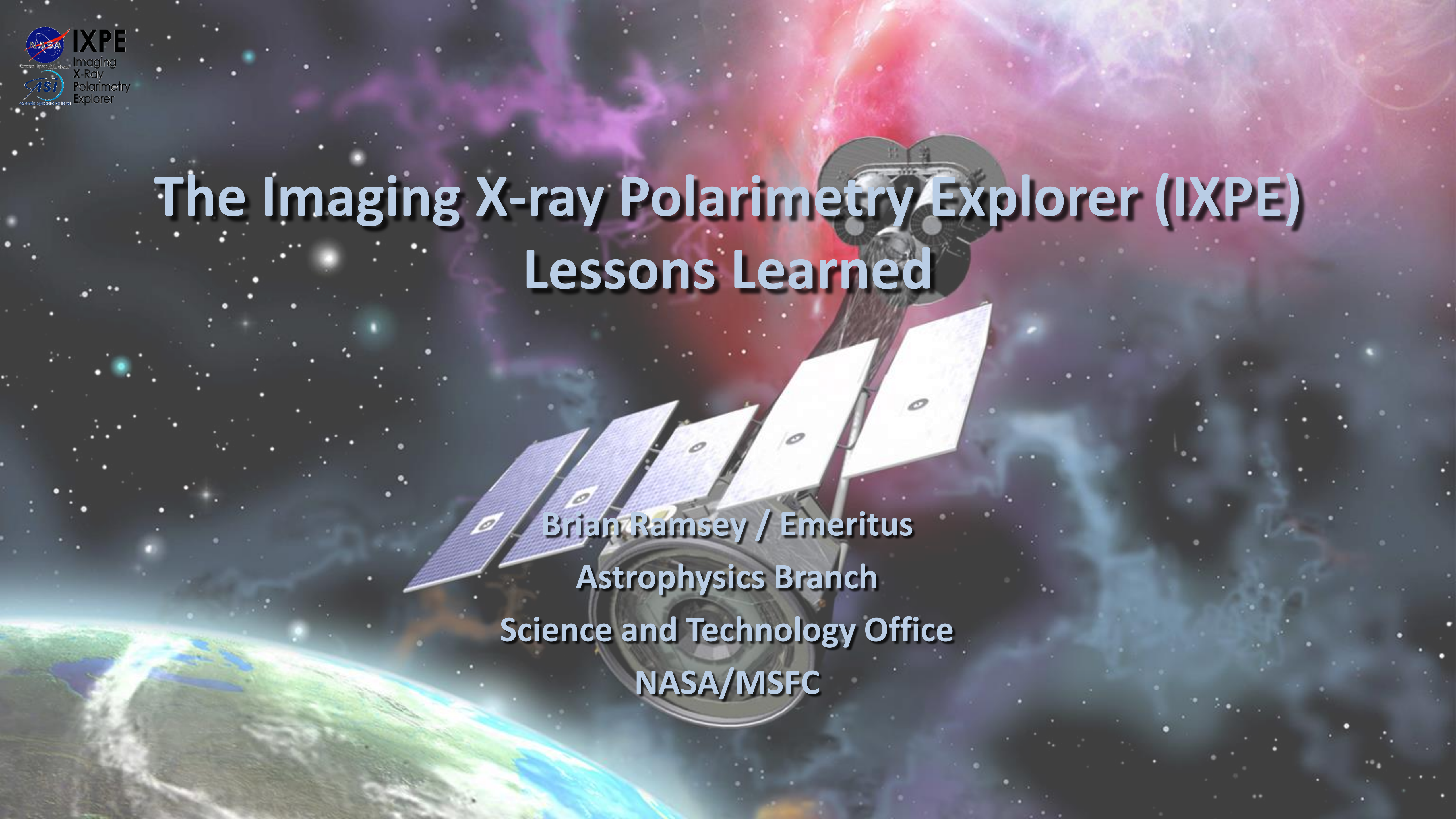


IXPE
Imaging X-Ray Polarimetry Explorer

# The Imaging X-ray Polarimetry Explorer (IXPE) Lessons Learned

Brian Ramsey / Emeritus
Astrophysics Branch
Science and Technology Office
NASA/MSFC

