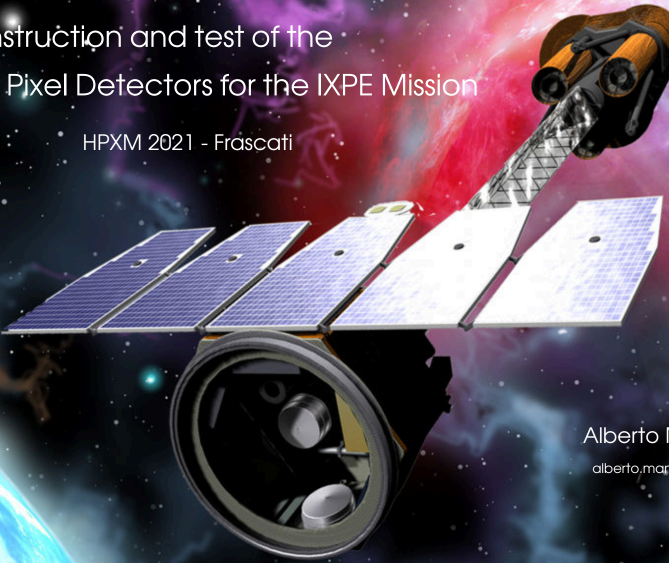
Construction and test of the Gas Pixel Detectors for the IXPE Mission

HPXM 2021 - Frascati



Alberto Manfreda

alberto.manfreda@pi.infn.it

INFN–Pisa

9 giugno 2021

X-ray polarimetry in astrophysics

- Polarimetry provides rich information on the physics of targets that cannot be obtained in any other way:
  - Internal geometry of sources of radiation
  - Strengths and orientations of magnetic fields
  - Distribution and orientation of scattering particles
  - Fundamental physics effects (GR, QED)
- Due to its technical challenges, soft X-ray polarimetry has been silent for $\sim$ 40 years . . .

THE ASTROPHYSICAL JOURNAL, 220:L117–L121, 1978 March 15

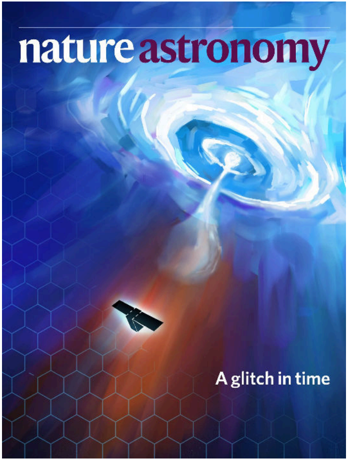
A PRECISION MEASUREMENT OF THE X-RAY POLARIZATION OF THE CRAB NEBULA WITHOUT PULSAR CONTAMINATION

M. C. WEISSKOPF, E. H. SILVER, H. L. KESTENBAUM, K. S. LONG, AND R. NOVICK
Columbia Astrophysics Laboratory, Columbia University
Received 1977 November 15; accepted 1977 December 22

ABSTRACT

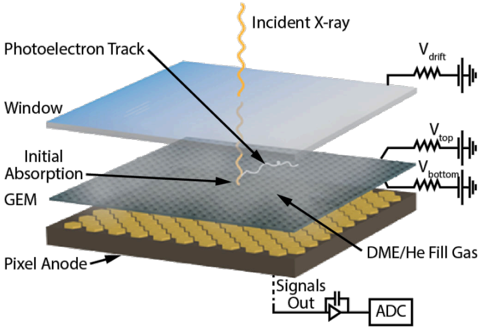
The linear X-ray polarization of the Crab Nebula has been precisely measured at 2.6 keV and 5.2 keV with the *OSO* 8 graphite crystal polarimeters. The 1.4 ms time resolution of these instruments permitted the removal of any contribution to the polarization from the pulsar. The nebular polarization is 19.2% ± 1.0% at a position angle of 156°.4 ± 1°.4 at 2.6 keV. At 5.2 keV the corresponding results are 19.5% ± 2.8% at 152°.6 ± 4°.0.
Subject headings: nebulae: Crab Nebula — polarization

The X-ray polarimetry window reopens



- ▷ . . . until the latest generation of detectors came to the rescue!

The Gas Pixel Detector concept



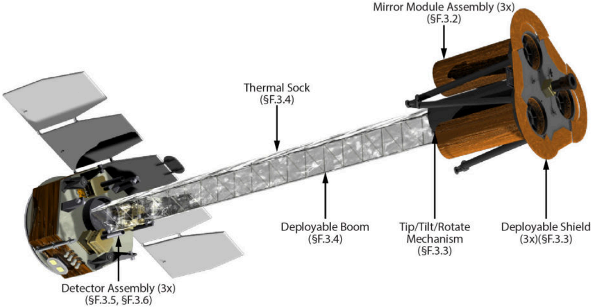
- ▷ Photoelectric effect dominant for soft (< 10 keV) X-rays
- ▷ K-shell photo-electron emission 100% modulated for linearly ploarized radiation:

$$\frac{d\sigma_C^K}{d\Omega} \propto Z^5 E^{-\frac{7}{2}} \frac{\sin^2\theta\cos^2\phi}{(1+\beta\cos\theta)^4}$$

- ▷ Typical track length ∼ µm in solid: a gaseous medium is needed!

