detector pixel and eight adjacent pixels, a time tag, and a bit indicating if the active CsI shield was triggered (54 bytes in total). *PolSTAR* can use *NuSTAR* algorithms to measure the energy of the photon striking the CZT detector based on the signal in the triggered and adjacent pixels. The processed *PolSTAR* data products include a list of events, and for each event the location of the energy deposition in the CZT detector, the sum $E_i$ of all the energies recorded in the CZT detectors owing to one or multiple interactions of the photon with the detector material, the time of the event trigger, the offsets of the optical axis from the center of the scatterer in detector coordinates, and the roll angle of the spacecraft. The data products include the instrument response matrices, i.e., lookup tables giving the distribution of the observables as function of energy, polarization fraction and angle, the offsets and roll angle. The science products consist of the constraints on the model parameters, i.e., the parameters describing the flux, polarization fraction and polarization angle as function of energy. The constraints are derived from forward folding the model with the instrument response matrices and comparing the resulting distributions with the measured ones (see next section).

3. Analysis Methods, Instrument Simulations, and Projected Performance

3.1. Analysis Methods

The polarization properties of a quasi-monochromatic electromagnetic wave can be described entirely by the four Stokes parameters (all having the units of intensity): the beam intensity $I$, the parameters $Q = p_0 I \cos(2\psi_0)$ and $U = p_0 I \sin(2\psi_0)$, describing linear polarization, where $p_0$ and $\psi_0$ are the polarization fraction and angle, and the circular polarization $V$ (Stokes, 1852). *PolSTAR* measures $I$, $Q$ and $U$ but is not sensitive to $V$. We use an analysis based on assigning Stokes parameters to each individual event (Kislat et al., 2015). The main advantage of the analysis described in the following over alternative methods (i.e. fitting the azimuthal scattering angle distribution with a suitable template) is (besides the ease of the involved calculations) that the Stokes parameters are normally distributed with a mean centered on 0 if the signal is unpolarized. The significance of a polarization detection and the confidence intervals on derived parameters (i.e. the polarization fraction and angle) thus follow from the well understood properties of Gaussian distributions. Assuming that the $i$th detected photon scattered along the optical axis, we use the position $x_i$, $y_i$ of the photon detection in the plane perpendicular to the optical axis to
calculate the azimuthal scattering angle $\alpha_i$ measured relative to the celestial North direction. We then define
\[ q_i = \cos \left( 2 \left( \alpha_i - \frac{\pi}{2} \right) \right), \]
\[ u_i = \sin \left( 2 \left( \alpha_i - \frac{\pi}{2} \right) \right), \tag{1} \]
where the terms $\frac{\pi}{2}$ account for the fact that photons scatter preferentially perpendicular to the polarization direction. As the Stokes parameters are additive, the Stokes parameters of the signal are simply the sum of the $q_i$ and $u_i$ of all $N$ observed events which pass the analysis cuts (i.e. which were not flagged as background events which triggered the CsI shield). We define the reduced Stokes parameters:
\[ Q_r = \frac{2}{\mu N} \sum_{i=1}^{N} q_i, \]  \[ U_r = \frac{2}{\mu N} \sum_{i=1}^{N} u_i \tag{2} \]
with $\mu$ being the modulation factor, i.e. the fractional amplitude of the azimuthal scattering angle distribution for a 100% linearly polarized X-ray beam. The measured polarization fraction and angle are then given by
\[ p = \sqrt{Q_r^2 + U_r^2}, \]  \[ \psi = \frac{1}{2} \arctan \frac{U_r}{Q_r}. \tag{3} \tag{4} \]

The Stokes parameters follow a Gaussian distribution, and the one sigma measurement error is given by [Kislat et al., 2015]:
\[ \sigma(Q_r) = \sqrt{\frac{1}{N-1} \left( \frac{2}{\mu^2} - Q_r^2 \right)}, \]  \[ \sigma(U_r) = \sqrt{\frac{1}{N-1} \left( \frac{2}{\mu^2} - U_r^2 \right)}. \tag{5} \]
The polarization fraction is restricted to values $p \geq 0$, with the probability distribution of the measurement $p$ given the true polarization fraction $p_0$ [Vinokur, 1965; Weisskopf et al., 2006; Krawczynski, 2011; Kislat et al., 2015]:
\[ P(p|p_0) = \frac{N \mu^2}{2} e^{-\frac{N \mu^2}{4} (p^2 + p_0^2)} I_0 \left( \frac{N \mu^2 p p_0}{2} \right), \tag{6} \]
where $I_0$ is the modified Bessel function of order zero. We use Equation [6] to estimate the measurement errors on the polarization fractions measured with PolSTAR. For this purpose, we numerically integrate Eq. (6) and find the range $[p_1, p_2]$ within which 67% of measurements are expected, such that $P(p_1|p_0) = P(p_2|p_0)$.

The polarization angle is described by a normal distribution with
\[ \sigma(\psi) \approx \frac{1}{p \mu \sqrt{2(N-1)}}. \tag{7} \]
The minimum detectable polarization (MDP) is defined as the 99% confidence level upper limit found for an unpolarized source [Weisskopf et al., 2006; Krawczynski, 2011; Kislat et al., 2015],
\[ \text{MDP} \approx \frac{4.29}{\mu \sqrt{N}}. \tag{8} \]

3.2. Measurements in the presence of backgrounds
PolSTAR intersperses science observations with slightly offset ($< 1^\circ$) observations to measure the local background (rate of events not initiated by the source, e.g. by cosmic rays and photons from the cosmic X-ray background), with offset pointing durations tailored on a per-target basis. The background regions would be chosen to avoid bright X-ray sources in the field of view.

For all but the brightest sources, $Q_r$ and $U_r$ are then measured independently for on-source and off-source observations. The Stokes parameters of the source are then
\[ Q_{\text{source}} = Q_{\text{on}} - w_{\text{off}} Q_{\text{off}}, \]
\[ U_{\text{source}} = U_{\text{on}} - w_{\text{off}} U_{\text{off}}, \tag{9} \]
where the weight $w_{\text{off}}$ is the ratio of the on-source observation time divided by the off-source observation time:
\[ w_{\text{off}} = \frac{t_{\text{on}}}{t_{\text{off}}}. \tag{10} \]
The optimal choice of $w_{\text{off}}$ depends on the expected signal rate $R_S$ and background rate $R_{BG}$ for a given source. By minimizing the expected uncertainties on $Q_{\text{source}}$ and $U_{\text{source}}$ from Equation (5), one finds the optimum value [Kislat et al., 2015]
\[ w_{\text{off}} = \sqrt{1 + R_{S/B}}. \tag{11} \]
with \( R_{S/B} = R_S/R_{BG} \). Accounting for the statistical errors on the Stokes parameters of the signal and the background, the MDP becomes

\[
MDP = \frac{4.29\sqrt{R_S + R_{BG}}}{\mu \sqrt{T(R_S + R_{BG} - \sqrt{R_{BG}(R_{BG} + R_S)})}}
\]

with \( T = t_{on} + t_{off} \) being the total on-source and background observation time. Based on the worst-case estimate of the PolSTAR background, PolSTAR would spend \( \sim 15\% \) of the observation time of the baseline mission on background observations.