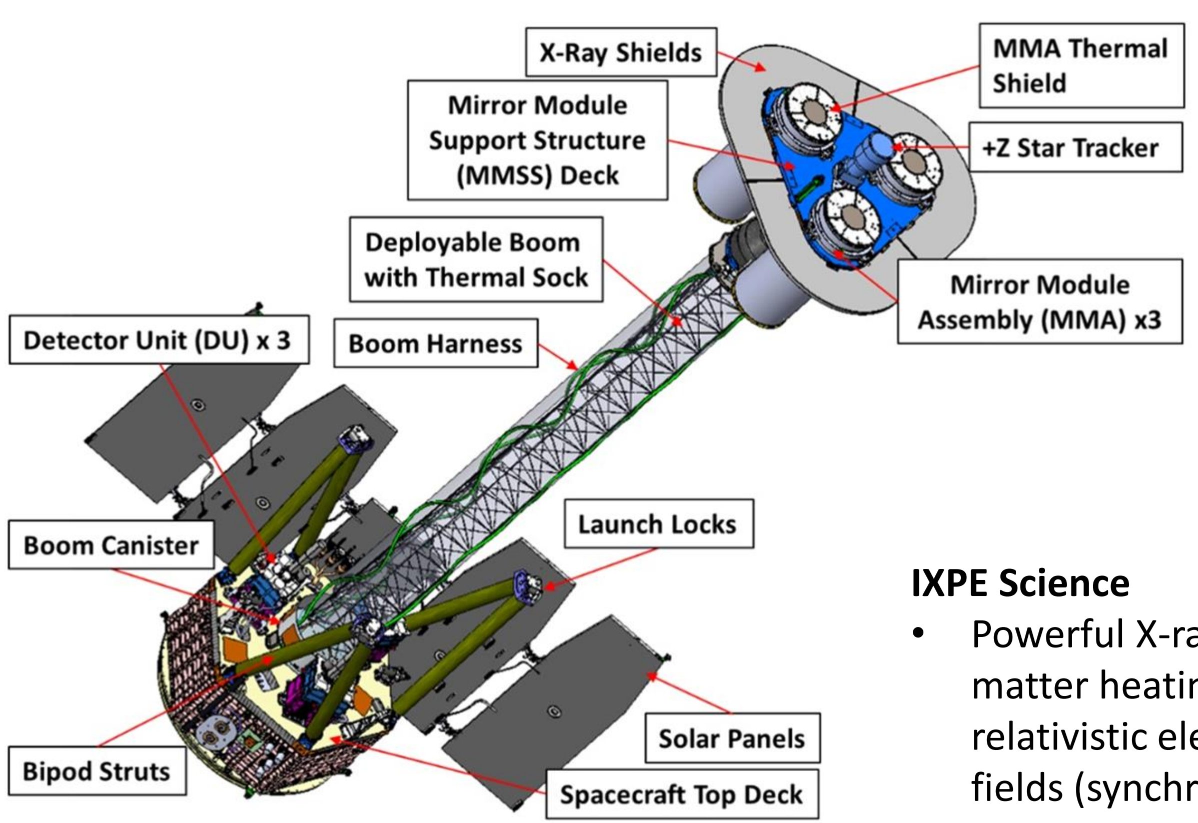
# IXPE Mission Overview

- Small Explorer Mission: First Observatory dedicated to X-ray Polarimetry
- Phase B started in Jan 2017
- Launched on Dec 9, 2021, ~ 1 month of commissioning
- SpaceX falcon 9 launch from cape into equatorial orbit
- Ground station in Malindi, Kenya (primary) with Singapore backup .
- Completed 2-year baseline mission. Now in General Observer phase

| | |
|---|---|
| NASA Marshall Space Flight Center | PI team, project management, SE and S&MA oversight, mirror module fabrication, X-ray calibration, science operations, and data analysis and archiving |
| ASI (agenzia spaziale italiana) | Detector system funding, ground station |
| BAE SYSTEMS | Spacecraft, payload structure, payload, observatory I&T |
| IAPS, INAF (Istituto Nazionale di Astrofisica / National Institute for Astrophysics), INFN, OAC, OHB Italia | Polarization-sensitive imaging detector systems |
| LASP | Mission operations |
| Roma Tre (Università degli Studi), Stanford University | Scientific theory |
| Nagoya University | Thermal shields |
| MIT (Massachusetts Institute of Technology) | Co-Investigator |

