PROCEEDINGS OF SPIE

SPIEDigitalLibrary.org/conference-proceedings-of-spie

The Globe Orbiting Soft X-ray (GOSoX) polarimeter concept study

Marshall, Herman, Heine, Sarah N. T., Davidson, Rosemary, Garner, Alan, Gullikson, Eric, et al.

Herman L. Marshall, Sarah N. T. Heine, Rosemary Davidson, Alan Garner, Eric M. Gullikson, H. Moritz Günther, Christopher Leitz, Rebecca Masterson, Eric D. Miller, June S. Stenzel, William W. Zhang, Rozenn Boissay-Malaquin, Ilaria Caiazzo, Deepto Chakrabarty, Luigi G. Gallo, Ralf K. Heilmann, Jeremy Heyl, Erin Kara, Norbert S. Schulz, "The Globe Orbiting Soft X-ray (GOSoX) polarimeter concept study," Proc. SPIE 11822, Optics for EUV, X-Ray, and Gamma-Ray Astronomy X, 118220O (23 August 2021); doi: 10.1117/12.2596186

Event: SPIE Optical Engineering + Applications, 2021, San Diego, California, United States

The Globe-Orbiting Soft X-Ray (GOSoX) Polarimeter Concept Study

Herman L. Marshall[a], Sarah N. T. Heine[a], Rosemary Davidson[a], Alan Garner[a], Eric M. Gullikson[b], H. Moritz Günther[a], Christopher Leitz[c], Rebecca Masterson[a], Eric D. Miller[a], June S. Stenzel[a], William W. Zhang[d], Rozenn Boissay-Malaquin[d,e], Ilaria Caiazzo[f], Deepto Chakrabarty[a], Luigi C. Gallo[g], Ralf K. Heilmann[a], Jeremy Heyl[h], Erin Kara[a], and Norbert S. Schulz[a]

[a]MIT Kavli Institute, Cambridge, MA, USA
[b]Lawrence Berkeley National Lab, Berkeley, CA, USA
[c]MIT Lincoln Lab, Lexington, MA, USA
[d]Goddard Space Flight Center, Greenbelt, MD, USA
[e]University of Maryland Baltimore County, Baltimore, MD, USA
[f]California Inst. of Technology, Pasadena, CA, USA
[g]Saint Mary's University, Halifax, NS, Canada
[h]University of British Columbia, Vancouver, BC, Canada

ABSTRACT

We describe an implementation of a broad-band soft X-ray polarimeter, substantially based on previous designs. This implementation, the Globe-Orbiting Soft X-ray Polarimeter (GOSoX) is a SmallSat, designed for NASA's call for Astrophysics Science SmallSat Studies (AS^3). As in a related mission concept PiSoX, the grating arrangement is designed optimally for the purpose of polarimetry with broad-band focussing optics by matching the dispersion of the spectrometer to a laterally graded multilayers (LGML). The system can achieve polarization modulation factors over 90%. For GOSoX, the optics are lightweight Si mirrors in a one-bounce parabolic configuration. Critical Angle Transmission (CAT) gratings from opposite sectors are oriented to disperse to a LGML forming a channel covering the wavelength range from 31 Å to 75 Å (165 - 400 eV). Upon satellite rotation, the intensities of the dispersed spectra, after reflection and polarizing by the LGMLs, give the three Stokes parameters needed to determine a source's linear polarization fraction and orientation. The design can be extended to higher energies as LGMLs are developed further. We describe the potential scientific return and traceability, proposed mission concept and design, and estimated mission costs, following the results of the JPL Team X concept study.

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

1. INTRODUCTION

This instrument, the Globe-Orbiting Soft X-ray Polarimeter (GOSoX), would be the first spectropolarimeter for the soft X-ray band. GOSoX will expand our view of polarized emission across the electromagnetic spectrum, complementing results from the Imaging X-ray Polarimetry Explorer (IXPE, 2-8 keV[1]), by measuring sources and their spectral components that cannot be examined with IXPE. The approach is nearly identical to that of a mission proposed for the NASA Astrophysics Pioneers program, PiSoX.[2] For this paper, we will describe the basic design of GOSoX and the concept study of the GOSoX mission, as carried out by JPL Team X (hereafter, Team X), funded by the NASA AS^3 program. The AS^3 program was an opportunity for mission concept studies in the scope of CubeSats, SmallSats, and secondary RideShare opportunities. We present the concept study carried out by Team X that examined all phases of the proposed mission, leaving out details of the instrument that can be found in the PiSoX paper.

Further author information: (Send correspondence to H.L.M.)
H.L.M.: hermanm@space.mit.edu, Telephone: 1 617 253 8573

Optics for EUV, X-Ray, and Gamma-Ray Astronomy X, edited by Stephen L. O'Dell, Jessica A. Gaskin, Giovanni Pareschi, Proc. of SPIE Vol. 11822, 118220O · © 2021 SPIE · CCC code: 0277-786X/21/$21 · doi: 10.1117/12.2596186

2. SCIENCE OBJECTIVES

The science objectives and observing plan are the same as for PiSoX, so we refer the reader to the PiSoX paper[2] for more details. In one year, the GOSoX mission would obtain spectropolarimetric measurements across the 0.2-0.4 keV band for about a dozen sources to measure polarization fractions as small as 3-10%. About half of the targets are isolated neutron stars with strong magnetic fields and the other half are active galaxies, including blazars.

It is customary to assess the performance of a polarimeter by the minimum detectable polarization, MDP, that is achievable in a given observation time. The MDP is usually defined as the lowest level of polarization that we can distinguish from random noise at the 99% confidence level. For an instrument with modulation factor μ, MDP $= 4.29/(\mu R T^{1/2})(R+B)^{1/2}$,[3] where μ is the ratio of the polarization-modulated signal to the average, R is the source count rate, T is the exposure time, and B is the background rate. When B is small, as it is for our design,[2] then MDP $= 4.29/(\mu[RT]^{1/2})$, so for a given exposure time and source flux density MDP $\propto 1/(\mu\mathcal{A}^{1/2})$, where $\mathcal{A} \equiv \int A d\lambda$ is sometimes referred to as the integrated area of the system.

Briefly, some of the strongest magnetic fields in the universe are observed in isolated neutron stars, making them ideal for studying the interaction of matter and fields, as well as for testing quantum electrodynamics (QED) effects.[4] GOSoX can be used to sample a large range of neutron star B-fields with different targets to understand the origin of atmospheric absorption lines and test atmosphere models. Neutron star atmospheres are generally observable only below 1 keV, which makes these measurements impossible for IXPE but perfect for GOSoX. Several of the candidate targets have absorption features in their phase-averaged 0.25-0.5 keV spectra that are thought to arise from proton cyclotron features when $B \gtrsim 10^{13}$ G[5–7] or gravitationally redshifted O VIII.[8] As the lines appear to be resolved with FWHM of $\sim$ 150 eV level,[5,7] we require a spectral resolution of better than 50 eV in order to measure the polarization change through the line, as predicted in atmosphere models.[9,10] To temporally resolve pulse variations requires an MDP $<$ 30% in 10 pulse phase bins, or a pulse averaged MDP of $\leq$ 10%. With periods in the 3-20 s range,[11] we require X-ray time-tagging to $<$ 0.1 s.

