The Imaging X-Ray Polarimeter Explorer (IXPE) Mission System Using a Small Satellite

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Abstract

The goal of the Imaging X-Ray Polarimeter Explorer (IXPE) Mission is to expand understanding of high-energy astrophysical processes and sources. IXPE will add two new dimensions to on-orbit x-ray science: polarization measurements and detailed imaging. Polarization uniquely probes physical anisotropies that are not otherwise measurable—ordered magnetic fields, aspheric matter distributions, or general relativistic coupling to black-hole spin. Detailed imaging enables the specific properties of extended X-ray sources to be differentiated. 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. MSFC provides the X-ray optics 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 polarization-sensitive detector units (DU) and detectors service unit (DSU) via the Italian Space Agency (ASI). The Observatory communicates with the ASI-contributed Malindi ground station via S-band link. The science team generates and archives IXPE data products at the HEASARC. The IXPE "mission system" is made up of the flight segment, ground segment and launch segment – this paper briefly summarizes the IXPE mission science objectives, overviews the flight segment (the payload, spacecraft, and Observatory implementation concepts), and summarizes the expected operations concept. A SpaceX Falcon 9 launch vehicle was selected in June 2019 to launch the IXPE Observatory. Mission CDR occurred in June 2019 and the IXPE Project is now firmly in the build phase.

The Science and Science Objectives

- IXPE's overarching science objective is to expand the understanding of high-energy astrophysical processes and sources in support of NASA's first scientific objective in astrophysics: "Discover how the universe works"
- IXPE will study targets over a broad range of types of astronomical X-ray sources with emphasis on black holes and neutron stars
- IXPE will: (some examples will follow)
  - Constrain the radiation processes and detailed properties of different types of cosmic X-ray sources
  - Investigate general relativistic and quantum effects in extreme environments
  - Constrain the geometry and the emission mechanism(s) of active galactic nuclei and microquasars
  - Establish the geometry and strength of the magnetic field in magnetars
  - Constrain the geometry and origin of the X-radiation from radio pulsars
  - Add to our knowledge as to how particles are accelerated in pulsar wind nebulae and in (shell-type) supernova remnants

Polarimetry of X-ray sources largely unmeasured; Opens a new window on the X-ray Universe

A Unique Step Forward

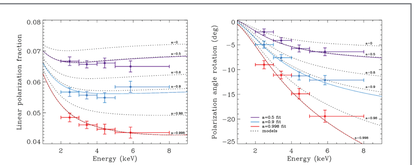
- IXPE continues NASA's leadership in science by providing a bold and unique step forward by doing things never done before
- IXPE will accomplish, for the first time, high-sensitivity measurements of the polarization of X-rays coming to us from some of the most exciting types of astronomical objects – neutron stars and black holes
- IXPE will accomplish, for the first time, imaging X-ray polarization measurements from extended objects such as exploded stars and jets attached to super-massive black holes
- IXPE measurements are made possible by new technology advanced by our Italian partners
- IXPE measurements are unique, adding two new dimensions to information space:
  - Polarization degree
  - Polarization angle

Measure Black Hole Spin

Microquasars

- Perform X-ray spectral polarimetry on microquasars to help localize the emission site (accretion disk, corona, jet)
- For at least one microquasar, constrain its spin parameter using general relativistic effects near black holes, including "gravitational Faraday rotation" of the polarization position angle

**For a micro-quasar in an accretion-dominated state, scattering polarizes the disk emission.
Polarization rotation versus energy is greatest for emission from inner disk.
Inner disk is hotter, producing higher energy X-rays.
Disk orientation from other experiments used to constrain GRX1915+105 model.
a = 0.50±0.04; 0.90±0.08%; 0.998±0.00003 (200-ks observation)**



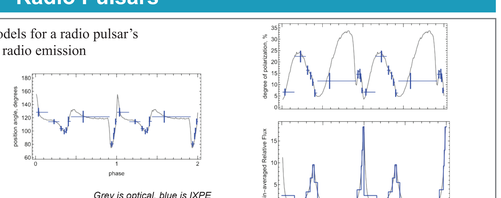
Radio Pulsars

- Perform X-ray *phase-resolved* polarimetry to test models for a radio pulsar's X-ray emission, which are distinct from those for its radio emission

Emission geometry and processes are still unsettled.
- **Competing models predict differing polarization behavior with pulse phase.**

X-rays provide clean probe of geometry.
- **Absorption likely more prevalent in visible band.**
- **Radiation process entirely different in radio band.**
  - **Recently discovered no pulse phase-dependent variation in polarization degree and position angle @ 1.4 GHz.**

140-ks observation gives ample statistics to track polarization degree and position angle.