Science Advisory Team

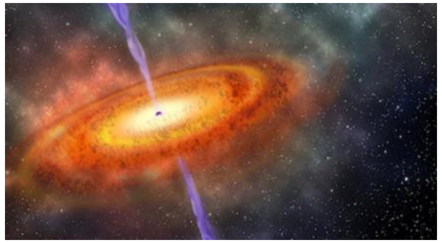
# IXPE Payload and Science

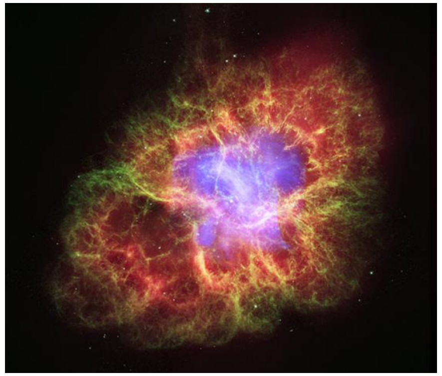



- 3 identical telescopes each comprised of mirror module assembly with polarization-sensitive X-ray detector at focus
- 4-m focal length system (deployed on orbit)
- 30 arcsec HEW angular resolution
- 12.8 arcmin x 12.8 arcmin detector-limited FOV
- 5.5% polarization sensitivity for ~1 mCrab source in 10 days

**IXPE Science**

- Powerful X-ray sources produce their radiation by matter heating as it spirals onto black holes or by relativistic electrons spiraling in intense magnetic fields (synchrotron radiation)
- Both these mechanisms give rise to polarization
- Polarimetry provides a powerful way of probing the emission geometry and emission mechanism in some of the most exciting cosmic sources





***Baseline science mission had 115 observations of 64 distinct targets from broad range of source types, of which 50% had highly significant (> 5 sigma) measured levels of polarization. Observatory continues to work perfectly***

# What did I wish I had known at Phase A kickoff ?

## Launch Vehicle

- It was assumed that the Pegasus rocket would be chosen for IXPE due to the equatorial orbit requirement
- Around CDR, it was announced that the launch provider would be SpaceX with a Falcon 9
- The low-frequency sine test plus acoustic test that this entailed as well as the change of thermal environment was challenging for the IXPE observatory, particularly for environmental testing
- We had not planned for a Cape launch (Pegasus would have been launched from Kwajalein)
  - Had to implement lightning protection after the fact on the launch vehicle

***Lesson: need to have proper accounting of all possible launch vehicles and launch sites for generation of requirements***

# What if HQ can't supply your budget profile – replanning on fly?

FY 2018 Replan

- NASA HQ proposed a budget cut for FY18 and funding rephasing
  - Cut was $21M, taking FY 18 budget from $42M to $21M, with reinstatement of $10M in FY19
  - Requested IXPE to try and maintain original PI cost cap plus inflation
  - Given 2 weeks to respond
- Replan Decision
  - Increase Phase B by 5 months and slip everything beyond by 5 months (including launch readiness date)
  - Increase funding required in FY20 ($6.7M) and 21 ($6.0M)
- Decision Timeline

**July 10, 2017**
PM Notified by NASA HQ

→ **July 14, 2017**
Provide IXPE Top-level impacts/rationale to I2C and Ball to discuss their schedule impacts & constraints

→ **July 19, 2017**
Provide Re-Plan to S&T Mgt; Center Mgt on July 20th

→ **July 20, 2017**
Update DRAFT IXPE Response to Revised Budget – Discuss with I2C and Ball Team members

→ **July 24, 2017**
Send Final IXPE Response to Revised Budget to NASA HQs

→ **~Aug 2, 2017**
Final Response expected from NASA HQs on IXPE FY18 budget in N2

# What if HQ can't supply your budget profile – replanning on fly?

FY 2018 Replan Impacts Noted at Time

- Launch Readiness Date (LRD) slips by ~5 months
- Total PI Managed Mission Cost (PIMMC) increases from $132.0M to $135.8M (~$1.7M increase due to inflation and remainder due to 5 month slip)
- Reduces Phase B (FY18 only) reserves to 15% (was 30%)
- Phase B contract with Ball Aerospace must be extended
- Instrument (I2C) schedule slightly ahead of IXPE Master Schedule
  - Increases Project Risk due to start of Instrument fabrication prior to Mission-PDR
- MMA-optics fabrication slips by ~2.5 months
  - Assumes delay in MMA-EU tests at MSFC from January 2018 to April 2018
  - Assumes MMA flight units completion slip from June 2019 to August 2019
- Delay in FY18 creates risk of losing key technical skills
  - Part-time employees facing further reduction may decide to leave for other projects