The soft X-ray emission of active galaxies can result from several different mechanisms that can be distinguished with observations by GOSoX, ranging from strongly magnetized jets to mildly polarized accretion disk atmospheres and coronae that current observations cannot discriminate. The soft spectral components of these sources makes GOSoX an excellent instrument for exploring models of the soft X-ray emission. While the jet launching mechanism is not completely understood, it is clear that magnetic fields must be involved via the Blandford-Payne or Blandford-Znajek mechanisms.[12] With GOSoX, we will measure the uniformity and orientation of the magnetic field in blazar jets to constrain their origin and evolution.

Some AGN, such as the subclass known as narrow line Seyfert 1s (NLS1s),[13] have an X-ray spectral component below 1 keV – a soft X-ray excess over a power law component that dominates the spectrum above 2 keV.[14] The nature of the soft excesses is uncertain and GOSoX would help us understand them. The flatter power law that dominates the 2-10 keV band is most often modeled as reflection of X-rays from a hot corona off of an accretion disk,[15,16] and its polarization properties are observable by IXPE. The polarizations of soft excesses, however, would only be measurable by GOSoX.

The science objectives were developed for an instrument with $\mathcal{A} = 8$ cm^{2}Å, achievable with our design (§ 3). The nominal observing plan includes 6 targets in each of our primary categories: neutron stars and AGN with soft spectra. A "minimum mission" we consider scientifically useful is to obtain $>$ 10% MDP for each of 3 sources from both of our two categories, driving the instrument requirements.[2] Published spectra for these sources were used to compute count rates in the GOSoX instrument. In addition to the science targets is a "null" calibrator – a bright, unresolved binary of cool stars with thermal coronae. The observing plan does not include the many other sources that may be polarized and are comparably bright to the primary targets. These secondary targets include magnetic dwarf novae, nearby Galactic X-ray binaries in outburst and other AGN that may be of interest to guest observers after the first year of operation. The science objectives and the observing plan are the same as for PiSoX and we refer the reader to the PiSoX paper[2] for more details.

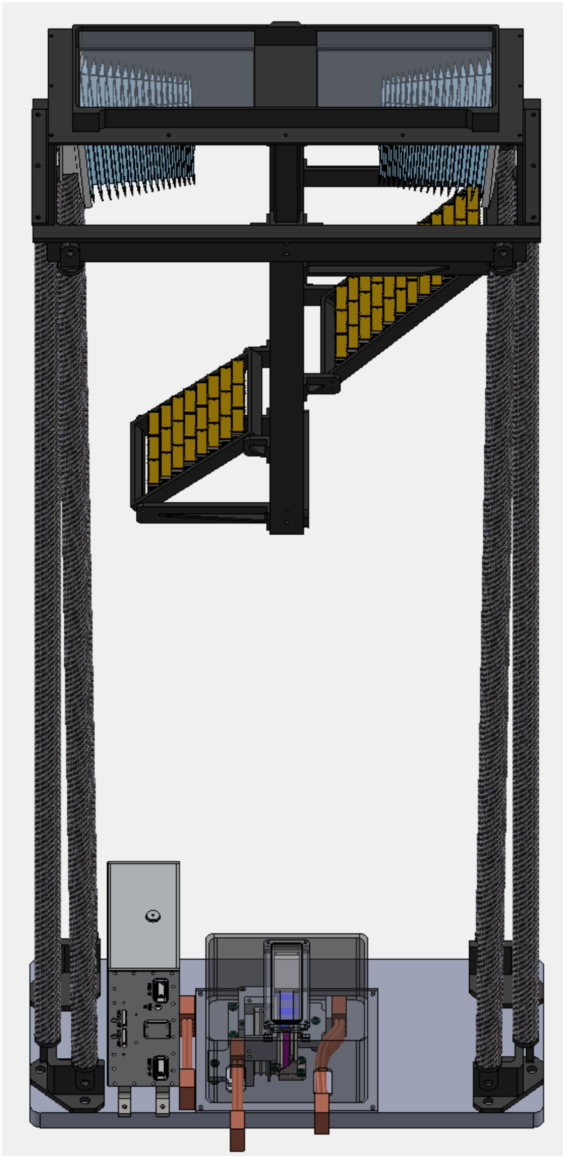

Figure 1. Cutaway rendering of the configuration for the GOSoX instrument which is the same as for PiSoX.[2] It is about 1.25 m tall, and has Si mirrors made of curved and polished segments about 100 mm tall, as developed by GSFC (colored light blue). The optics section is 400 mm wide, 400 mm tall, and 100 mm deep, including the gratings (colored gold). The orientation of the grating bars is parallel to the long dimension of the aperture and gratings are blazed so that they disperse a focused spectrum at the laterally graded multilayer mirror (LGML, magenta) inside the detector housing. The detector housing is shown as a translucent box but is designed to be light-tight with optical blocking filters. There is only one polarization channel, so the instrument has to be rotated through 180° during observations.

3. PAYLOAD DESIGN

The science instrument leverages previous funding various grants to make focusing optics, multilayers, gratings, and CCDs. Together, these high technical readiness level (TRL) technologies enable us to build GOSoX with minimal risk. Schematically, the design is the same as for PiSoX,[2] which itself was modeled after the REDSoX Polarimeter.[17] Here, we just provide an overview of the design.

3.1 Instrument Components

The GOSoX mirrors are based on the Si metashell optics developed by the Goddard Space Flight Center (GSFC) group under the direction of Dr. William Zhang.[18] The point spread function (PSF) of the mirror assembly will have a half-power diameter (HPD) of $\lesssim 5''$. Mirrors should be maintained at +20 C during flight to avoid contamination buildup. For more details, see the PiSoX paper.[2]

As with the REDSoX Polarimeter, we employ Critical Angle Transmission (CAT) gratings[19–21] developed in the Space Nanotechnology Lab (SNL) at MIT. Over a dozen CAT gratings of 200 nm period and 4 μm membrane thickness have been tested in the MIT polarimetry beamline, including several in a 27 mm square format fabricated as part of *Arcus*[22] phase A development. Efficiencies of 20% are achieved in lab measurements in first order as needed for GOSoX (Garner, et al. in prep.). Alignment is performed at the mount and assembly level based on a method prototyped for *Arcus*.[23]

LGMLs have been made by Eric Gullikson at the Lawrence Berkeley National Lab (LBNL) Center for X-ray Optics that are suitable for our design. The $Cr/B_4C/Sc$ layer combination has a reflectivity over 7% between 31 and 70 Å based on measurements at the Advanced Light Source at LBNL.[24,25] In this design, with only one multilayer, the Stokes I, Q, and U are best measured by rotating the multilayer's orientation though at least 180°. This rotation must be provided by the spacecraft (§ 4). The data would then be associated with the position angle (PA) of the LGML as projected onto the sky and the modulation curve with PA would be fit to obtain I, Q, and U, providing the polarization fraction and the electric vector PA.

