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Small Satellite Platform Imaging X-Ray Polarimetry Explorer (IXPE) Mission Concept and Implementation

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ABSTRACT

The goal of the Imaging X-Ray Polarimetry Explorer (IXPE) Mission is to expand understanding of high-energy astrophysical processes and sources, in support of NASA's first science objective in Astrophysics: "Discover how the universe works." Polarization uniquely probes physical anisotropies—ordered magnetic fields, aspheric matter distributions, or general relativistic coupling to black-hole spin—that are not otherwise measurable. The IXPE Observatory consists of spacecraft and payload modules built up in parallel to form the Observatory during system integration and test. The payload includes three polarization sensitive, x-ray detector arrays paired with three x-ray mirror module assemblies (MMA). A deployable boom provides the correct separation (focal length) between the detector units and MMAs. This paper summarizes the IXPE mission science objectives and instrument concept, describes the Observatory implementation concept and overviews mission operations. Additional information can be found at: https://wwwastro.msfc.nasa.gov/ixpe/

INTRODUCTION

IXPE is a NASA Small Explorer (SMEX) Mission.[1-6] The IXPE Mission is an international collaboration lead by NASA Marshall Space Flight Center (MSFC) as the Principal Investigator (PI) institution (Dr. Martin Weisskopf) and includes Ball Aerospace (Ball), University of Colorado / Laboratory for Atmospheric and Space Physics (CU/LASP), as well as the Italian Space Agency (ASI) with Istituto di Astrofisica e Planetologia Spaziale/Istituto Nazionale di Astrofisica (IAPS/INAF) and Istituto Nazionale di Fisica Nucleare (INFN) as major international partners.

The goal of IXPE is to expand understanding of high-energy astrophysical processes and sources, in support of NASA's first science objective in Astrophysics: "Discover how the universe works." Polarization uniquely probes physical anisotropies—ordered magnetic fields, aspheric matter distributions, or general relativistic coupling to black-hole spin—that are not otherwise measurable.

MSFC provides the x-ray optics[7] and Science Operations Center (SOC) along with mission management and systems engineering. Ball is responsible for the spacecraft, payload mechanical elements and flight metrology system and payload, spacecraft and system I&T along with launch and operations. The MOC is located at CU/LASP. IAPS/INAF and INFN provide the unique polarization-sensitive detectors[3,8,9], detector units (DU) and detectors service unit (DSU) (the payload computer).

IXPE is designed as a 2-year mission with launch in November 2020. IXPE launches to a circular low Earth orbit (LEO) at an altitude of 540 km and an inclination of 0 degrees. The payload uses a single science operational mode capturing the X-ray data from the targets. The mission design follows a simple observing paradigm: pointed viewing of known X-ray sources (with known locations in the sky) over multiple orbits (not necessarily consecutive orbits) until the observation is complete. The mission is operated by LASP under contract to Ball using existing facilities similar to the way the Ball-built Kepler and K2 missions have been operated for NASA. The Observatory communicates with the ASI-contributed Malindi ground station, primary ground station, via S-band link. The science team generates and archives IXPE data products in HEASARC.

The IXPE Project completed its Phase A activities in July 2016 with the submission of the Concept Study Report (CSR) to the NASA Explorers Program Office. NASA considered three SMEX mission concepts for flight and selected the IXPE Project as the winner in January 2017.[10] The Project entered Phase B on February 1, 2017.

This paper summarizes the IXPE mission science objectives and instrument concept, describes the Observatory implementation concept, and overviews mission operations at the time of the CSR. The paper also highlights the flexibility of the Ball Configurable Platform (BCP)-100 spacecraft.