Grey is optical, blue is IXPE

Acknowledgements

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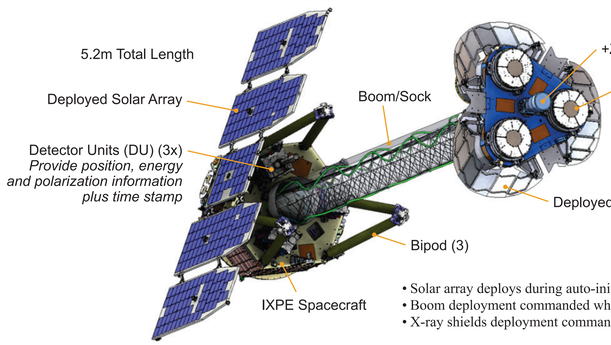
- The work described in this presentation is a culmination of efforts from teams at NASA MSFC, Ball Aerospace, ASI, INFN, IAPS, CU/LASP, Stanford, McGill University and Università degli Studi di Roma TRE

IXPE Observatory – Deployed

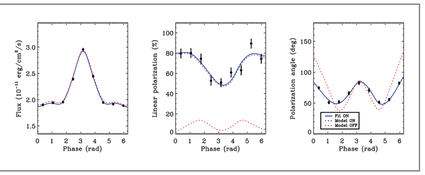


- Solar array deploys during auto-initialization sequence, arrays sun-pointed
- Boom deployment commanded while over Malindi ground station
- X-ray shields deployment commanded while over Malindi ground station

Magnetars and Quantum Electrodynamics (QED)

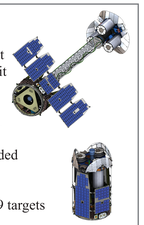
- Perform X-ray phase-resolved polarimetry to enable measurement of magnetic-field strength and geometry, along with a quantum-electrodynamic (QED) effect – "vacuum birefringence – that is detectable only in super-strong magnetic fields

**Magnetar is a neutron star with magnetic field up to 10^{15} Gauss.
Non-linear QED predicts magnetized-vacuum birefringence.
Refractive indices of the two polarization modes differ from unity and each other which impacts polarization and position angle as functions of pulse phase.
Example is 1RXS J170849.0-400910, with an 11-s pulse period.
Can exclude QED-off at better than 99.9% confidence in 250-ks observation.**

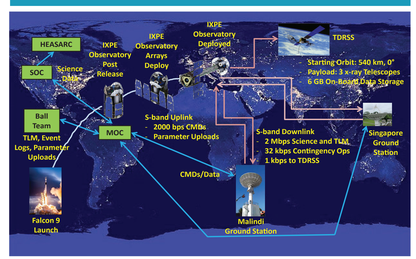


IXPE has a Straight-Forward Mission Concept

- NASA Small Explorer (SMEX) Mission
  - Class D Mission
- XPE Observatory is a single flight element
- Observatory launched to a 540 km, 0° orbit
- Launch vehicle is being selected
- 3 deployments, all during contacts
- Omni-directional S-band uplink/downlink
- Launch April 2021
- 2-year baseline mission with 1-year extended mission option
- Point and stare at known targets
- 12-month primary observing program – 49 targets
- 12-month follow-up observing program

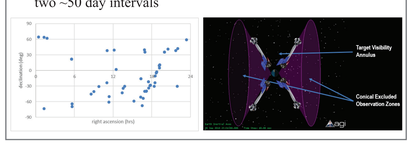


General IXPE CONOPS Overview

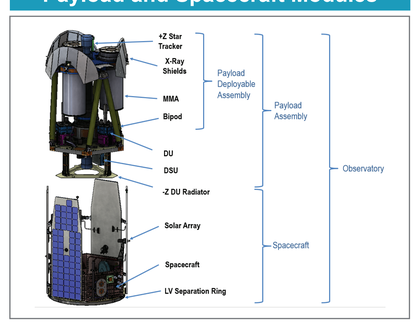


Observation Schedule Based on Sun Constraints

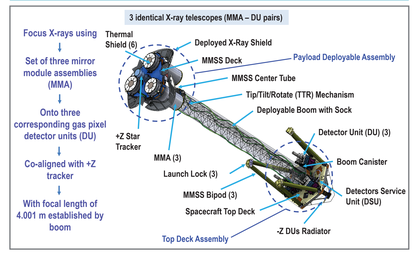
- Target list from science team – plotted to right
  - 49 X-ray sources
  - Not evenly distributed over the celestial sphere
- Observation constraints
  - Line of sight > 5 degrees above Earth's limb
  - Solar panel normal to sun < 25 degrees
- Can observe in an annulus between 65 and 115 degrees from the sun – plotted to right
  - Rotates during a year – can observe each right ascension for two ~50 day intervals