The CCD detectors for GOSoX are designed and fabricated by the MIT Lincoln Laboratory (MITLL). The two CCID-94 devices baselined to fly on GOSoX are backside-illuminated (BI), 50×25-mm (2048×1024-pixel), frame-store CCDs that are equivalent to two side-by-side Suzaku CCID-41 devices, with 24-μm pixels. They trace direct heritage from the Suzaku XIS BI CCD that performed exceptionally well for the nearly 10-year mission lifetime in a low-Earth, high-inclination orbit that regularly traversed the South Atlantic Anomaly.[26,27] CCD features include a 3-phase polysilicon gate structure, low noise (<4 e^-) readout amplifiers, and charge injection to ameliorate the effects of in-orbit particle damage.[28]

One CCD will record the spectrum polarized by the LGML, and the second will image zeroth-order to ensure proper acquisition of the target and monitor its broad-band flux, giving us a redundant measurement of Stokes I. Frame integration times will be 1 s but have an additional "parallel sum" mode to provide time resolution of better than 100 ms for phase-dependent observations for pulsars. The CCD spectral resolution is sufficient to reduce background and to separate overlapping orders in the dispersed spectrum. The temperature will be controlled to between -50 C and -60 C to $\pm$ 1 C by thermo-electric coolers (TECs). While Team X suggested that the instrument use cryocoolers due to sturdiness and experience, TECs have excellent flight heritage and are much lighter. The TECs for GOSoX are manufactured by II-VI Marlow, which fabricated similar TECs for Suzaku XIS that worked flawlessly over the course of the 10-year mission. See § 9.2 for further discussion of the cooling system tradeoff. There will be a warm, thin Al-coated polyimide filter and the CCD is coated with 50 nm of Al to block optical light. The power needed to run the CCDs is about 15 W; Team X added another 13 W for a thermal control system for a total instrument power of 28 W, or 40 W with margin (see Table 1).

Particle and sky background are negligible.[2] Using detailed analytical models of the reflectivity and QE curves and raytracing, we obtain $\mathcal{A} = 8.3$ cm^{2}Å, consistent with the 1 year science plan.[2] The minimum mission would still be possible if the overall performance is degraded to $\mathcal{A} = 4$ cm^{2}Å, giving us about 108% margin. The zeroth order count rates for our targets are 0.2-20 cnt/s.

3.2 System Considerations

This section describes other aspects of the design of GOSoX. Tolerances were determined using analytical formulae verified by raytracing.[2,17] Mechanical machining and assembly tolerances are sufficient for most aspects of the system. Alignment of the gratings and the grating assemblies is carried out on an optical bench and in the MIT X-ray Polarimetry beamline; see the PiSoX paper for details.[2] The payload component masses and structure are the same as in PiSoX, for a total instrument mass of 30 kg,[2] The Team X estimate of the instrument mass came to 46 kg, due to additional mass for a cooling system and for structural stability (see Table 1).

In the MIT X-ray Polarimetry beamline, we can test combinations of components such as the optics module, which is a combination of the mirror and grating assemblies, and the focal plane, which has both flight CCDs and the LGML. The beamline is an 11m long X-ray beamline that is extendable to 17m and is described elsewhere.[24,25,29–31] Using a laser-alignment tool, the GOSoX CAT gratings will be aligned relative to one another as a complete subsystem and to an optical alignment cube mounted to the grating assembly.[31] Using the beamline, we will be able to separately test each component of GOSoX, from optics through the focal plane. Furthermore, the assembled payload will fit into the 1.3m diameter chamber to complete the performance and alignment testing. MIT is acquiring a simple module of Si shell optics from GSFC to be installed within the MIT X-ray beamline in the fall of 2021. Thus, we will complete an end-to-end test of the polarimeter design

Table 1. JPL Team X Mass and Power Estimates

Component	Mass (kg)			Power (W)		
	CBE[a]	JPL Margin	MEV[b]	CBE[a]	JPL Margin	MEV[b]
Optics	5.0	2.1	7.1	0	0	0
Electronics	4.3	1.9	6.2	15	6.5	21.5
Structures	30.8	13.3	44.1	0	0	0
Detector	0.55	0.25	0.8	0	0	0
Thermal System	5.6	2.4	8.0	12.8	5.4	18.2
Total	46.3		66.2	27.8		39.7

[a] Current Best Estimate
[b] Maximum Expected Value

with all essential components: a 100% polarized source, focusing optics, an internally aligned grating assembly, a multilayer mirror, and the current lab CCD detector, raising the TRL of the integrated system and validating assembly procedures.

3.3 JPL Team X Analysis

During the Team X study, the GOSoX science goals and requirements were used to approximate the mass and power for first the payload, followed by the entire spacecraft. The instrument is broken down into the optical, electronics, structures, detector, and thermal mass and power, as shown in Table 1. The JPL-imposed mass and power margins were 43%, conservatively adding 10% on top of a standard 30%. The mass and power estimates for all components are based on estimates from both the GOSoX team and Team X. For example, the mass estimate of the grazing incidence mirror assembly has been provided by GSFC, while the mass of the components that make up the door assembly have been estimated by Team X.

4. SPACECRAFT

Generic requirements on the spacecraft and operations were evaluated by Team X. Vendor-specific spacecraft characteristics will follow.

4.1 Overview from JPL Team X

The concept study began with a three channel design but downscoped to a single channel for detailed study, which is reported here. See § 9.1 for a discussion of the tradeoff involving the number of channels. In order to fit in the Astrophysics Science SmallSat Studies program, the GOSoX spacecraft must be in the CubeSat, ESPA or ESPA-grande class form factor. Except for the spatial limitations of the ESPA Grande rideshare, Team X concluded that the instrument has sufficiently low mass, power and data volume and a sufficiently coarse pointing requirement that the instrument could be accommodated on an off-the-shelf small spacecraft bus from a commercial spacecraft vendor.

With margin, the total satellite mass was 246 kg, which is comfortably within the limit for ESPA grande. The daily data volume is 20 Mbits, while peak data volume during calibration is 150 Mbits. The study assumed that the instrument is thermally decoupled from the spacecraft and provides its own radiators and shrouds. The instrument imposes no special environmental constraints on the spacecraft.

Mechanically, the instrument must be aligned with the spacecraft rotation axis and has a narrow field of view that is along that axis. The spacecraft attitude determination and control system (ADCS) is required to hold the orientation of the telescope's boresight to $<20''$ (3σ).[2] In order to change the position angles of the LGML mirrors with respect to the sky, the spacecraft roll angle will be varied to span a range of 180° by continuously rotating or stepping at periodic intervals through the observation. Team X settled on an 3-axis stabilization approach with 11 roll positions at 18° intervals per orbit for an average of about 3 minutes per dwell. The peak power needed is less than 100 W. Assuming articulated solar panels, the solar array area needed was estimated to be 6 m^2, given the requirement for $\pm 90°$ roll.

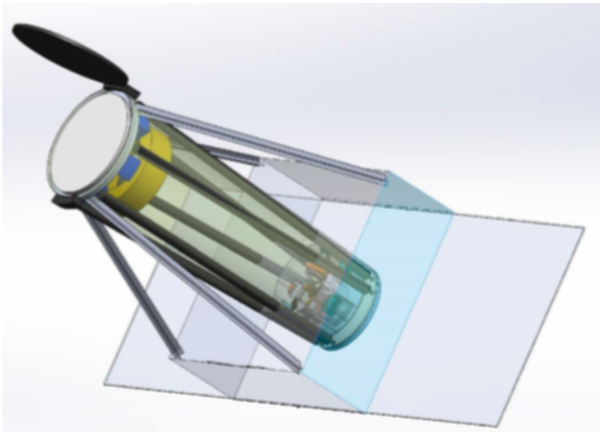

Figure 2. Notional configuration of the GOSoX instrument and spacecraft bus. The spacecraft components would occupy the translucent rectangular box at the bottom right The instrument design for this rendering from early in the concept study consisted of three independent channels for circular entrance aperture. The instrument complement was later scaled down to just one channel. (Image credit: JPL Team X.)

Another potential challenge involves the mission lifetime. Team X found that GOSoX would have a high probability of completing a 1 year mission when starting at an altitude of 500 km if the ballistic coefficient, $BC = m/A/C_d > 65$ kg/m^2, where C_d is about 2.2. With a solar array size of $A = 6$ m^2 and mass of $m = 246$ kg, $BC = 18.6$ kg/m^2. While ballast could be added due to the mass margin in the ESPA Grande, it would not be enough to raise BC sufficiently. A higher altitude orbit could be requested to compensate or another arrangement of the solar panels could be devised.