An offset of the focal point from the center of the scattering element leads to an asymmetry in the azimuthal scattering distribution owing to the direction dependent absorption in the scattering element and a geometrical bias from folding the mirror PSF with the cross section of the scattering element (Beilicke et al., 2014b). The full PolSTAR data analysis corrects for pointing offsets with the help of a forward-folding analysis. The latter uses a template library of simulated events generated according to an \( E^{-1} \) power-law spectrum for a matrix of focal spot offsets with Stokes parameters \( Q, U \) being \( \pm 1 \). A particular observation is modeled by drawing events from the library to mimic the pointing history during the observation. Events with certain \( Q \) and \( U \) values are drawn to simulate a beam with certain net Stokes \( Q \) and \( U \) values, and are weighted according to the assumed energy spectrum. A chi-square minimization is then used to find the best-fit model parameters and to derive model uncertainties. The details of this analysis are the subject of a future paper.

3.3. PolSTAR Instrument Simulations and Performance

We estimate the PolSTAR performance by combining NuSTAR pre-flight and in-orbit results with Monte Carlo simulations of the polarimeter response. The simulations use the GEANT-4 simulation package with the Livermore Low-Energy Electromagnetic Models physics list (Agostinelli et al., 2003). The simulations use the results from a ray-tracing code developed for NuSTAR and include the NuSTAR-measured energy-dependent quantum efficiency of the CZT detectors. The latter include the effects of photon absorption by the cathode and the inactive transition layer between the cathode and the CZT. The simulations account for the possibility of multiple interactions of the high-energy photons within the scatterer and the detectors.

Figure 9 presents the total effective area \( A_{\text{eff}} \) of PolSTAR (including the optics, scatterer, and detector efficiencies) as a function of energy as well the product of the modulation factor \( \mu \) times the square root of the effective detection area \( \mu \sqrt{A_{\text{eff}}} \) follows the scaling law \( MDP \propto \mu \sqrt{A_{\text{eff}}}^{-1} \). For a source with a Crab-like flux and energy spectrum the 3-15 keV detection rate is \( R_{\text{src}} = 108 \) Hz (CBE, 97 Hz requirement). The modulation factor \( \mu \) gives the amplitude of the sinusoidal modu-
PolSTAR’s energy resolution is limited by the CZT detector/readout resolution to about 0.4 keV FWHM at low (<10 keV) energies. At higher energies (>10 keV) an increasing fraction of the primary photon’s energy is given to the Compton electron. Figure 10 shows the detector response for a few exemplary incident photon energies. After re-normalizing the energies deposited in the CZT detectors to the incident photon energy, we infer energy resolutions of 0.4 keV FWHM at <10 keV, 1.65 keV FWHM at 20 keV and 8.5 keV FWHM at 50 keV. The full (forward folding) analysis makes use of the fact that each ring of pixels surrounding the scattering element sees photons preferentially from the front-end of the scattering element with an energy dependent exponentially suppressed distribution of scattering locations deeper into the element. Taking into account where the photons strike the CZT detector assembly, the energy resolutions can be improved for a subset of the events. For example, the energy of 50 keV events detected at the front end of the second detector ring (counted from the front end) can be reconstructed with an effective energy resolution of 4 keV FWHM.

For dim sources, PolSTAR’s sensitivity depends on the level of background counts. We conservatively assume the background per detector measured in-orbit with the NuSTAR CZT detectors (Wik et al. 2014). For NuSTAR stray cosmic X-ray background light leaking through the aperture stop dominates the background below ~ 20 keV. Internal radiation activated by the orbital environment dominates above 20 keV. The PolSTAR background should be substantially lower than the NuSTAR background as the
Table 4: *PolSTAR* worst-case systematic errors (99.7% CL) for a source consistently offset by 3 mm (62") from the center of the field of view.

| Effect                                      | Pol. fraction error for non-rotating instrument [%] | Error suppressed by rotation? |
|---------------------------------------------|-----------------------------------------------------|-------------------------------|
| **Energy range (keV):**                     | 3-15                                               | 15-50                         |
| Detector and background inhomogeneities     | 0.25                                               | 0.25                          | Y                             |
| LiH mechanical tolerances (0.2 mm)          | 0.04                                               | 0.13                          | Y                             |
| PSF unc. (pre-/post-launch *NuSTAR* comparison) | 0.28                                               | 0.24                          | Y                             |
| 0.1 keV energy calibration error, limiting pointing offset corrections | 0.1                                               | 0.001                         | Y                             |
| Pointing knowledge error                    | 1.4/0.25<sup>a</sup>                               | 1.3/0.1<sup>a</sup>          | N                             |

<sup>a</sup> Two values are given: the first one is for the required performance (62" offset, 15° knowledge), and the second for the CBE performance (17° offset, 8° knowledge).

![Figure 12](image-url)  
Figure 12: Monte Carlo simulation of the systematic 3-15 keV polarization fraction error as a function of the pointing knowledge error. For a nominal position centered on the LiH stick (black circles), a 15° (8°) positional uncertainty translates into a systematic polarization fraction uncertainty of 0.6% (0.2%). For a nominal position centered 62" from the LiH stick center (red triangles), a 15° positional uncertainty can produce polarization fraction errors as high as 1.4%. All systematic uncertainties quoted at the 99.7% CL.

detectors do not see the sky directly but are oriented towards the scattering slab, and the latter absorbs a considerable fraction of the events at ≤ 10 keV energies. The *NuSTAR*-based estimate predicts a worst-case 5-20 keV background rate of $R_{\text{bkg}}$ =0.94 Hz. Simulations are underway to improve this estimate. Bright sources within 5° of a target cause additional stray light issues for *NuSTAR* which is only a concern for five targets in the *PolSTAR* baseline observation program (§ 4). This can be mitigated through a combination of modeling, off-target measurements, and data censoring. We are also evaluating the merits of incorporating a flight-ready stray light baffle that was built too late for *NuSTAR* to be incorporated.