*Plan agreed upon by Center, Partners and HQ* ✓

# Other Necessary Replanning

Example: 2019 Replan

- Feb 2019: Government shutdown for 5 weeks. Work stopped at MSFC, but not at Ball or in Italy. Resulted in a 5-week delay of mirrors to calibration
  - Decision: perform end–to-end calibration on spare telescope only (instead of 3 flight plus spare)
    - Had extensive calibration data on detectors (Italy) and mirrors (at MSFC)
      - Needed only 1 system to show that telescope calibration can be synthesized from mirror and detector calibration data.
  - Freed up flight units immediately to ship to Ball for integration
  - Minimal risk and preserved schedule with additional margin

## Pandemic

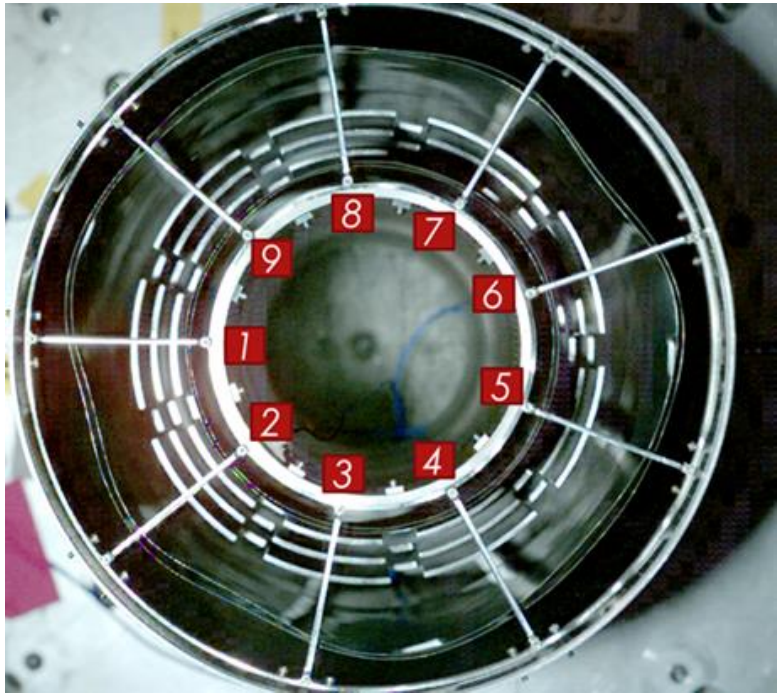
- This hit (March 2020) just as we were building and testing hardware. MSFC was shut down for several months, then startup packages were approved for limited access for continuing work
- Main problem for Italy and MSFC was travel to Ball Aerospace for payload integration and testing
- Worked around this by training Ball to inspect, test and integrate the Italian instrument hardware and the MSFC-provided mirror module assemblies
    - Made possible by willingness of Ball to take on this role and by flexible contracting which allowed for quick changes in scope to Ball tasks without doing a time-consuming contract modification
        - Funded a notice of change ‘pool’ so that new tasks could be implemented quickly
- Similar problem for X-ray end-to-end calibration (of spare flight units) , where Italy was to operate the instrument at the MSFC test facility
    - MSFC modified Italian handling and test procedures and practiced on an instrument engineering unit
    - Italian colleagues were able to participate in the calibration through the use of Teamviewer software

***Lesson: negotiate flexible contracts up front that allow you to respond quickly if additional contractor support is needed (we used this many times for all sorts of unforeseen problems)***