Team X compared these payload accommodation requirements against the capabilities of commercially available SmallSat buses in a database that is maintained by JPL and concluded that they can be met by an off-the-shelf small spacecraft bus from several commercial vendors, such as Blue Canyon Technologies.

4.2 Blue Canyon Technologies

One spacecraft provider that may be able to provide the spacecraft bus for GOSoX is Blue Canyon Technologies (BCT). The X-SAT series Venus class bus can meet the pointing requirement with a stated performance of 0.002° (1σ).[*] The Venus class has a 15″ ESPA ring mounting interface while the X-SAT Saturn class interface is a 24″ ring, which is appropriate for ESPA Grande. Both versions can handle a payload mass of at least 90 kg and provide 100 W power easily with one solar panel "wing". Additionally, the bus can meet the GOSoX roll requirement of 1°/sec. Because of the experience and expected costs of this vendor, BCT is a suitable vendor for the GOSoX budget, launch rideshare, and pointing needs.

There are two primary issues that the GOSoX project would need to address with BCT. The first is thermal; the standard X-SAT assumes that the payload can handle all of its own heat dissipation. More thermal analysis is needed to determine how the GOSoX payload can provide its own thermal management. The second challenge involves payload accommodation. The instrument is just over 1.2 m long but the off-the-shelf BCT X-SAT indicates that the maximum payload dimension should be 1 m, depending on the launch vehicle fairing. Given that the longest dimension of the ESPA Grande envelope is 1.42 m (with a 5 m rocket fairing), there are a few options for accommodation: 1) embed the telescope partly into the bus, 2) expand the optical bench in flight using a short boom, 3) adopt an unconventional orientation/configuration, or 4) reduce the instrument length. All four options are feasible at some level, so a bit further study is required to determine the most cost-effective accommodation. Figure 2 shows a notional configuration suggested by Team X, for which the spacecraft is mounted about the base of the instrument, with the entire satellite fitting within the ESPA Grande volume constraints.

4.3 NanoAvionics

The GOSoX team worked with NanoAvionics for the PiSoX mission proposal.[2] The result was a custom platform including subsystems from NanoAvionics and other companies with high heritage in low Earth orbit (LEO),

[*]See `https://www.bluecanyontech.com/static/datasheet/BCT_JanTradeshow_Brochure_04-2021.pdf` for BCT X-SAT specifications.

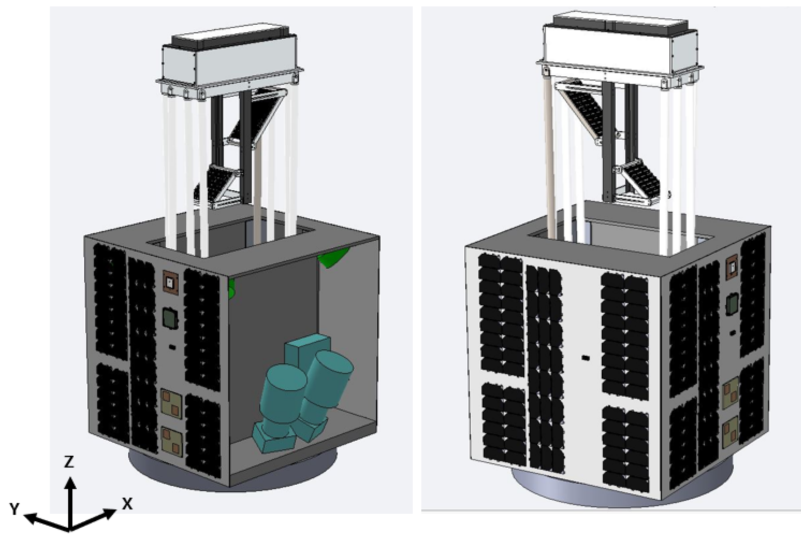

Figure 3. Renderings of the PiSoX design, based on a spacecraft supplied by NanoAvionics.[2] It has an external radiator panel that is hidden on the side with the star trackers. Generally, the $+Z$ and $-Y$ faces are in shadow, while $+Y$ and $\pm X$ are used for power generation. In both cases the sheathing and thermal layer around the payload are not shown.

with a cold-redundant, dual string architecture. See the PiSoX paper for more details.[2] Briefly, the structure is composed of a 700 mm $\times$ 700 mm baseplate, below which the Ruag PAS 610S separation system is mounted for attachment to an ESPA Grande ring. The GOSoX instrument is centrally mounted on top of this base plate with shear panels incorporating most of the spacecraft subsystems around the instrument. This concept embeds the instrument in the bus, ensuring a fit within the ESPA Grande payload accommodation volume. Three communications channels are available, all with redundant components. A link budget was established for each of UHF, S-Band and X-Band assuming an orbital altitude of at least 550 km. X-band can be used in ground station tracking mode with a 5 m dish for all elevations above 5°. A rendering of the structure and subsystems is provided in Fig. 3. One feature of this design is that $m/A = 210$ kg/m^2,[2] giving $BC = 95$ kg/m^2, which is sufficient to ensure a year of operation if launched into a 500 km orbit. The small area derives from the use of body-mounted solar panels, which reduces A considerably.

5. MISSION DESIGN

5.1 Launch Vehicle and Orbit

The mission is designed for operations in LEO for a lifetime of one year. While low inclinations (equatorial orbits) are preferred due to reduced particle background, a sun synchronous orbit would allow for greater rideshare opportunities as well as greater sun exposure during the roll needed to obtain data.

5.2 Operations

Given the long exposures, satellite maneuvers and data download are only required only about once per week. At the maximum instrument data rate and 40% observing efficiency, a week of data amounts to about 300 MB, easily downloaded in a few minutes via X-band. Operations are based on one S-band uplink per day and one X-band contact per week. Alternatively, data can be downloaded via S-band in 2-3 passes per day.

6. TECHNOLOGY DEVELOPMENT

Several systems of GOSoX instrument – the Si metashell mirrors, the CAT gratings, the CCID-94 detectors and the LGMLs – would be flown in orbit for the first time on this mission and are vital to future missions. Thus, GOSoX would raise the TRLs of these components. See the PiSoX paper for development prospects.[2]

Table 2. Operations Phases

Launch & Deployment	Science Operations	End of Life
• Liftoff • Orbital Insertion • Post-Launch Test • First Light and Downlink	• First Target Observation • Primary Mission • Extended Mission	• Loss of altitude due to atmospheric drag • Disintegration in Earth's atmosphere

7. CONCEPT OF OPERATIONS

7.1 Design Reference Mission

We have identified 10 sources to advance our science goals. Additionally, we will first use Capella as a null reference for calibration. Capella is a bright X-ray source that has been used for past missions, such as the Chandra X-ray Observatory's Low Energy Transmission Grating and is likely to be unpolarized because the X-ray emission is bremsstrahlung from hot plasma of the stellar coronae. The primary goal of this calibration observation is to assess and correct for unexpected bias. Once data from Capella has been analyzed, processed, and calibrated, we will study the targets in a sequence that prioritizes the sources with the highest expected science benefit first, as visibility allows. We have made sure to evenly distribute AGN and NS targets in the observing timeline in order to ensure maximal coverage of science goals over time. During the primary mission, a minimum of 6 targets (3 of each type, with $> 10^6$ s exposure each) will be observed. We expect an average observational efficiency of 40% per day, notwithstanding the effects on observation scheduling of a high inclination orbit, time spent in eclipse, and passage through the South Atlantic Anomaly. After the primary mission, we would revisit some of the original targets to measure polarization variability and add new targets. Moreover, we hope to exploit synergies with IXPE and NICER, as well as work with other space- and ground-based observatories.