The *PolSTAR* sensitivity is best between 5-15 keV (see Figure 11). The sensitivity decreases at lower energies owing to the limited scattering efficiency in the scattering element. At higher energies, the assumed steep energy spectrum of the astrophysical source and the declining mirror effective area limit the sensitivity.

We used simulated data sets to estimate systematic errors. The relevant figure of merit is the spurious polarization measured for an unpolarized X-ray beam. Table 4 lists the main sources of systematic errors before accounting for their suppression through the spacecraft roll. The largest error stems from the practical limitations of flattening the detectors. Note that the spacecraft roll suppresses most systematic errors by averaging over detector non-uniformities and spacecraft asymmetries. The main contribution to the residual systematic error is expected to come from the pointing knowledge error which varies as the spacecraft rolls. Figure 12 presents the resulting spurious polarization for a target both centered on-axis and offset by 3 mm (62°). Based on these simulations, we find that in order to meet the requirement that systematic polarization fraction
errors be ≤ 1.5%, we are required to maintain the
target within 62″ of the LiH stick center and have
reconstructed pointing knowledge ≤ 15″, where
all numbers are at the 99.7% CL. Table 5 presents
the budgeted requirements on the pointing sys-
tem derived from the science constraints on the
systematic errors and compares them to the Pol-
STAR CBE and the NuSTAR actuals. By requir-
ing pointing control ≤ 40″ (from the spacecraft)
and pointing stability ≤ 40″ (from the combined
motions of the spacecraft and mast), we can main-
tain the target within 62″ of the desired location
aligned with the LiH stick center (Root of Sum
of Squares (RSS)=57″; CBE is 17″). Using the
metrology and star tracker data on the ground,
NuSTAR achieves reconstructed pointing knowl-
dge to an accuracy of 8″ (99.7% CL). The ro-
tation of PolSTAR is sufficiently slow that this
performance is not degraded.

4. Science Investigations

We designed PolSTAR for a mission duration
of 18 months. In this time, PolSTAR can observe
the 24 sources listed in Table 6. The sources in-
clude the brightest and best-studied sources of
several source classes as well as two targets of
opportunity. The PolSTAR observations can be
used for physics-type experiments, validating or
falsifying the leading paradigms of where and how
the X-ray emission originates in these sources.
The science objectives can be summarized as fol-
lows:

Objective 1: Reveal black hole accretion
flows: PolSTAR combines spectroscopic, timing,
and polarimetric information to map the inner-
most accretion flows around stellar mass and su-
permassive black holes, where gravitational po-
tential energy is converted into radiation and
mechanical energy. PolSTAR’s 3-D information
about the structure of the accretion flow tests
theories of black hole accretion (Dovˇ ciak et al.,
2004, 2008; Li et al., 2009; Schnittman and Kro-
lik, 2009, 2010; Dovˇ ciak et al., 2011). PolSTAR’s
energy band is ideally suited to decomposing the
spectra of accreting objects into components from
accretion disks (3-8 keV; only in the case of stellar
mass black holes), hot coronal regions (3-50 keV),
coronal emission reflected and re-processed off the
accretion disk (6-50 keV, including the > 10 keV
Compton hump), and, in some cases jets (which in
some scenarios may contribute significantly above
∼ 40 keV). Einstein’s theory of General Relativity
(GR) makes as-yet untested predictions about the
behavior of matter and radiation in the extremely
curved and twisted spacetime around black holes.
PolSTAR can search for the predicted signatures
of the general relativistic Lense-Thirring preces-
sion and Bardeen-Peterson warp of the inner ac-
cretion flow in the strong gravity regime.

Objective 2: Reveal the magnetic backbone
of blazar jets: PolSTAR can test leading theories
of how actively accreting supermassive black holes
form, accelerate, and collimate powerful outflows
(jets) by accurately measuring the time evolution
of the polarization angle of the X-ray emission
from blazars (supermassive black holes with jets
pointing at us). The theories invoke a helical
magnetic field moving through the X-ray emis-
sion region, and predict smooth swings of the
polarization angle of the synchrotron continuum
emission over time (Marscher et al., 2008). Po-
larization angle swings are predicted to be more
pronounced in the X-ray band than in the radio
or optical bands because the X-ray emitting re-
gions are smaller and more uniform, as evidenced
by their fast, large amplitude flares (Krawczynski
et al., 2013).

|                  | PolSTAR Req’t (99.7% CL) | PolSTAR CBE (99.7% CL) | NuSTAR Actuals |
|------------------|-------------------------|------------------------|---------------|
| Control          | ≤ 40″                    | 11.3″                  | 8″            |
| Stability - science orbit | ≤ 40″                  | 12.9″                  | 11″           |
| Combined         | ≤ 62″                    | 17.1″                  | 13.6″         |

Table 5: PolSTAR pointing requirements.
Table 6: The 24 targets of the baseline PolSTAR mission. Tabulated minimum detectable polarization fraction (MDP) and polarization fraction errors represent the statistical uncertainties for mission requirements.