SCIENCE OBJECTIVES

IXPE directly supports NASA's first strategic objective in Astrophysics: "Discover how the universe works".[11] In particular, it addresses a key science goal of NASA's Science Mission Directorate: "Probe the origin and destiny of our universe, including the nature of black holes, dark energy, dark matter and gravity." It does this by expanding our understanding of high energy astrophysical processes, specifically the polarimetry of cosmic sources with special emphasis on objects such as neutron stars and black holes. By obtaining X-ray polarimetry and polarimetric imaging of cosmic sources, IXPE addresses two specific science objectives:

- Determine the radiation processes and detailed properties of specific cosmic X-ray sources or categories of sources
- Explore general relativistic and quantum effects in extreme environments.

NASA's Astrophysics Roadmap, "Enduring Quests, Daring Visions", also recommends such measurements.

IXPE uses X-ray polarimetry to expand dramatically X-ray observation space, which historically has been limited to imaging, spectroscopy, and timing. This advance will provide new input to our understanding as to how X-ray emission is produced in astrophysical objects, especially systems under extreme physical conditions—such as neutron stars and black holes. Polarization uniquely probes physical anisotropies—ordered magnetic fields, aspheric matter distributions, or general relativistic coupling to black-hole spin—that are not otherwise easily measurable. Hence, IXPE complements all other investigations in high-energy astrophysics by adding the important and relatively unexplored dimensions of polarization to the parameter space for exploring cosmic X-ray sources and processes, and for using extreme astrophysical environments as laboratories for fundamental physics.

The primary science objectives of IXPE are:

- Enhance our understanding of the physical processes that produce X-rays from and near compact objects such as neutron stars and black holes.
- Explore the physics of the effects of gravity, energy, electric and magnetic fields at their extreme limits.

PAYLOAD CONCEPT

IXPE's payload is a set of three identical, imaging, X-ray polarimetry systems mounted on a common optical bench and co-aligned with the pointing axis of the spacecraft.[1-6] Each system, operating independently, comprises a 4-m-focal length Mirror Module Assembly (grazing incidence x-ray optics) that focuses X-rays onto a polarization-sensitive imaging detector. The focal length is achieved using a deployable boom. Each Detector Unit (DU) contains its own electronics, which communicate with the payload computer that in turn interfaces with the spacecraft. Each DU has a multi-function filter wheel assembly for in-flight calibration checks and source flux attenuation.

Designing an instrument of appropriate sensitivity to accomplish the science objectives summarized above involved a trade of MMA design, detector design, and the number of telescope systems, all versus focal length, and considered boundary conditions of mass and power that are within spacecraft and launch vehicle constraints. These trades were completed and the result is the three telescope system described here which meets science objectives and requirements with margin while placing reasonable and achievable demands on the spacecraft, launch vehicle, and the deployable optical bench. Specifically, three identical systems provide redundancy, a range of detector clocking angles to mitigate against any detector biases, shorter focal length for given mirror graze angles (i.e., given energy response) and thinner/lighter mirrors compared to a single telescope system.

Figure 1 shows the IXPE observatory with key payload elements. The payload uses a deployable x-ray shield to prevent off-axis x-rays from striking the detectors. The deployable boom is covered with a thermal sock (not shown) to maintain a more constant thermal environment. A metrology system consisting of a deployed section-mounted camera which images a metrology target (diode string) on the spacecraft top deck is used to monitor motions between the two ends of the Observatory during science observations.

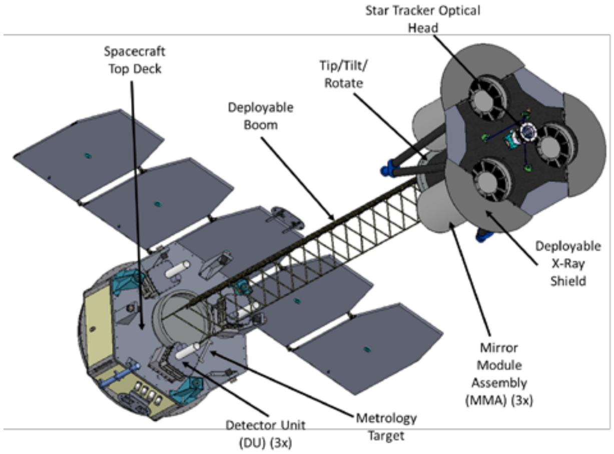

Figure 1: IXPE Observatory Showing Key Payload Elements.