Table 2 provides a simple listing of the mission phases and events within these phases.

7.2 Launch & Deployment

The spacecraft will be launched as a rideshare payload on a rocket into low-Earth orbit. The spacecraft will use the ESPA Grande ring to interface with the rideshare rocket. Post-launch test (PLT) occurs shortly after Launch and Orbital Insertion. The GOSoX payload will be launched in a powered-down state. After GOSoX has separated from the launch vehicle a power-on sequence and test will commence. Next will be a 2-3 week waiting period to facilitate outgassing, which will limit non-volatile material contaminating the mirrors and detectors. After outgassing, the telescope door will open, and calibration will begin. All PLTs are led by the instrument team, with support from the control team.

7.3 A Day in the Life

7.3.1 General Considerations

GOSoX will fly in LEO requiring daily to weekly downlinks for data and status, monthly downlinks for large-volume calibration data, and about weekly command uplinks. GOSoX will maximize the time spent observing the current target. When not observing, such as during target occultation by the Earth, the spacecraft can manage momentum, engage in uplink and downlink, and continue to track the target as possible. Observations of any given target will typically require many consecutive orbits.

Although the average observational efficiency across an orbit is 40%, in reality each orbit will look different. For some orbits, the South Atlantic Anomaly may significantly impact observing time as the detector background is too high and the detector power may be turned off. The observing schedule will have to take into account that some sources of interest will be within 90° of the Sun and thereby unobservable.

7.3.2 Spacecraft and Payload Modes

- **Deploy**. This mode is activated upon deployment. The satellite will detumble, deploy solar arrays and radio antennae, and enter safe mode until commands are uplinked. The post-launch test, led by the instrument team, will then commence. This will include power-testing, an off-gassing period of 2-3 weeks, opening the instrument cover, and then an initial payload test and calibration.

- **Nominal**. This mode corresponds to nominal data taking status while GOSoX is calibrating or observing. Targets are observed for ~300 hours each, with pauses as necessary to slew to a new target. The spacecraft maintains precise pointing and executes stored roll commands during observation. Onboard software processes the large CCD images to identify and measure X-ray events, which are held in spacecraft storage until the next downlink.

- **Idle**. This mode is activated when the target is not available for observation either when the target is occulted by the Earth or when the spacecraft enters the South Atlantic Anomaly. These timespans of these conditions is expected to vary from orbit to orbit. The spacecraft will stabilize CCD temperature and attitude because CCD cooling and target acquisition can require a substantial fraction of the nominal observation period if not maintained. Roll commands and data collection will be paused to reduce power use. The spacecraft will also use time in idle mode to desaturate its reaction wheels.

- **Downlink/Uplink**. With a data generation rate of 10 kb/s and assuming an observational efficiency of 40%, an average of 2840 kilobytes (not including spacecraft telemetry) is generated per orbit. Approximately 2-3 downlinks per day will be needed if S-band is used for data download. There will be sufficient margin to download spacecraft health data in addition to science data. If X-band is used, data downlinks will only be needed about once per week. Telemetry downlink opportunities should occur daily and can be used to monitor instrument health. X-band radio requires a larger power draw than S-band radio, so data acquisition can be paused to ensure sufficient power. Approximately once a week, commands will need to be uplinked. Commands will include a schedule of reorientation quaternions for slewing to targets and rolling during observation, commands for when and where to downlink, and changes in detector parameters or modes.

- **Safe**. This mode is activated if an issue with the spacecraft is detected either by onboard attitude determination algorithms or by the ground team. All non-essential systems are shut down, the spacecraft will orient itself such that its solar panels receive maximum solar illumination, telemetry data will be downlinked, and the spacecraft will await commands from the ground team. This mode will be maintained until it can be determined what triggered safe mode and necessary changes can be made to ensure the spacecraft can safely return to normal operations.

7.3.3 Orbit Scenarios

In each orbit, GOSoX will perform some combination of science data acquisition and processing, command and data handling, and station-keeping. GOSoX will be launched on a rideshare and will fly in a low-Earth orbit. While a lower inclination (equatorial) is preferable for observing due to lower background radiation noise and avoidance of the South Atlantic Anomaly, a polar sun-synchronous orbit may provide more options for rideshare, launch dates, and ground stations. A lower inclination will also see less data corruption due to cosmic rays. Although most orbits are consistent with the science goals, orbits closer to equatorial will have higher observing efficiencies. Observing efficiency must be weighed against rideshare availability for orbit selection.

7.3.4 Attitude Determination and Control System (ADCS) Operations

The ADCS will provide attitude control of the spacecraft and payload. The ADCS will first slew to point the payload optical axis at the target. This initial slew maneuver must point the payload optical axis at the target with an accuracy of $30''$. An adjustment maneuver may be needed to improve the acquisition to the required level, especially right after opening the telescope door. Instrument to ADCS calibration may obviate the need for attitude adjustments after in-orbit checkout. Once a science observation begins, the ADCS will maintain the stability of the instrument optical axis for the entire duration of data collection. Simultaneously, during part of the observation, the ADCS will roll the telescope at a rate of 0.01-1.0 deg/s in order to sample the $\pm 90°$ range. The ADCS must provide at $< 1°$ of attitude knowledge about its roll axis for valid data acquisition.

7.3.5 Power and Thermal Control Subsystem Operations

The peak power consumption of GOSoX is expected to be 40 W (CBE). Its power consumption in the standby mode is expected to be about 20W in order to maintain CCD temperatures. GOSoX will be fitted with batteries capable of storing enough power to compensate for power draw during times of eclipse. They will be charged by solar arrays when the satellite is not in Earth shadow. Solar arrays have efficiencies of about 30% at the beginning of life and will be spending approximately 60% to 65% of the orbit charging the batteries. Articulation of solar panels will depend on the choice of the bus.

The key thermal requirements for GOSoX are:

- the CCDs shall be operated at a temperature between -50 C and -60 C,
- the CCD temperatures shall be stable to ± 1 C and consistent prior to and during all observations,
- GOSoX optics shall be thermally isolated from other spacecraft components, and
- GOSoX optics shall be kept at a temperature of approximately 20 C, which will be higher than the temperature of the surrounding components.

Active cooling will be necessary to achieve the thermal control required for the CCDs. A multi-stage Thermoelectric Cooler (TEC) attached to each CCD is a cost-effective solution for CCD thermal control. Thermal straps may need to be attached to the TECs to carry the heat away from the CCDs to the dedicated radiators on outer walls of the satellite or instrument for rejection into space. The tradeoff between the use of TECs or cryocoolers is addressed in § 9.2. Cooling will also be required for the electronics box. Possible options for its cooling include using heat pipes, louvers, and coatings. Temperature control and thermal isolation of the optical components of GOSoX shall be accomplished using heaters and multi-layered insulation (MLI) respectively.