# Lessons Learned

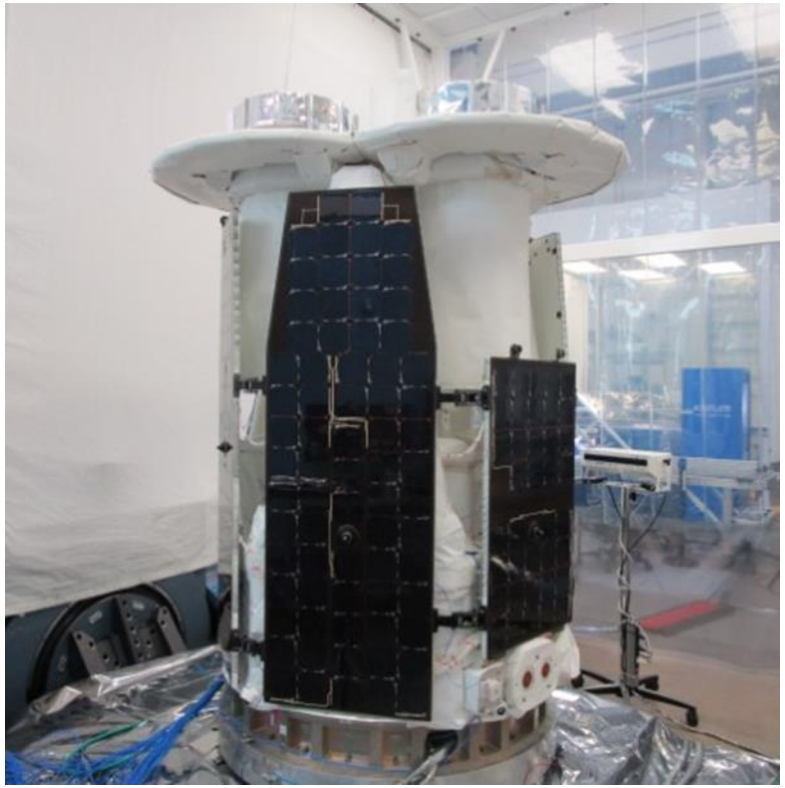
## Heritage Claims

- Built many flight mirrors before, but slightly thinner shells, poor environmental controls and over-testing hardware contributed to failure when engineering unit was first tested
- Non-linear behavior of thin mirror shells
- Weakened epoxy (shows value of process development) due to high humidity in assembly room. (Same epoxy we had used extensively before). Manufacturer's data sheet gave no requirements on this
- For delicate hardware such as optics need to test at appropriate levels (MEL+3 dB) for example. Not some generic value
- Did show the great value of engineering units. Used extensively for verifying mechanical and optical design, for testing handling fixtures and procedures, ditto for calibration practice and testing, etc.




***Lesson: even small changes in design can negate heritage/TRL claims. Do not over-test sensitive hardware. An engineering unit is extremely valuable.***

# Lessons Learned



Removal of Structural Test Model

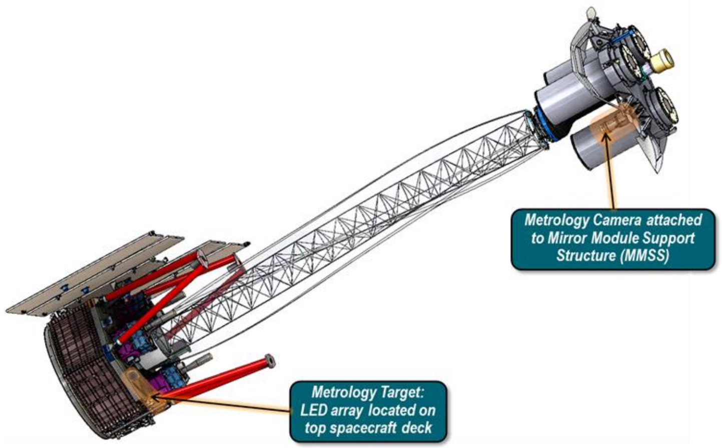
- For cost and schedule saving, we removed the structural test model that was intended to verify Observatory structures and stresses prior to integrating the payload into the observatory
- This meant that we ended up qualifying Observatory structure with all flight hardware in place
  - Due to some uncertainty in modal tests which, because of the way the Observatory was stowed, gave different modal frequencies at low Observatory input load levels than at high levels we were unsure of the loads that the delicate mirror modules were seeing
    - Had to heavily instrument the Observatory and analyze data at each step in input power to make sure MMAs were not damaged

***Lesson: structural test models are very important to avoid potential damage in complex flight systems***

# Lessons Learned

## Removal of Metrology System

- For cost and schedule saving, we removed the metrology system that was to keep track of relative motion between the two ends of the extended boom
- This decision was based on a stop analysis that showed that motions would be smaller than the angular resolution of the telescopes
- On orbit, these boom motions were found to be significantly larger
  - For bright point X-ray sources it is possible to use 'X-ray aspect' to remove this motion
  - For the few faint extended sources we had to develop a model of distortions vs pointing direction to remove the motion
    - Luckily this seems to work okay
- We also incorporated a tip/tilt/rotate system to reposition images if the boom deployed outside of its expected location. Fortunately, we kept that