| Source       | Source Type | Flux 2-12 keV [mCrab] | On-source time [days] | MDP [%] 3-15 keV, 99%CL | Pol. Fraction Error [%] 3-15keV |
|--------------|-------------|-----------------------|----------------------|-------------------------|----------------------------------|
| Cyg X-1      | Stellar BH  | 414                   | 3.4                  | 0.2                     | 0.09                             |
| GRS 1915+105 | Stellar BH  | 717                   | 15.2                 | 0.1                     | 0.03                             |
| LMC X-3      | Stellar BH  | 20.1                  | 13.3                 | 0.7                     | 0.35                             |
| Cyg X-3      | Stellar BH  | 168                   | 0.9                  | 0.7                     | 0.30                             |
| Flaring source| Stellar BH | 82.8                  | 2.1                  | 0.7                     | 0.31                             |
| NGC 4151     | Supermass. BH| 5.9                 | 5.5                  | 2.6                     | 1.51                             |
| MCG-5-23-16  | Supermass. BH| 4.4                 | 6.3                  | 3.0                     | 1.84                             |
| MCG-6-30-15  | Supermass. BH| 3.9                 | 7.8                  | 3.0                     | 1.85                             |
| Mrk 421      | HSP Blazar  | 14                    | 5.7                  | 1.3                     | 0.71                             |
| Mrk 501      | HSP Blazar  | 5.1                   | 10.0                 | 2.1                     | 1.28                             |
| 3C 273       | FSRQ        | 4.9                   | 1.9                  | 5.1                     | 3.05                             |
| PKS 1510-08  | FSRQ        | 2.57                  | 5.9                  | 5.0                     | 3.13                             |
| Flaring Blazar| Blazar     | 10                    | 0.5                  | 7.2                     | 4.30                             |
| 1E 2259+586  | AXP         | 10.2                  | 9.3                  | 1.3                     | 0.72                             |
| 4U 0142+61   | AXP         | 4.8                   | 10.1                 | 2.3                     | 1.35                             |
| SGR 1806-20  | SGR         | 4.5                   | 11.2                 | 2.2                     | 1.35                             |
| Vela X-1     | Acc. Pulsar | 48.3                  | 0.7                  | 1.8                     | 0.81                             |
| GX 301-2     | Acc. Pulsar | 22                    | 1.9                  | 1.7                     | 0.86                             |
| Her X-1      | Acc. Pulsar | 13.5                  | 3.8                  | 1.6                     | 0.89                             |
| Sco X-1      | Acc. NS     | 1173                  | 0.1                  | 1.0                     | 0.35                             |
| 4U 1700-377  | Acc. NS     | 50.7                  | 0.6                  | 1.8                     | 0.81                             |
| Cyg X-2      | Acc. NS     | 50                    | 0.6                  | 1.8                     | 0.81                             |
| Crab         | Rot. Pulsar | 1000                  | 0.1                  | 1.0                     | 0.35                             |
| Vela         | Rot. Pulsar | 7.9                   | 2.2                  | 3.2                     | 1.85                             |

**Objective 3:** Explore the new physics of strongly magnetized neutron stars: *PolSTAR* observations of anomalous X-ray pulsars (AXPs) and soft gamma-ray repeaters (SGRs) test the magnetar hypothesis, which posits that the high-energy emission from these objects is driven by extremely strong ($10^{14} - 10^{15}$ G) neutron star magnetic fields. The magnetar model predicts extremely high (~20-100%) polarization fractions in the *PolSTAR* energy band (e.g., Shaviv et al., 1999; Fernández and Davis, 2011). *PolSTAR* observations of magnetars and strongly magnetized accreting neutron stars can afford, for the first time, the capability to detect vacuum birefringence, a prediction of quantum electrodynamics (QED) in ultra-strong magnetic fields that cannot be tested in terrestrial laboratories (Kii, 1987; Meszaros et al., 1988; Taverna et al., 2014). Again, *PolSTAR*’s broad energy band pass is key for this study as the effects manifest themselves in the 5-50 keV energy band. In accreting pulsars with magnetic field strengths of $\sim 10^{12}$ G, this band covers the vacuum resonance (where plasma and vacuum birefringence compete) as well as the cyclotron line energy (Kii, 1987; Mészáros, 1992; Krawczynski et al., 2011).
In the following, we discuss the observations for each of the three objectives.

4.1. Dissect the Black Hole Accretion Flows onto Stellar Mass Black Holes

**PolSTAR Can Measures the Polarization Properties of Multiple Emission Components**

The observation plan includes five bright stellar mass black holes in Galactic X-ray binaries with particularly deep observations of the bright systems Cyg X-1 and GRS 1915+105. **PolSTAR** can measure polarization fractions with statistical accuracies of 0.5% (1σ) in as many as 40 (Cyg X-1) to 320 (GRS 1915+105) independent temporal and energy bins. The high signal-to-noise data sets sample the polarization properties as functions of time, flux, and emission state. Figure 13 (left) shows a simulated three-day observation of Cyg X-1 in the soft state highlighting the quality of the data with detailed information about the polarization properties of the thermal disk emission and the direct and reflected coronal emission. Observing the source in different states can disentangle the polarization of the individual emission components.

**Studies of Black Hole Coronas**

Spectroscopic observations of black holes require the presence of a hot plasma to explain the power law spectral component dominating the emission at higher energies as Comptonized accretion disk photons (see e.g. Sunyaev and Thorne 1973, Thorne and Price 1975, Shapiro et al. 1976, Katz 1976, Sunyaev and Titarchuk 1980). Although coronas have been the subject of intense...
studies, their shapes, origin, and the roles they play in accretion systems are still a matter of debate (e.g. Zhang 2013; Gilfanov and Merloni 2014). X-ray polarimetry offers additional information that can be used to constrain the corona properties. Figure 13 (right) shows the simulated results of a three-day observation of GRS 1915+105 in the power law state. The polarization properties of the two corona models differ markedly. *PolSTAR*’s results enable using the corona as a diagnostic tool to understand the processes driving black hole accretion and jet formation.

**Measurement of Black Hole Spin and the Orientation of the Inner Accretion Disk**

Figure 14 shows that a seven-day exposure of GRS 1915+105 in the thermal state promises to measure its black hole spin and inner accretion disk orientation. We performed a quantitative analysis of how well *PolSTAR* can measure the spin by generating a library of fitting templates derived from modeling the thermal emission from an optically thick, geometrically thin accretion disk for an array of black hole spin values. The modeling assumes the standard general relativistic Novikov-Thorne emissivity profile, and traces photons emanating from the accretion disk forward in time (see Krawczynski 2012, for a detailed description of the general relativistic ray tracing code). The initial polarization and the polarization change associated with photon scattering off the accretion disk are modeled with the classical Chandrasekhar equations giving the Stokes parameters for the emission and reflection by a optically thick atmosphere (Chandrasekhar 1960). The fitting templates are generated by folding the simulated Stokes parameter energy spectra with the detector response. After simulating one observed *PolSTAR* data set, a least squares fit is performed to determine the best-fit black hole parameters and the associated errors. The least squares analysis (see the right panel of Fig. 14) recovers the input dimension-less spin parameter and inclination and position angle of the inner accretion disk with 1σ (combined statistical and systematic) accuracies of 0.02 (spin) and ~2–3° (inclination and position angle). The measurement errors for such a bright source are dominated by the systematic uncertainties (if we neglect astrophysical uncertainties); achieving measurements at this accuracy drive the systematic error requirements for *PolSTAR*. Spin measurements based on modeling the thermal X-ray continuum assume that the inner accretion disk is aligned with the binary orbit and that the disk emission from within the innermost stable circular orbit is negligible (e.g. see Gou et al. 2011, 2014, and references therein). Measurements based on modeling the iron line and reflection component rely on a number of assumptions regarding the geometry of the corona, the illumination profile, and the thermo-dynamic state of the reflecting disk material (e.g. see Tomsick et al. 2014, and references therein). *PolSTAR* can provide independent checks of these assumptions.