GOSoX will be controlled by a Main Electronics Board (MEB), housed in an electronics box along with the CCD (Detector) electronics. The MEB that will interface with spacecraft bus subsystems, the CCDs (Detector electronics), and any external payload sensors or monitors. The MEB will provide the processing power and speed required to accomplish all payload, flight software, and housekeeping activities as applicable to the various modes of flight. It will also control and provide sufficient volatile, non-volatile, and flash memory for GOSoX operations. Through its interface with the detector electronics, the MEB along with the flight software will process and package images and frames for transmission or storage. The MEB will provide watchdog timer and interruption management capability for fault detection, isolation, and recovery. It will also have the capability to test individual subcomponents. Critical components of the MEB such as memories and any Field Programmable Gate Array (FPGA) will be EMI and radiation hardened, depending on the level of risk tolerance required for mission success. Thermal control of the GOSoX electronics box will be critical to the mission. The (passive) options to dissipate heat from the box may include the use of conductors with high thermal conductivities in circuit board designs that will conduct heat out of the box to the outside radiator walls for dissipation into space.

7.3.6 Software Operations

The flight software will serve three main purposes: enable collection of science data, facilitate communication with spacecraft bus, and identify and respond to faults. To facilitate collection of science data, the software will command the CCDs to observe and standby states. The flight software (along with the MEB) will act as the intermediary between the payload and spacecraft The software will process and package science data and subsequently, hand over the packaged data to the spacecraft command and data handling subsystem for transmission to the ground station.

The software will also process commands received from the ground station via the spacecraft. In addition, it will keep its time synchronized with the spacecraft clock and will reset the watchdog timer periodically. Upon detection of a fault condition or when commanded by the ground station, the software will transition into the safe mode to protect the payload and related systems and will notify the ground station in the next downlink event. If the software fails to correct or handle the detected fault, it will request assistance from the ground station via the spacecraft communication subsystem. The flight software architecture will support a power-on sequence, interface initializations, and resets in accordance with the on-board fault response logic or when commanded. It will also package and provide housekeeping data. The housekeeping data will include (but is not limited to) counters, event rate, voltages, temperatures, and health parameters of CCD electronics and the Main Electronics Board. The software will also confirm "aliveness" for the ground station by periodically sending automated health status messages to the spacecraft.

7.4 End Of Life

For the concept study, launch was scheduled for 2025, with scientific mission objectives taking an estimated 2 years. Given that the launch year coincides with a solar maximum, the GOSoX orbit should decay within two years if the starting altitude is near or below 500 km. It is not likely that a plan to actively de-orbit the satellite will be needed.

8. COST ESTIMATION

Throughout the study, the GOSoX team worked with both the NASA JPL Team X group and with several vendors to develop cost estimates. Once mass and power estimates had been developed for the GOSoX instrument (§ 3.3), the Team X group used the NASA Instrument Cost Model (NICM) System Tool and Subsystem Tool[†] to generate cost estimates. One of the primary differences in these tools is in how mass is used for estimating cost. In the System Tool, the total mass is the primary cost driver, while in the Subsystem Tool, subsystem masses are utilized. The average of the two tools was used to provide a 50% cost estimate of the total development (Phases B/C/D) of the GOSoX payload. Building from the payload cost estimate, the total mission cost was then estimated in the Team X study. The cost estimate itself was derived through comparisons to other missions with similar payload requirements and profiles.

The spacecraft bus costs were estimated from a database of spacecraft bus vendor costs, taken from previous missions with similar payload requirements. Because the instrument is estimated to have sufficiently low mass, low power, low data volume, and coarse pointing requirements, Team X determined that GOSoX can use an off-the-shelf spacecraft bus from a commercial spacecraft vendor. The costs for project management, systems engineering, science investigation, safety and mission assurance, mission operations, and ground operations is similarly estimated based on comparable NASA missions with similar mass, power, and mission class requirements to GOSoX. Rideshare launch costs were not included, based on the specifications of the AS^3 and the Pioneer call for proposals. The Team X summary was that the GOSoX mission would readily fit within the expected cost cap of a NASA Astrophysics Small Complete Mission, an option for a Mission of Opportunity as part of the next Explorer call for proposals.

A ground-up approach was also used to develop a cost estimate for the GOSoX payload and mission. The largest difference between the ground-up approach and the Team X cost estimates appears in the estimated payload costs. The primary reason for this is because the GOSoX team obtained separate cost estimates for optics, gratings, and LGML mirrors, and has a significant experience with comparable X-ray CCD detectors. This "grassroots" approach placed the total mission cost beneath the cap for a Pioneer mission.

9. TRADEOFF STUDIES

9.1 Number of Channels

The largest tradeoff available to the mission is the number of channels. Each channel consists of an opposing pair of mirror shells that focus incoming X-rays through an array of gratings onto a single LGML. For each channel, those X-rays that are s-polarized are then reflected efficiently onto a detector, which allows us to measure polarization. At a minimum, we need one channel to measure polarization. However, adding more channels provides additional benefits, at the expense of cost.

[†]The software is available from NASA at `https://www.nasa.gov/offices/ocfo/functions/models_tools/nicm`.

As part of this concept study, we examined the trade-off between a 1-channel design ("1CD") and a 3-channel design ("3CD"). The 1CD is our baseline, and is the most economical of the two options. It benefits from having the lowest mass, the lowest hardware cost, and the lowest power and thermal requirements. It comes at the cost of having 33% of the effective area of the 3CD and requires a $\pm 90°$ roll range in order to measure the three Stokes parameters (§ 3). The 3CD was developed for the REDSoX Polarimeter, a proposed sounding rocket payload.[17] In the 3CD each channel has a LGML that is offset from the others by 120°, which would allow us to determine the polarization without rolling the instrument about its optical axis to change the position angle of the instrument relative to the target. Instead in the 3CD, rolling would only be desired in order to cross-check the various LGML/detector combinations, which can be done with $\pm 30°$ roll angles. Operationally, there is very little impact upon the spacecraft requirements except on average power production by solar panels.

The cost, mass, and power budgets do not increase proportionally between the 1CD and the 3CD. This is because there is significant overhead that is independent of the number of channels. Nonetheless, the increase in cost that arises from the 3CD was estimated by Team X to be significant enough that the 3CD was not considered further during the concept study.

9.2 Cooling

Another tradeoff that was examined is the use of thermoelectric coolers (TECs) or cryocoolers to maintain the temperatures of the CCDs. This trade arose during the Team X study with JPL and largely highlights the difference in experience between the MIT Kavli Institute (MKI) and JPL. TECs have successfully been used in flight X-ray detectors and in missions with CCDs,[32] including missions led by MKI.[33] By contrast, JPL has used cryocoolers quite extensively on many missions[34] but primarily for optical telescopes.

For the purposes of this study, the Ricor K508 cryocooler was compared to the Marlow II-VI NL2064T two-stage thermoelectric module. It is important to note that the thermal requirements for GOSoX require both of these modules to operate at or close to their limits, so the module that is decided will require testing to ensure the requirements can be met. The advantage of the Ricor K508 is that it requires about 8 W less power than the TECs to draw out a similar heat load. However, the required CCID-94 operating temperature is at the lower operational limit of the cryocooler. Additionally, cryocoolers can induce significant vibration into the spacecraft,[35] and the efficiency in terms of mass, power, and heat lift capabilities of cryocoolers can be impacted by efforts to reduce the scale or number of moving components within cryocoolers.[36] Comparatively, TECs are much simpler because they do not have moving components and can operate without inducing vibration into the payload. The sizes and masses of TECs are also very small but they can be fragile, so they must be handled with care.