SPACECRAFT CONCEPT

The IXPE Observatory is based on the BCP-100 spacecraft architecture. The modular design allows for concurrent payload and spacecraft development with a well-defined, clean interface that reduces technical and schedule risk. The BCP-100 design supports the project goal of incorporating a low-risk spacecraft by using flight-proven components, a simple structural design, and significant design and software reuse from prior missions. The design balances a low-cost and low-risk approach with significant spacecraft capability and flexibility. IXPE is leveraging the BCP-100's flexibility for science payload accommodation. The IXPE payload is mounted on the spacecraft top deck. The IXPE Observatory is designed to launch on a Pegasus XL or larger launch vehicle.

Background

The BCP-100 design, based on the Space Test Program (STP) Standard Interface Vehicle, supports the project goal of incorporating a low-risk spacecraft by using flight-proven components, a simple structural design, and significant design and software reuse from prior missions. The design balances a low-cost and low-risk approach with significant spacecraft capability and flexibility. The BCP-100 capabilities support a variety of potential small payloads. The standard capability spacecraft can operate over a wide range of low earth orbit altitudes (400 – 850 km) and inclinations (0º to sun-synchronous). The spacecraft design provides the required power over the full range of sun angles. A star tracker is a key element of the attitude determination and control system. It is mounted directly to and aligned with the deployed payload to minimize alignment errors between the spacecraft and payload.

BCP-100 Applications

STP Satellite -2 (STPSat-2) (**Figure 2**) was the first use of the STP vehicle and was launched 19 November 2010 on a Minotaur IV from the Kodiak Launch Complex, Alaska. It accommodates 2 separate SERB payloads [11-15]. STPSat-2 continues extended operations well beyond its 13 month design life, and achieved 6 years on-orbit in December 2016.

STPSat-3 (**Figure 2**) is the second use of the STP vehicle and was launched in November 2013 on a

Figure 2 – STPSat-2 and STPSat-3 Space Vehicles. The first two space vehicles in the product line, designed to increase access to space for small payloads via standardization and lower costs.

Minotaur I from NASA Wallops Flight Facility. It accommodates 6 different payloads by partitioning resources from its four payload interfaces[16-19]. The space vehicle is operating beyond its 13-month design life and achieved 3 years of on-orbit operations in December 2016.

The Green Propellant Mission (GPIM) (**Figure 3**) is the third build of this space vehicle and first as a BCP-100[20-24]. The Project started in October 2012 with launch now scheduled for April 2018 as an auxiliary payload (ESPA-class) on the STP-2 mission on a Space X Falcon Heavy Launch Vehicle. The GPIM Space Vehicle carries the green propellant propulsion subsystem as the primary payload and three secondary SERB payloads.

IXPE Spacecraft

IXPE is the fourth build of the BCP-100 class spacecraft. IXPE is leveraging the flexibility of the BCP-100 architecture to accommodate the IXPE science payload. It is re-configured for launch on a Pegasus XL launch vehicle with the IXPE payload mounted on the spacecraft top deck. The solar array wraps around the spacecraft body and payload.

Figure 3: GPIM Space Vehicle. The GPIM mission leverages a flight heritage BCP-100 spacecraft and a flight demonstration AF-M315E propellant propulsion subsystem.

IXPE OBSERVATORY CONCEPT

The Observatory is designed to support IXPE measurement requirements. Key design drivers include pointing stability in the presence of various disturbances, particularly gravity gradient, and minimization of SAA passes which makes the zero degree inclination orbit the best available choice. A nominal IXPE target list is known in advance with targets distributed over the sky. The observatory has observational access to an annulus normal to the Sun line at any given time with a width ±30° from Sun-normal. This orientation allows the payload to collect all necessary science data during the mission while keeping the solar arrays oriented toward the sun and maintaining sufficient power margins. Typically, each science target is visible over an approximate 60 day window and can be observed continuously for a minimum time of 56.7 minutes each orbit. Changes in the IXPE orbit over mission lifetime are sufficiently small, eliminating the need for a propulsion system and its resulting operational complexity.