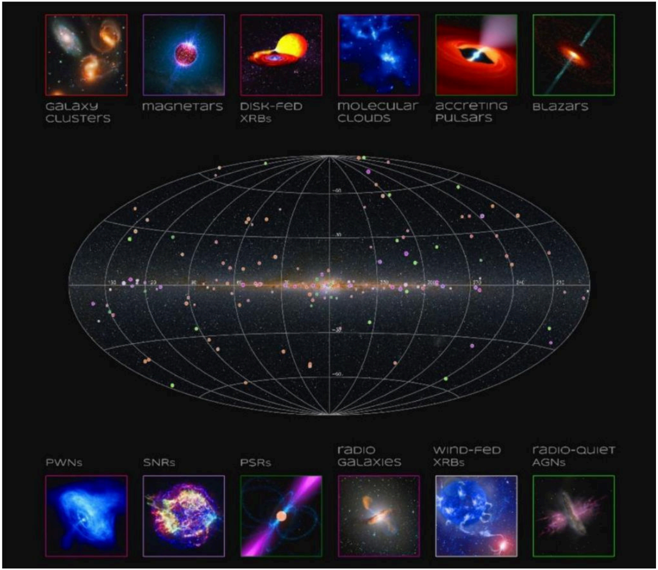
- ▷ X-ray absorption in a gas gap
- ▷ Signal amplification via a Gas Electron Multiplier (GEM)
- ▷ Finely pixelized ASIC as readout anode
- ▷ Sensitive in the $\sim 2-8$ keV band
- ▷ Full two-dimensional imaging and spectroscopy

The Imaging X-Ray Polarimetry Explorer mission

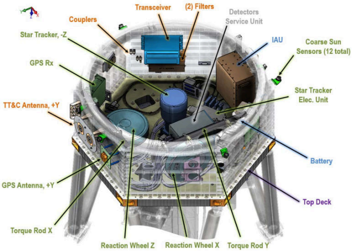


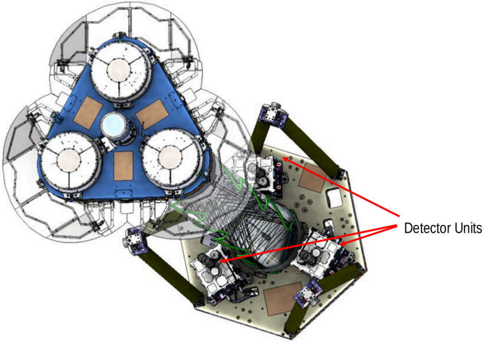
- ▷ Selected in 2017 by NASA as its next SMEX (SMall EXplorer) mission, to be launched in November 2021
- ▷ Funded by a NASA-ASI partnership, completely dedicated to X-ray polarimetry
- ▷ For the first time simultaneously perform imaging, spectrometry, polarimetry and timing of tens of x-ray sources
- ▷ 2 years of on-orbit operations + 1 years extension

IXPE science targets



The spacecraft

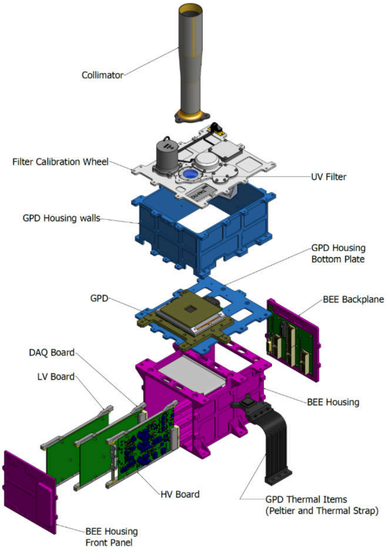




- 300 kg total mass, 200 W power budget
- Deployable boom, 4 m focal nominal length
- Will be launched by a Space-X Falcon 9
- Hosts 3 identical telescopes, each comprised of:
  - A Mirror Module Assembly (MMA) for light collection
  - A Detector Unit (DU) equipped with a polarization-sensitive detector
- DUs are rotated by 120° respect to each other (reduce systematic effets)