ACKNOWLEDGMENTS

Support for this work was provided in part through NASA grants 80NSSC20K1249, NNH18ZDA001N, and NNX15AL14G. Laboratory supplies and equipment were funded in part through the MIT Kavli Research Investment Fund. Support for this work was also provided in part through NASA grant NNX17AG43G and Smithsonian Astrophysical Observatory (SAO) contract SV3-73016 to MIT for support of the *Chandra* X-Ray Center (CXC), which is operated by SAO for and on behalf of NASA under contract NAS8-03060. We thank the JPL Team X group, led by Alfred Nash, for their work on the GOSoX concept study. We also thank the students of MIT's AeroAstro course 16.851 who worked on the GOSoX concept, especially in the areas of requirements and operations.

REFERENCES

[1] O'Dell, S. L., Baldini, L., Bellazzini, R., Costa, E., Elsner, R. F., Kaspi, V. M., Kolodziejczak, J. J., Latronico, L., Marshall, H. L., Matt, G., Mulieri, F., Ramsey, B. D., Romani, R. W., Soffitta, P., Tennant, A. F., Weisskopf, M. C., Allen, D. Z., Amici, F., Antoniak, S., Attina, P., Bachetti, M., Barbanera, M., Baumgartner, W. H., Bladt, J., Bongiorno, S. D., Borotto, F., Brooks, T., Bussinger, S., Bygott, H. K., Cavazzuti, E., Ceccanti, M., Citraro, S., Deininger, W. D., Del Monte, E., Dietz, K. L., Di Lalla, N., Di Persio, G., Donnarumma, I., Erickson, J., Evangelista, Y., Fabiani, S., Ferrazzoli, R., Foster, M., Giusti,

M., Gunji, S., Guy, L., Johnson, S., Kalinowski, W., Kelley, A. R., Kilaru, K., Lefevre, C., Maldera, S., Manfreda, A., Marengo, M., Masciarelli, J., McEachen, M., Mereu, P., Minuti, M., Mitchell, M. A., Mitchell, S., Mitsuishi, I., Morbidini, A., Mosti, F., Nasimi, H., Negri, B., Orsini, L., Osborne, D., Pavelitz, S. D., Pentz, C., Perri, M., Pesce-Rollins, M., Peterson, C., Piazzolla, R., Pieraccini, S., Pilia, M., Pinchera, M., Puccetti, S., Ranganathan, J., Read, T., Rubini, A., Santoli, F., Sarra, P., Schindhelm, S., Sciortino, A., Seckar, C., Sgrò, C., Smith, B. T., Speegle, C. O., Tamagawa, T., Tardiola, M., Tobia, A., Tortosa, A., Trois, A., Weddendorf, B., Wedmore, J., and Zanetti, D., "The Imaging X-ray Polarimetry Explorer (IXPE): technical overview," in [*SPIE Conference Series,*], *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **10699**, 106991X (Aug 2018).

[2] Marshall, H. L. and others, "A Small Satellite Version of a Broad-band Soft X-ray Polarimeter," *arXiv e-prints* , arXiv:2012.TBD (Dec. 2020).

[3] Weisskopf, M. C., Elsner, R. F., and O'Dell, S. L., "On understanding the figures of merit for detection and measurement of x-ray polarization," in [*Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*], Arnaud, M., Murray, S. S., and Takahashi, T., eds., *Space Telescopes and Instrumentation 2010: Ultraviolet to Gamma Ray* **7732**, 77320E, SPIE (2010).

[4] Harding, A. K. and Lai, D., "Physics of strongly magnetized neutron stars," *Reports on Progress in Physics* **69**, 2631–2708 (Sep 2006).

[5] Haberl, F., Zavlin, V. E., Trümper, J., and Burwitz, V., "A phase-dependent absorption line in the spectrum of the X-ray pulsar RX J0720.4-3125," *A&A,* **419**, 1077–1085 (June 2004).

[6] Haberl, F., "The magnificent seven: magnetic fields and surface temperature distributions," *Ap&SS,* **308**, 181–190 (Apr. 2007).

[7] Borghese, A., Rea, N., Coti Zelati, F., Tiengo, A., Turolla, R., and Zane, S., "Narrow phase-dependent features in X-ray dim isolated neutron stars: a new detection and upper limits," *MNRAS,* **468**, 2975–2983 (July 2017).

[8] Hohle, M. M., Haberl, F., Vink, J., de Vries, C. P., and Neuhäuser, R., "Narrow absorption features in the co-added XMM-Newton RGS spectra of isolated neutron stars," *MNRAS,* **419**, 1525–1536 (Jan. 2012).

[9] Suleimanov, V., Potekhin, A. Y., and Werner, K., "Models of magnetized neutron star atmospheres: thin atmospheres and partially ionized hydrogen atmospheres with vacuum polarization," *A&A,* **500**, 891–899 (Jun 2009).

[10] Suleimanov, V., Hambaryan, V., Potekhin, A. Y., van Adelsberg, M., Neuhäuser, R., and Werner, K., "Radiative properties of highly magnetized isolated neutron star surfaces and approximate treatment of absorption features in their spectra," *A&A,* **522**, A111 (Nov. 2010).

[11] Staubert, R., Trümper, J., Kendziorra, E., Klochkov, D., Postnov, K., Kretschmar, P., Pottschmidt, K., Haberl, F., Rothschild, R. E., Santangelo, A., Wilms, J., Kreykenbohm, I., and Fürst, F., "Cyclotron lines in highly magnetized neutron stars," *A&A,* **622**, A61 (Feb 2019).

[12] Blandford, R., Meier, D., and Readhead, A., "Relativistic Jets from Active Galactic Nuclei," *ARA&A,* **57**, 467–509 (Aug 2019).

[13] Gallo, L., "X-ray perspective of Narrow-line Seyfert 1 galaxies," in [*Revisiting Narrow-Line Seyfert 1 Galaxies and their Place in the Universe*], 34 (Apr. 2018).

[14] Arnaud, K. A., Branduardi-Raymont, G., Culhane, J. L., Fabian, A. C., Hazard, C., McGlynn, T. A., Shafer, R. A., Tennant, A. F., and Ward, M. J., "EXOSAT observations of a strong soft X-ray excess in MKN 841.," *MNRAS,* **217**, 105–113 (Nov. 1985).

[15] Haardt, F. and Matt, G., "X-ray polarization in the two-phase model for AGN and X-ray binaries," *MNRAS,* **261**, 346–352 (Mar. 1993).

[16] Marin, F., Goosmann, R. W., Dovčiak, M., Muleri, F., Porquet, D., Grosso, N., Karas, V., and Matt, G., "X-ray polarimetry as a new tool to discriminate reflection from absorption scenarios - predictions for MCG-6-30-15," *MNRAS,* **426**, L101–L105 (Oct. 2012).

[17] Marshall, H. L., Günther, H. M., Heilmann, R. K., Schulz, N. S., Egan, M., Hellickson, T., Heine, S. N. T., Windt, D. L., Gullikson, E. M., Ramsey, B. D., Tagliaferri, G., and Pareschi, G., "Design of a Broad-band Soft X-ray Polarimeter," *Journal of Astronomical Telescopes, Instruments, and Systems* **4**, 11004 (Mar. 2018).

[18] Zhang, W. W., Allgood, K. D., Biskach, M. P., Chan, K.-W., Hlinka, M., Kearney, J. D., Mazzarella, J. R., McClelland, R. S., Numata, A., Riveros, R. E., Saha, T. T., and Solly, P. M., "High-resolution, lightweight, and low-cost x-ray optics for the Lynx observatory," *Journal of Astronomical Telescopes, Instruments, and Systems* **5**, 021012 (Apr 2019).