A view of the deployed IXPE Observatory is shown in **Figure 4**, while **Figure 5** shows the Observatory stowed in a Pegasus XL launch vehicle fairing. When deployed, IXPE is 5.2 m from the bottom of the spacecraft structure to the top of the payload and is 1.1 m in diameter. The solar panels span 2.7 m when deployed. The Observatory launch mass is approximately 300 kg.

The Payload is mounted on the +Z face of the spacecraft structure (top deck). This simplifies alignment and integration, and minimizes mass by providing the shortest possible load paths. The star tracker optical heads (OH) are mounted on opposite ends of the Observatory anti-boresighted from one another to prevent simultaneous Earth obscuration. One OH is mounted on top of the telescope support structure, co-located and boresighted with the X-ray optics. The second OH is mounted on the bottom of the spacecraft top deck looking out through the PAF ring. Two hemispherical S-band low-gain antennas are mounted on opposite sides of the spacecraft and coupled together to provide omnidirectional communications coverage.

IXPE MISSION OPERATIONS

IXPE flight operations have three components: Launch and Commissioning, Science Operations, and Decommissioning. The IXPE Observatory will launch into a 540-km equatorial orbit no earlier than November 20, 2020. Upon separation from the LV, the spacecraft autonomously performs solar acquisition, placing itself in a power-positive attitude. Payload checkout begins as soon as the spacecraft has been verified to be active. X-ray targets are known in advance and observed with a single science mode.

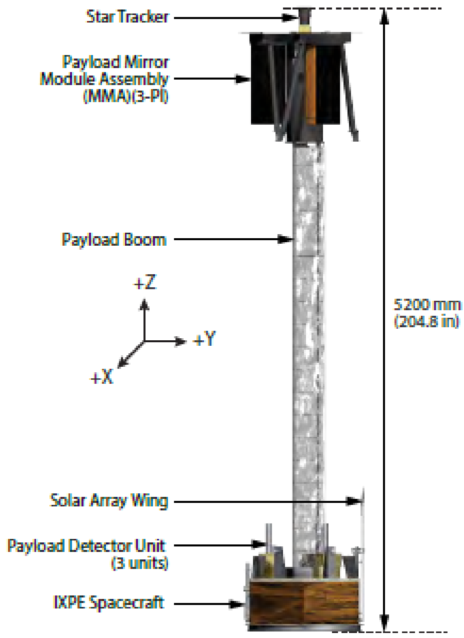

Figure 4: IXPE Observatory in its deployed configuration.

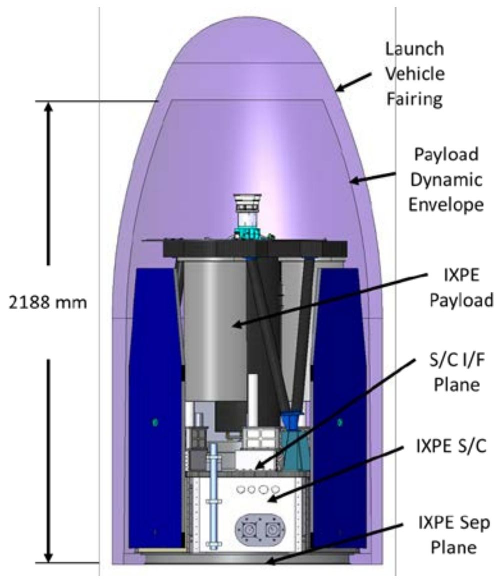

Figure 5: IXPE Observatory stowed in a Pegasus XL fairing.