***Lesson: STOP analysis of a complex system is very difficult. Check carefully and have a backup plan !***

# Lessons Learned

## Requirements

- Be realistic in Level-1 requirements, and do not change these
- Hold margin at lower levels to ensure level 1 requirements are met
- Think carefully about how you will verify these requirements
- Use cross-team tool for managing requirements (DOORS)

## MAAR

- First full SMEX mission at MSFC did some light tailoring but the whole thing took a long time (~ 9 months)

## Quality Assurance@MSFC

- Negotiate the appropriate level of oversight to avoid being swamped by paperwork
- What needs to be witnessed or what can be verified after the fact
    - Don’t underestimate how time consuming this paperwork can be can

International Partners- Communications

- Make sure international agreements are in place to allow early exchange of technical information
- Face to face meeting are invaluable to establish good relationships and avoid mis-communication
  - Participate in on-site subsystem reviews. Often held in English

International Partners- Shipping

- Flight hardware and support equipment travelled in both directions (mainly Italy)
- Freight to Italy was not cleared by shipper. Italian representatives did that but process was very long, particularly for returning items (shipping documents had to match exactly …leading to lengthy delays)
  - Get information on country custom processes up front
- Even very-well-packed items were sometimes damaged in shipping. Assume items will be turned on side or upside down (despite labelling). Include environment monitors inside
- Assume shipping will take a long time. Current lead time for trucks and planes can be significant

***Lesson: work everything in advance. Hold face-to-face meetings when possible. Pack hardware extremely well and plan for someone on project to spend time on careful paperwork, inspections, packing, etc.***

# Italian P.I. Lessons Learned

Companies come and go

The company that was to assemble the flight detectors (with decades of experience) pulled out of the project and a decision was made to do the work in-house. Their funding agencies were very skeptical about this and wanted to put more pressure on the company, but in the end the in-house approach worked very well

***Lesson: be open minded to changes (despite pressure to not change original plan) and make decisions early***

Expect the unexpected (also heritage)

Gas pressure slowly changed in the flight and spare detector. In retrospect the information was there in various forms since the early detector development (many years earlier) but was never attributed to a pressure change. After it was realized (during flight unit calibration) it was then possible to put forward a simple model to show that by launch it would stabilize. This caught us completely by surprise, despite ~20 years experience

***Lesson: be ready to discover things you had not anticipated with hardware you think you know well***

Software doesn't write itself

In the intense rush to build hardware, software can often be overlooked. It is vitally important to dedicate enough resources to the infrastructure for software development and testing. For IXPE, this was a much bigger task than was anticipated

***Lesson: think carefully about software requirements and allocate appropriate resources***

# Lessons Learned

## Concept Study

- Get outside experts to participate on red/gold teams for proposals reviews
    - Try and pick members with past explorer experience

## Program

- Standing-Review-Board (SRB) members were very knowledgeable and experienced
- IXPE had a very good working relationship with the SRB, particularly the Chair
    - Called on SRB members to advise when problems arose
    - Used SRB members for subsystem reviews also

# Lessons Learned (miscellaneous)

## Mockups

- We built a full-size simulator of the observatory (from wood and plastic) to practice installing very thin thermal shields (1.4 micron) on the mirror module assemblies and for doing mirror inspections after the Observatory environmental testing. Given the tight packing of delicate hardware this was extremely useful for developing procedures

## Transporting Observatory

- Don't take for granted that environmentally-controlled means what you think it does

# Lessons Learned Post Launch

## Mission Lifetime Assessment

- Original Pegasus launch vehicle placed tight constraints on launch mass and altitude achievable. Original assessment was that observatory would re-enter in 4 years, so lifetime of limiting components were sized accordingly
- The actual launch vehicle enabled a higher orbit with consequently-longer (18 y) lifetime before re-entry
- The battery became the limiting item for operation well beyond the baseline mission
  - Specifically, the capacity of the battery was slowly degrading, increasing the depth of discharge during eclipse
  - To increase the overall lifetime, measures were taken to reduce overall power consumption, and consumption during eclipse periods, including lowering overall operating temperatures and not transmitting during end of eclipses. The earlier these are implemented, the longer the battery lifetime.
  - In this way, battery projected lifetime is significantly increased, providing operation through end of decade

***Lesson: Do an early, detailed assessment of limiting lifetime items to see what can be done to maximize lifetime without incurring inappropriate costs***

# GOOD LUCK !