[19] Heilmann, R. K., Ahn, M., Bautz, M. W., Foster, R., Huenemoerder, D. P., Marshall, H. L., Mukherjee, P., Schattenburg, M. L., Schulz, N. S., and Smith, M., "Development of a critical-angle transmission grating spectrometer for the International X-Ray Observatory," in [*Optics for EUV, X-Ray, and Gamma-Ray Astronomy IV*], *SPIE Conference Series,* **7437**, 74370G (Aug. 2009).

[20] Heilmann, R. K., Bruccoleri, A. R., and Schattenburg, M. L., "High-efficiency blazed transmission gratings for high-resolution soft x-ray spectroscopy," in [*Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*], *SPIE Conference Series,* **9603**, 960314 (Sept. 2015).

[21] Heilmann, R. K., Bruccoleri, A. R., Song, J., Kolodziejczak, J., Gaskin, J. A., O'Dell, S. L., Cheimetz, P., Hertz, E., Smith, R. K., Burwitz, V., Hartner, G., La Caria, M.-M., and Schattenburg, M. L., "Critical-angle transmission grating technology development for high resolving power soft x-ray spectrometers on Arcus and Lynx," in [*Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*], *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **10399**, 1039914 (Aug. 2017).

[22] Smith, R. K., Abraham, M., Allured, R., Bautz, M., Bookbinder, J., Bregman, J., Brenneman, L., Brickhouse, N. S., Burrows, D., Burwitz, V., Cheimets, P. N., Costantini, E., Dawson, S., DeRoo, C., Falcone, A., Foster, A. R., Gallo, L., Grant, C. E., Günther, H. M., Heilmann, R. K., Hertz, E., Hine, B., Huenemoerder, D., Kaastra, J. S., Kreykenbohm, I., Madsen, K. K., McEntaffer, R., Miller, E., Miller, J., Morse, E., Mushotzky, R., Nandra, K., Nowak, M., Paerels, F., Petre, R., Poppenhaeger, K., Ptak, A., Reid, P., Sanders, J., Schattenburg, M., Schulz, N., Smale, A., Temi, P., Valencic, L., Walker, S., Willingale, R., Wilms, J., and Wolk, S. J., "Arcus: exploring the formation and evolution of clusters, galaxies, and stars," in [*Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*], *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **10397**, 103970Q (Aug. 2017).

[23] Song, J., Heilmann, R. K., Bruccoleri, A. R., Hertz, E., and Schatternburg, M. L., "Scanning laser reflection tool for alignment and period measurement of critical-angle transmission gratings," in [*Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*], *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **10399**, 1039915 (Aug. 2017).

[24] Marshall, H. L., Schulz, N. S., Windt, D. L., Gullikson, E. M., Blake, E., Getty, D., and McInturff, Z., "The use of laterally graded multilayer mirrors for soft X-ray polarimetry," in [*Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*], *SPIE Conference Series,* **9144**, 1 (July 2014).

[25] Marshall, H. L., Schulz, N. S., Windt, D. L., Gullikson, E. M., Craft, M., Blake, E., and Ross, C., "The use of laterally graded multilayer mirrors for soft x-ray polarimetry," in [*Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*], *SPIE Conference Series,* **9603**, 960319 (Sept. 2015).

[26] Koyama, K., Tsunemi, H., Dotani, T., Bautz, M. W., Hayashida, K., Tsuru, T. G., Matsumoto, H., Ogawara, Y., Ricker, G. R., Doty, J., Kissel, S. E., Foster, R., Nakajima, H., Yamaguchi, H., Mori, H., Sakano, M., Hamaguchi, K., Nishiuchi, M., Miyata, E., Torii, K., Namiki, M., Katsuda, S., Matsuura, D., Miyauchi, T., Anabuki, N., Tawa, N., Ozaki, M., Murakami, H., Maeda, Y., Ichikawa, Y., Prigozhin, G. Y., Boughan, E. A., Lamarr, B., Miller, E. D., Burke, B. E., Gregory, J. A., Pillsbury, A., Bamba, A., Hiraga, J. S., Senda, A., Katayama, H., Kitamoto, S., Tsujimoto, M., Kohmura, T., Tsuboi, Y., and Awaki, H., "X-Ray Imaging Spectrometer (XIS) on Board Suzaku," *PASJ,* **59**, 23–33 (Jan. 2007).

[27] LaMarr, B., Bautz, M., Kissel, S., Miller, E., and Prigozhin, G., "Performance evolution of the X-ray Imaging Spectrometers aboard the Suzaku X-ray astronomy satellite," in [*Space Telescopes and Instrumentation 2012: Ultraviolet to Gamma Ray*], Takahashi, T., Murray, S. S., and den Herder, J.-W. A., eds., *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **8443**, 84434A (Sept. 2012).

[28] Bautz, M. W., LaMarr, B. J., Miller, E. D., Kissel, S. E., Prigozhin, G. Y., Burke, B. E., Gregory, J. A., Uchiyama, H., Hyodo, Y., Yamaguchi, H., Mori, H., Tsuru, T., Matsumoto, H., Koyama, K., Torii, K., Katsuda, S., Hasuike, K., Nakajima, H., Hayashida, K., Tsunemi, H., Murakami, H., Ozaki, M., and Dotani, T., "Mitigating CCD radiation damage with charge injection: first flight results from Suzaku," in [*UV, X-Ray, and Gamma-Ray Space Instrumentation for Astronomy XV*], Siegmund, O. H., ed., *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **6686**, 66860Q (Sept. 2007).

[29] Murphy, K. D., Marshall, H. L., Schulz, N. S., Jenks, K., Sommer, S. J. B., and Marshall, E. A., "Soft x-ray polarimeter laboratory tests," in [*Space Telescopes and Instrumentation 2010: Ultraviolet to Gamma Ray*], *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **7732**, 77322Y (July 2010).

[30] Marshall, H. L., Schulz, N. S., Remlinger, B., Gentry, E. S., Windt, D. L., and Gullikson, E. M., "Progress toward a soft x-ray polarimeter," in [*Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*], *SPIE Conference Series,* **8861** (Sept. 2013).

[31] Garner, A., Marshall, H., Heine, S., Heilmann, R., Song, J., Schulz, N., LaMarr, B., and Egan, M., "Component testing for x-ray spectroscopy and polarimetry," in [*Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*], *SPIE Conference Series,* **11118**, 1111811–1–12 (Sept. 2019).

[32] Stanton, M., Phillips, W. C., O'Mara, D., Naday, I., and Westbrook, E., "Area detector design part ii. application to a modular ccd-based detector for x-ray crystallography," *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **325**(3), 558–567 (1993).

[33] LaMarr, B., Grant, C., Kissel, S., Prigozhin, G., Bautz, M., Tsuru, T. G., Tsunemi, H., Dotani, T., Hayashida, K., and Matsumoto, H., "Front- and back-illuminated x-ray CCD performance in low- and high-Earth orbit: performance trends of Suzaku XIS and Chandra ACIS detectors," in [*Space Telescopes and Instrumentation 2008: Ultraviolet to Gamma Ray*], *SPIE Conference Series,* **7011**, 70112C (July 2008).

[34] Ross Jr, R., Boyle, R., and Kittel, P., "Nasa space cryocooler programs—a 2003 overview," in [*AIP Conference Proceedings*], **710**(1), 1197–1204, American Institute of Physics (2004).

[35] Zagarola, M. and Chen, W., "Vibration-free, hybrid cryocooler for 4 k space applications," Georgia Institute of Technology (2008).

[36] Pettyjohn, E., "Cryocoolers for microsatellite military applications," Georgia Institute of Technology (2008).