Launch and Commissioning

IXPE launch and commissioning operations will be conducted from the MOC during the first 30 days on-orbit. An expanded ground team will be resident at MOC during this phase. Malindi coverage will be up to 15 passes/day although it is anticipated only half of this number will be used during this phase. During launch and the first week of commissioning the IXPE orbit will be determined by using SN Doppler data. Ball/LASP navigation will perform all ephemeris format conversions as needed for data products. The MOC will monitor the spacecraft using orbit DOWD via SN until the navigation team at Ball/LASP has sufficient data to take over orbit determination duties, which can take up to two weeks after launch.

For the first week of commissioning, the Operations Team will conduct spacecraft subsystem commissioning operation including C&DH, power, telecom, and ADCS calibration. Once the spacecraft is fully operational, the remainder of the commissioning phase (3 weeks) is dedicated to payload turn-on and check out, which includes boom deployment, x-ray shield deployment, DSU checkout and activation and calibration of the detector units. IXPE boom and x-ray shield deployments are not time critical. The boom deployment is treated as a critical event. The time for set up, deployment and confirmation occur over three passes. The commanded deployment events are scheduled to occur over the Malindi ground station.

Science Operations

The predictable and repetitive nature of the observations of known targets and high margin for onboard data storage (50%) allow for ease in science planning and operations. Typically, each science target is visible over an approximate 60 day window and can be observed continuously for a minimum time of 56.7 minutes each orbit. Since routine pass operations are handled by ground automation with no spacecraft sequence involvement, changes in the target list may be incorporated until final approval of the sequence. This information is then forwarded on a weekly basis to the MOC by the SOC. The target list is encoded in command sequences and uplinked once every 3 days. The overall observing plan will be refined prelaunch, and modified as needed to respond to Observatory anomalies, missed observations and Targets of Opportunity (TOOs). Any missed targets can be generally included in the next week's scheduling queue because the science program is robust to individual missed visits.

Normal Phase E science operations commence with uplink of the first weekly science observation sequence.

Malindi coverage transitions to 2-8 passes per day of 10 minutes each. Many of the pre-defined targets can be observed using one observation period with 2 ground contacts per day while other targets are data intensive and require splitting the observations into 2 to 4 observing sequences, filling the recorder (with 50% margin) and downlinking on average 7.5 times per day. Science and calibration data are stored in the C&DH and downlinked daily during the scheduled passes. Downlinks are initiated and monitored by ground automation. The downlink will be through the Malindi station at a rate of 2.0 Mbps (Singapore backup). If communications passes are missed, the data are stored in the C&DH memory and downlinked on subsequent passes.

Since science and communications are decoupled due to the omni-directional passively coupled S-Band low gain antennas (LGAs), operations scheduling is straightforward. Science collection and communications can occur simultaneously as long as an LGA is within the required FOV for the 2.0 Mbps downlink

Decommissioning

The Observatory will be decommissioned per NASA guidelines. There are no consumables on IXPE (i.e., propellant). Atmospheric drag will cause the Observatory to deorbit. The Observatory will de-orbit approximately 4.1 years after launch from its nominal 540 km orbit, which occurs well after the primary mission and well before the 25 year requirement.

CONCLUSION

IXPE brings together an international collaboration for flying an imaging X-ray polarimeter on a NASA Small Explorer. IXPE will conduct X-ray polarimetry for several categories of cosmic X-ray sources from neutron stars and stellar-mass black holes, to supernova remnants, to active galactic nuclei that are likely to be X-ray polarized. This paper summarized the IXPE mission science objectives and instrument concept, described the Observatory implementation concept, and provided an overview of the novel Ball BCP-100 small spacecraft. The Project kicked off in February 2017. SRR is planned for September 2017, PDR planned for February 2018 with launch planned for November 2020.

Acknowledgments

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The work described here is a culmination of efforts from teams at NASA MSFC, Ball Aerospace, ASI, INFN, IAPS/INAF, CU/LASP, Stanford University, McGill University, and Roma TRE University.

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APPENDIX A – IXPE SCIENCE TEAM

The IXPE science team members are:

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