The orientation of the inner accretion disk can be compared to the orientation of the binary orbit and jet, if present (Figure 15). A misalignment between the inner accretion disk and the orbital plane would provide strong evidence for the general relativistic Bardeen-Peterson effect, while a non-zero angle between the spin axis of the inner disk and the jet would suggest mechanisms to bend the jet away from its original direction.

**Testing General Relativity’s Prediction of Lense-Thirring Precession**

Low frequency quasi-periodic oscillations (hereafter QPOs) are regularly observed in the X-ray light curves of accreting black holes (e.g. Remillard and McClintock 2006, and references therein). The QPO and power spectral break frequencies are correlated in black hole X-ray binaries (Wijnands and van der Klis 1999), and the QPO amplitude depends on system inclination (Motta et al. 2015; Heil et al. 2015). Both of these properties suggest that the QPOs are geometric in origin independent of any specific model. Broadband X-ray polarization probes geometry, and so can test the nature of black hole QPOs.

Perhaps the most successful model to explain QPOs considers precession of the inner accretion flow due to the relativistic effect of frame
Figure 14: PolSTAR can provide an independent, geometric measure of black hole spin. **Left:** Simulated seven-day observation of GRS 1915+105 in the thermal state. We used the measured energy spectrum of (Ueda et al., 2010). The lines show the polarization fractions and angles from the simulations of a 10 solar mass black hole accreting at 10% of the Eddington luminosity for different values of the black hole spin as seen at an inclination of $i = 75^\circ$ (from Schnittman and Krolik, 2009, Fig. 7). The simulated data points assume the polarization properties for the model with spin $a = 0.99$ shown by the solid line. The flux is given in the same units as in Figure 13. **Right:** results of a quantitative analysis of simulated PolSTAR data, using a least squares fit to determine the black hole spin, inclination, and the orientation of the spin axis in the sky (not shown). The white dot shows the best-fit value of the $\chi^2$ fit at $a = 0.952$, inclination=69$^\circ$ (input values: $a = 0.95$ and inclination=66$^\circ$). The white cross shows the combined 1$\sigma$ statistical and systematic errors, which are primarily systematic for this bright source.

dragging. A spinning black hole twists up the surrounding space-time, inducing Lense-Thirring precession in test mass orbits. The model of Ingram et al. (2009) assumes that the entire inner accretion flow ($r < 20r_g$) precesses as a solid body, motivated by the simulations of Fragile et al. (2007). If this is indeed the true QPO mechanism, the X-ray polarization signature from black holes should also contain a QPO. PolSTAR’s broadband sensitivity is ideally suited for this kind of study. The precession leads to quasi-periodic large-amplitude changes of the polarization of the Comptonized 10-20 keV emission. Since the thin accretion disk is not expected to precess and dominates the soft X-ray emission, low-energy (<10 keV) observations are poorly poised to address this question, while PolSTAR’s broadband sensitivity can establish the physical basis of the QPO phenomenon as predicted by the calculations of Ingram et al. (2015).

GRS 1915+105 displays very strong QPOs with periods ranging from ~10-0.1 s (e.g. Zhang et al., 2015b, and references therein). The brightness of the source, and the amplitude of the QPOs peak when the QPO period is $t_{qpo} \sim 1$ s. However, accurate time resolved polarization measurements require fairly large time bins, and therefore this favors longer QPO periods. We choose an example of $t_{qpo} = 2$ s as these considerations balance well for this period. PolSTAR measures a count rate of ~70 cs$^{-1}$ from GRS 1915+105. We assume the modulations in flux, polarization degree and polarization angle calculated by Ingram et al. (2015) for an inclination angle of $i = 70^\circ$, which is appropriate for GRS 1915+105.

We simulate the QPOs taking into account that they are quasi-periodic as opposed to periodic and are observed coincident with broadband noise, which is intrinsic to the source rather than instrumental. We simulate the phase of the QPO to drift on a random walk away from that of a strictly periodic sine wave (Figure 16, top panel),
as is observed for QPOs in GRS 1915+105 (Morgan et al. 1997). We also simulate noise, which has a broad Lorentzian power spectrum but exhibits the statistical correlations observed in the light curves of accreting objects (the so-called linear rms-flux relation: Uttley and McHardy 2001). To do this we use the exponential method of Uttley et al. (2005). We multiply the QPO and broad band noise light curves together (again to mimic statistical properties observed in the data: Ingram and van der Klis 2013) to obtain the expected number of photon counts per time bin. Finally, we simulate PolSTAR detecting an integer number of photons per time bin by choosing a Poisson random variable from the calculated expectation value for every time bin. For each photon in each time bin, we then simulate where that photon lands on the PolSTAR detector based on the true polarization vector at that time and the modulation factor of PolSTAR, \( \mu = 0.5 \).

The lower panel of Fig. 16 shows the power spectrum of the 205 ks simulated light curve. We see a QPO and broadband noise, consistent with real observations. Measurement of Stokes parameters in 0.125 s time bins are too noisy to discover a QPO in the polarization signature by simply taking a power spectrum of a Stokes parameters time series. We use the phase-folding method of Tomsick and Kaaret (2001): we filter timescales much longer and shorter than the QPO period out of the flux time series and identify peaks in the filtered time series as QPO peaks. We then assign a QPO phase value to every time bin based on the time since the last peak relative to the time until the next peak. We then stack into 16 QPO phase bins. Figure 17 shows the mean count rate (top), polarization angle (middle) and polarization degree (bottom) in each phase bin. Red points are recovered from the data and black lines are the input models. We see that the modulations in both polarization degree and angle are recovered and constant polarization properties can be ruled out with a high statistical significance. PolSTAR can

Figure 15: PolSTAR can use polarization to measure the orientation of the inner accretion disk of stellar mass black holes with an accuracy of a few degrees. Left: PolSTAR can measure the amount of misalignment between the inner disk and the binary plane owing to the general relativistic Bardeen-Peterson effect (warped accretion disk image from Lodato and Price 2010). Right: PolSTAR is also sensitive to misalignments between the disk spin axis and the jet axis. (image from Rob Hynes, www.phys.lsu.edu/~rh/).
thus detect the precession of the inner accretion flow. The PolSTAR detection would constrain accretion disk and corona models and would confirm a strong-field prediction of general relativity (e.g. Abramowicz, 2005).