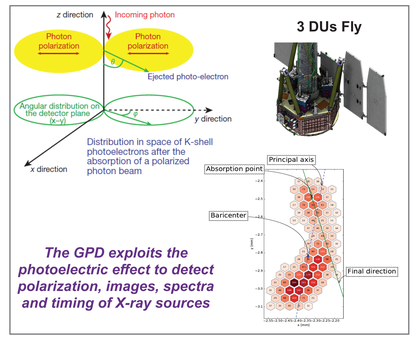
IXPE Observatory Built Up from Payload and Spacecraft Modules



Payload Overview



Detection Principle



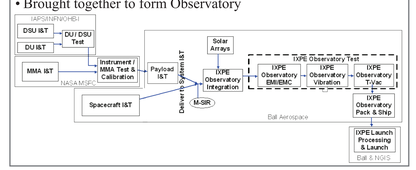
The GPD exploits the photoelectric effect to detect polarization, images, spectra and timing of X-ray sources

System Integration and Test Levels and V&V

IXPE AI&T effort broken into 3 major segments:

- Spacecraft module
- Payload module
- Brought together to form Observatory

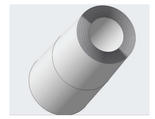
Assembled in parallel



IXPE Mirror Module Assembly Design

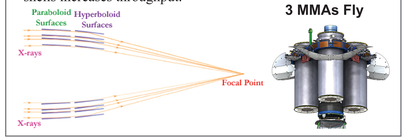
IXPE MMA Configuration

- 24 Nested Shells
- Wolter-1 prescription with equal length (300 mm) parabolic and hyperbolic segments combined
- Nickel/Cobalt alloy mirror shells
- No additional coating



X rays are efficiently reflected at shallow angles

- A Wolter-1 configuration combines a parabolic and hyperbolic surface for improved imaging. Concentrically nested mirror shells increases throughput.

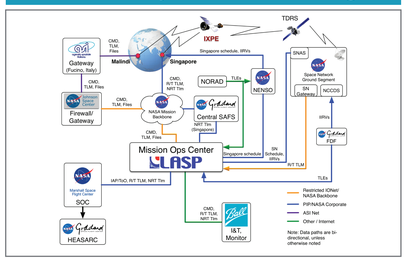


Key Spacecraft Features

- 3-axis stabilized S/C bus
  - Reaction wheel, torque rods, star trackers (2 optical heads), sun sensors, magnetometer
- Simple UART CMD/TLM interface to Instrument via CCSDS space packets
- S-Band communications (ground & TDRSS)
- Integrated structure with instrument bench (S/C Top Deck)
- Full-sky GPS coverage with 2 antennas & time distribution to P/L
- 6 gigabyte science data storage, 4 gigabyte non-volatile memory for housekeeping
- Table driven flight software
- Deployable 5-panel solar array
- Single string S/C with areas of redundancy
- System, subsystem, and component level fault protection

Straight-forward bus design with heritage components

IXPE Ground System Network Diagram



Conclusions

- IXPE is scientifically outstanding and truly unique amongst NASA's X-ray Missions
- IXPE brings together an international collaboration to fly imaging X-ray polarimetry on a NASA Small Explorer
- IXPE will conduct X-ray polarimetry for several categories of cosmic X-ray sources: neutron stars and stellar-mass black holes, to supernova remnants and active galactic nuclei
- IXPE payload uses 3 identical imaging X-ray telescopes (MMA – DU pair) to collect science data
  - X-ray optics (MMA) are developed and provided by MSFC
  - Detector Units (DU) are developed and provided by the IXPE Italian Team
- Purpose-built, small spacecraft from the Ball product line to support unique science payload
- IXPE Project proceeding on schedule
  - IXPE Project Phase B Kicked off February 2017
  - Mission SRR held 1September 2017
  - Mission PDR held June 2018
  - Mission CDR held June 2019
  - Falcon 9 Launch Vehicle selected June 2019
- Launch planned April 2021
- The IXPE Project will conduct world-class science on a Small Explorers budget with a Small spacecraft

IXPE Observatory in Falcon 9 Fairing

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