**Numerical Modeling of the Data**

The studies of black hole accretion disks, corona, and jets would benefit and be in dialog with the rapidly progressing field of numerical simulations of accreting black hole systems. General relativistic magnetohydrodynamic simulations can provide a self-consistent physical model for accretion flows and jets (e.g., De Villiers and Hawley, 2003; Gammie et al., 2003) and can be used to derive testable predictions. Simulations predict that ordered magnetic fields with large fluxes (area time magnetic field strength) lead to more powerful jets (Tchekhovskoy et al., 2011), and that black holes with misaligned spin and accretion disk axes may lead to twisted jets.

**4.2. Dissect the Black Hole Accretion Flows onto Supermassive Mass Black Holes**

Accretion is key in understanding how black holes grow and influence the galaxies in which they reside. The energy released from accretion on to a supermassive black hole is 100 times greater than the gravitational binding energy of its host galaxy, and yet the mass of the black hole is 1000 times less than that of the galaxy’s bulge.
Most of the energy released in accretion is concentrated within a few tens of gravitational radii from the central black hole. This corresponds to microparsec scales, which are far smaller than the angular resolution power of current or future telescopes. Therefore, we must rely on other properties of the emission in order to understand the geometry and kinematics of the complex regions around supermassive black holes.

Traditional spectral analysis has revealed two clear components that help us characterize the inner accretion flow: the broad $\sim 5$-8 keV Fe K-\(\alpha\) emission line and the strong Compton hump component above 10 keV. These two spectral features are produced through the irradiation of the inner accretion disc by the X-ray corona, and are broadened due to relativistic effects in the strong potential well of the central black hole. NuSTAR, with its large effective area and broad energy coverage, has been ideal for measuring these two important spectral components, which has allowed for the most precise measurements of black hole spin to date (e.g. Risaliti et al., 2013; Walton et al., 2014; Marinucci et al., 2014a; Parker et al., 2014). Furthermore, NuSTAR measurements of the reverberation time delays associated with the broad Fe K-\(\alpha\) line and Compton hump indicate a small light travel distance between the continuum emitting corona and the inner accretion disc (Zoghbi et al., 2012; 2014). MCG-6-30-15 is of particular interest. While it is highly variable, the continuum emission does not appear to vary with the broad Fe K-\(\alpha\) emission, and therefore reverberation is not detected (Vaughan et al., 2003; Papadakis et al., 2005; Kara et al., 2014). Muniatti et al. (2003) suggests that this behaviour is due to strong relativistic light bending effects from a corona within a few gravitational radii of the black hole. PolSTAR can test this conjecture since the scenario predicts large polarization degrees for the reflected emission. The observed data can also be compared to simulated data from general relativistic radiation magnetohydrodynamic (GRRMHD) simulations (Sadowski et al., 2013; McKinney et al., 2014).

4.3. Reveal the Magnetic Back-bone of Blazar Jets

Active galactic nuclei (AGN) can launch extremely powerful and highly relativistic out-flows (jets). These jets appear to play an important role in galaxies and galaxy clusters as they can heat the interstellar and intracluster medium and thus impact the rate at which gas cools to form stars and feed the central black hole (e.g. Fabian, 2012, and references therein). Although jets have been studied intensively, their governing physics is still largely unknown (Boettcher et al., 2012). Over the last decade, the magnetic model of jet formation has emerged as the standard paradigm to explain the observed jet characteristics and relativistic velocities (Spruit, 2010).
PolSTAR observations of blazars can reveal the helical magnetic field by detecting swings of the polarization angle. This simulation of PolSTAR observations of a Mrk 421 flaring epoch assumes a polarization fraction of 6% (similar to what is measured at optical wavelengths, e.g., Tosti et al., 1998; Blasi et al., 2013). It clearly shows that PolSTAR has sufficient sensitivity to detect such polarization angle swings (Figure 19), which would provide clear evidence for a helical magnetic field topology (Zhang et al., 2014, 2015a).

Even if PolSTAR does not detect ubiquitous polarization swings, it can still constrain magnetic fields inside jets (Krawczynski et al., 2013). If flares are associated with the shock-compression of magnetic fields, a correlation of X-ray flux and polarization fraction is predicted. Relatedly, correlations between the X-ray spectral index and polarization fraction constrain the magnetic field homogeneity in the emitting region. Finally, multiwavelength studies, comparing simultaneous optical and X-ray polarization measurements, provide information on the co-spatiality of the optical and X-ray emitting regions. This is an essential ingredient for modeling blazar physics.

The PolSTAR baseline program includes two flat-spectrum radio-loud quasars (FSRQs), 3C 273 and PKS 1510-08. These observations can help solve a second long-standing question in the blazar community by distinguishing between the two main flavors of radiation models to explain the X-ray to gamma-ray emission: leptonic models (including both synchrotron self-Compton and external Compton models) vs. hadronic models. As hadronic models predict higher polarization fractions (up to ~ 70% in the case of a perfectly ordered magnetic field in the high-energy emission region) than leptonic models (less than ~ 30%), a measurement of very high X-ray polarization fractions would vindicate the hadronic model (Krawczynski, 2012; Zhang and Böttcher, 2013). This in turn would imply that blazars can accelerate ions to \(10^{19}\) eV, comparable to the energies of ultra-high energy cosmic rays.

### 4.4. Study of Extremely Magnetized Neutron Stars

The observation plan includes two AXPs and one SGR. Both types of sources are explained by the magnetar hypothesis as neutron stars with extremely strong \((10^{14} - 10^{15} \text{G})\) magnetic fields.
The magnetar model predicts that the soft X-ray emission is a combination of highly polarized thermal photons at energies $< 4$ keV, with resonant Compton upscattering providing a non-thermal tail at energies $> 4$ keV. The different lines show predictions for different polarization properties of the thermal seed photons from the magnetar surface (from Fernández and Davis, 2011). The bright flares from this class of objects are thought to be magnetically powered events in which the field stresses deform or break the stellar crust, releasing a large amount of energy which leads to a reconfiguration of the magnetosphere (Thompson and Duncan, 1995). The magnetic fields are so strong that they lead to a unique phenomenology with telltale observational signatures, both for flare emission, and also for the steady, persistent signal that PolSTAR can focus on through pointed observations.

The quiescent thermal ($<4$ keV) X-ray emission from magnetars is predicted to be nearly 100% polarized since the extremely magnetized plasma near the neutron star surface is birefringent, with the lowest opacity mode carrying most of the radiation (e.g., Özel, 2001; Lai and Ho, 2003). The non-thermal, low-energy X-rays ($\sim 4$-10 keV) are thought to be produced by resonant cyclotron/Compton upscattering of thermal photons in the inner magnetosphere, a process enabled by extremely strong magnetic fields. The scattering process is expected to impart a moderate polarization amplitude ($\sim 10 - 30\%$) to the outgoing photons, provided the observer samples viewing perspectives at significant angles to the local field direction. Phase-averaged observations by PolSTAR can test this basic emission mechanism since they will provide a polarization signal averaged over a variety of instantaneous magnetic viewing angles (Figure 20).

PolSTAR’s detection of the extremely polarized ($\sim 30-80\%$) phase-resolved emission predicted by the magnetar model would distinguish between alternatives such as the fallback accretion model.
which attributes the non-thermal emission to a combination of thermal and bulk Compton scattering in the accretion flow (Trümper et al., 2010, 2013), leading to lower (<10%) polarization fractions (Figure 21). This low expectation is an estimate based on non-magnetic Comptonization scenarios in laminar geometries, for which computed polarization degrees typically in this range were obtained by Sunyaev and Titarchuk (1985) in the context of black hole accretion disks.

The phase-resolved 3-15 keV polarization angle measurements can distinguish between a pure dipole field geometry and the twisted magnetic field at the heart of the magnetar model (Fernández and Davis, 2011). This is because each phase corresponds to a particular viewing orientation relative to the mean magnetic field direction sampled in the emission region, for either surface/atmospheric signals or radiation generated in the inner magnetosphere. PolSTAR can contrast polarization signatures (fraction and direction) between quiescent and post-outburst states, and search for evidence of a magnetic reconfiguration initiated by the outburst activity. At even higher (>10 keV) energies, PolSTAR can detect the flat hard X-ray tails of magnetars (Kuiper et al., 2004; Götz et al., 2006; den Hartog et al., 2008) believed to be polarized to >50% owing to resonant inverse Compton/cyclotron scattering (Baring and Harding, 2007). In such upscattering models, the polarization degree increases at higher photon energies due to an increased contribution from photons backscattered in an electron’s rest frame.

The PolSTAR observations of magnetars and accreting pulsars can probe the dielectric properties of the strongly magnetized quantum vacuum to test predictions of the theory of Quantum Electrodynamics (QED) in extremely strong magnetic fields not accessible in terrestrial laboratories. At field strengths above the quantum critical field, $4.41 \times 10^{13}$ G, the vacuum itself is polarized by QED coupling to virtual $e^+e^-$ pairs, thereby rendering the magnetosphere birefringent, i.e., the refractive index differs for the two photon polarizations (e.g., see Harding and Lai, 2006; Fernández and Davis, 2011). X-ray photons of different polarizations therefore travel at slightly different speeds, and their electric field vectors can re-orient during propagation through the magnetosphere, rotating about the local magnetic field direction. This effect is more pronounced in magnetars than for pulsars of lower magnetization.

While magnetars serve as the best type of neutron stars with which to study magnetospheric propagation influences of vacuum birefringence, accreting pulsars with much lower magnetic field strengths of around $10^{12}$ G present another opportunity to test fundamental QED predictions of dispersion of the magnetized vacuum. This is in reference to the so-called vacuum resonance feature, discussed in detail in the review by Harding and Lai (2006). This corresponds to the critical photon frequency $\omega$ where the vacuum modifications to the refractive index $n$ (which depend only on the magnetic field $B$) approximately equal the dispersion correction imposed by a plasma, which scales as $\omega_p^2/\omega^2$, where $\omega_p$ is the familiar plasma frequency. The vacuum resonance frequency therefore depends on the plasma den-
sity and the magnetic field strength. Accretion columns impacting neutron stars provide density and $B$ values for which the feature naturally appears above a few keV. In contrast, magnetars will elicit such a feature in their atmospheres at energies below 1 keV, a band that generally leads to obscuration of its signatures.

As the photon frequency rises through the resonance from plasma to vacuum dispersion domains, the character of the photon propagation eigenstates changes profoundly, leading to distinctive swings in polarization degree and angle (Kii 1987; Mészáros 1992) when integrated over emission volumes. PolSTAR is well-suited to conduct a search for QED signatures in the 5-50 keV polarization spectra of accreting pulsars at the energies of the vacuum resonance and cyclotron lines where these effects are strongest (see Figure 22 for examples). Observational demonstration of the existence of the vacuum resonance feature through X-ray polarimetry would be a huge advance for the fundamental theory of QED in strong field domains.

4.5. Observations of Accretion Powered Neutron Stars and Pulsars

The nature of the accretion flow onto neutron stars with lower surface magnetic fields (e.g. $B \leq 10^9$ Gauss) remains uncertain, despite decades of X-ray timing and spectroscopy. Persistently accreting neutron stars trace well-known “Z” and “atoll” tracks in X-ray color-color diagrams over time (Hasinger and van der Klis 1989), indicating that accretion is somehow regulated. Both strong quasi-periodic oscillations tied to the inner accretion disk and relativistic radio jets change in characteristic ways along these tracks (Migliari and Fender 2006). It is likely the case that the Z/atoll tracks, QPOs, and jet production are all affected or even driven by the interaction of the neutron star magnetic field with accreting matter, but strong evidence of this has remained elusive. By sensitively searching for changes in polarization fraction and angle along color-color tracks, PolSTAR brings an entirely new diagnostic tool to bear on neutron star accretion. Observations of bright sources such as Scorpius X-1 and Cygnus X-2, among others, can achieve this science within reasonable observing times.

PolSTAR observations of accretion-powered pulsars can demonstrate the cyclotron nature of the hard X-ray absorption lines seen in neutron stars based on energy-dependent polarization measurements across the lines. PolSTAR’s energy resolution should be sufficiently good as the cyclotron lines exhibit typical widths of 5-10 keV. The results refine neutron star magnetic field strength measurements and probe the geometry of the accretion shock (and the particle acceleration region) by distinguishing between pencil beam and fan beam approximations to the accretion column geometry (Mészáros, 1992).

4.6. Observations of the Crab and Vela Pulsars and Pulsar Wind Nebulas

The rotation powered Crab pulsar and nebula remains a prime target of high-energy astrophysical research. The system is a paragon of a high-energy astrophysical source, e.g. AGN and GRB models are based on models developed for explaining Crab observations. The recent discovery of flares with the AGILE and Fermi gamma-ray telescopes (Tavani et al., 2011; Abdo et al., 2011) may require a re-evaluation of the basic assumptions about the physical processes accelerating high-energy emitting particles in these sources (Clausen-Brown and Lyutikov, 2012; Cerutti et al., 2012; Lyubarsky, 2012). As one of the brightest sources in the X-ray sky (flux of $3 \times 10^{-8}$ erg cm$^{-2}$ sec$^{-1}$ in the 1-10keV range, Kellogg, 1971), it is the only one for which X-ray polarization has been measured with a high degree of confidence (Weisskopf et al., 1978).

PolSTAR would observe the Crab and Vela pulsars and pulsar wind nebulae. Although PolSTAR does not have imaging capabilities, phase-resolved analyses can be used to constrain the polarization properties of the magnetospheric emission. The phase- and energy-resolved polarization fraction and angle can discern synchrotron and curvature emission (because of their contrasting position angle sweeps with pulse phase) and provide excellent diagnostics on the locale of the magnetospheric emission (see Dyks et al., 2004 and references
Figure 23: PolSTAR covers the most important emission components of accreting black holes, blazars, and accretion, rotation, and magnetically powered neutron stars. The measurement of the polarization properties of several emission components allows for powerful tests of the leading models.

5. Summary

The PolSTAR X-ray polarimeter offers the capability to measure the linear polarization of X-rays over the broad 2.5-70 keV energy range. The approach combines a Si/W multilayer coated X-ray mirror assembly with a scattering element and CZT solid state detectors, all covering the 2.5-70 keV energy range. The combination leads to a high O(100%) efficiency at energies exceeding 10 keV. The modest scattering efficiency at <10 keV energies is offset by the large and approximately constant modulation factor of $\mu \approx 0.5$. For the brightest objects of the baseline observation program (accreting stellar mass black holes, neutron stars, blazars), PolSTAR delivers data sets with very high signal to noise ratios allowing dynamic studies of such phenomena as QPOs and blazar flares. Even for the dimmest of the objects of the baseline observation program (AGNs and magnetars), the polarization measurements can answer important astrophysical questions.

A scattering polarimeter like PolSTAR offers a broad energy range covering the most important emission components of black holes, jets, magnetars and neutron stars (Figure 23). Simultaneous observations of multiple emission components are not only crucial for disentangling the polarization properties of the individual components, but also for measuring the relative polarization angles and thus the relative orientation of different emission regions. The measurements of the polarization of key accreting black hole components can be used to tighten existing constraints on the black hole parameters (including the black hole spin) and to study the corona whose geometry is poorly understood and plays an important role in X-ray spectroscopy and timing black hole studies. Furthermore, the hard X-ray coverage has the potential to reveal the origin of low-frequency QPOs and possibly to detect Lense-Thirring precession in the extreme spacetime of rapidly spinning black holes. The observations of blazar jets have the potential to validate the paradigm that helical magnetic fields accelerate and collimate AGN jets. The observations of magnetars enable the confirmation of the magnetar paradigm and the detection of polarization from resonant cyclotron scattering. Furthermore, a mission like PolSTAR can scrutinize the emission for imprints of the birefringent QED vacuum. The science described here can best be addressed with a broad energy band-
pass polarimeter like PolSTAR. As mentioned in the introduction, we are considering proposing a somewhat larger version of PolSTAR to the next MIDEX announcement of opportunity.

At the time of writing this article we are preparing a first one-day long science flight of the balloon-borne X-Calibur experiment planned for Fall 2016. As mentioned above, X-Calibur is (like PolSTAR) a scattering polarimeter. The one-day flight should allow us to observe the Crab, the stellar mass black holes GRS 1915+105 and Cyg X-1, and the accreting neutron star Sco X-1. Depending on the flux state of the sources during the observations, X-Calibur will be able to measure the polarization of the 30-60 keV X-ray emission down to 5-10% polarization fractions. The most significant results of the one-day flight will be the polarization properties of the power law (presumably corona) emission from GRS 1915+105 and Cyg X-1, and the energy resolved polarization properties of the Crab emission. The one-day balloon flight will be followed up by a ~28-day long LDB (long duration balloon) flight from McMurdo (Ross Island) in December 2018-January 2019. The longer flight will be used to measure the X-ray polarization of a sample of accreting X-ray pulsars, flaring X-ray binaries, and the extragalactic radio galaxy Cen A.

X-ray polarimetry missions can build on the successes of the past and current X-ray missions and are complementary to future X-ray missions. For example, traditional X-ray spectroscopy observations have revealed the broad Fe K-α line at ~5-8 keV and the Compton hump above 10 keV in the energy spectra of stellar mass and supermassive black holes (e.g. Reynolds [2014] and references therein). These features can be well described through a relativistic reflection model in which an irradiated inner accretion disc produces fluorescence and Compton scattering that appears to the observer to be blurred due to relativistic effects close to the central black hole (Fabian et al. [1989]; Ross and Fabian [1993]). The AGN Fe K-α observations constrain black hole spins to ~1% statistical uncertainty (e.g. Risaliti et al. [2013]; Marinucci et al. [2014a]). Recently, AGN X-ray reverberation mapping has indeed confirmed the basic premises of this model (Kara et al. [2013]; Zoghbi et al. [2014]; Uttley et al. [2014]). X-ray polarimetry would allow us to further refine our knowledge about the geometry of the inner flow, and thus improve on the systematic uncertainties associated with the spin measurements (Dovciak et al. [2004]; 2008; Li et al. [2009]; Schnittman and Krolik [2009]; 2010; Dovciak et al. [2011]). These measurements are of particular interest in light of ESA’s planned Athena mission (planned to be launched in 2028) (e.g. Wilms et al. [2014]). Athena, with unprecedented effective area (2 m$^2$ at 1 keV and 0.25 m$^2$ at 6 keV), has the ability to put strong constraints on the broad iron line in a large sample of supermassive black holes out to a redshifts of 2 or 3. Measuring the distribution of spin in high-redshift quasars constrains the growth of supermassive black holes in the universe (e.g. Berti and Volonteri [2008]). The X-ray polarimetric observations of AGNs in our local Universe would directly benefit those studies.

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