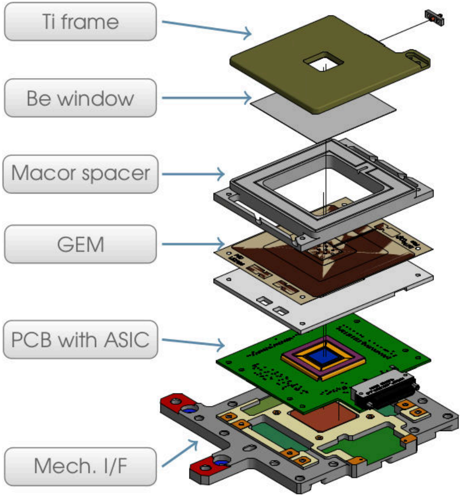
The Detector Unit (DU)

Exploded view

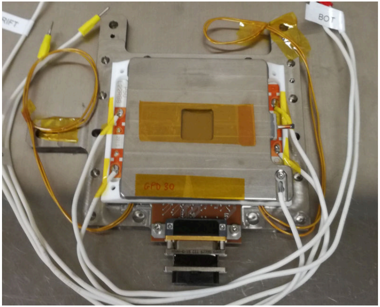


- The DU is the basic unit of the IXPE instrument
  - Designed, assembled and tested at INFN
- Back-end electronics mounted below the GPD on a dedicated housing
- GPD thermal control via TEC (Peltier), heater and thermal strap
- Filter and Calibration Wheel on top of the detector for in–flight calibration and performance monitoring
  - One polarized (2 energies) and 3 unpolarized sources
- Stray light collimator to block diffuse light
  - Carbon fiber and Mo (and Au) coating

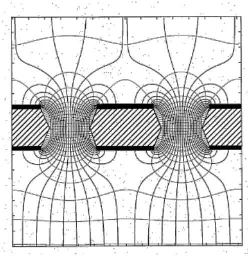
GPD exploded view

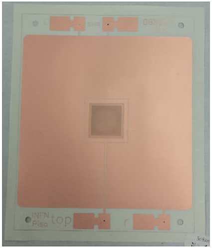


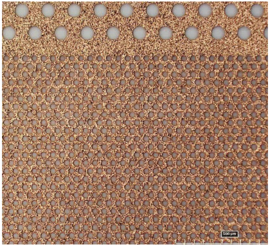
- Sealed detector, no gas system needed
- X-ray window in Be, 50 μm thick
- Gas cell thickness 1 cm
- Gas mixture: DME @ 0.8 bar
  - Optimized for 2-8 keV energy range



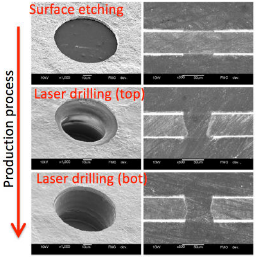
The GEM





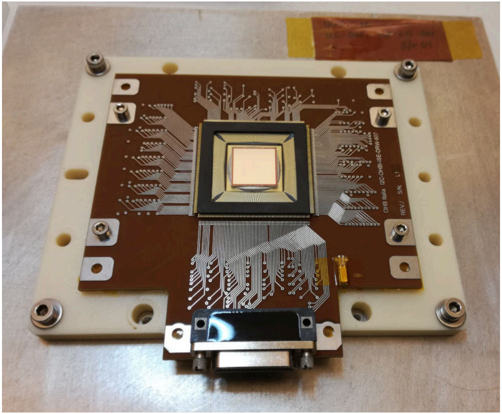


- ▷ Produced by RIKEN and SciEnergy in Japan
- ▷ 50 μm thick Liquid Crystal Polymer (LCP) insulator, 5 μm copper layer
- ▷ Hexagonal hole pattern, with 50 μm pitch, diameter of 30 μm
- ▷ Pushing the technology to its limits
- ▷ Production process refined iteratively with input from our test

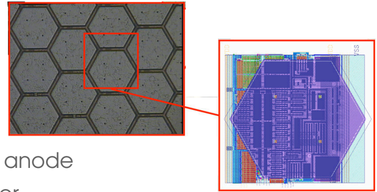


The readout ASIC

Bellazzini et al., NIM A **535**, 477–484 (2004)



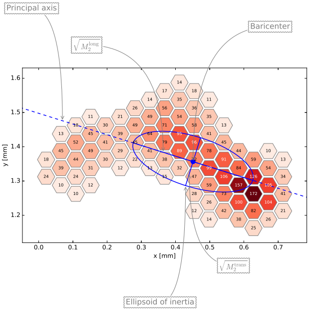
Technology	CMOS 0.18 μm
Active area	$\sim$ 15 $\times$ 15 mm
Fill factor	92 %
Number of pixels	300 $\times$ 352
Pixel pitch	50 μm
Pixel density	$\sim$ 470/mm 2
Pixel noise	$\sim$ 20 ENC
Shaping time amplifiers	3 - 10 μs
Readout clock	typically 5 MHz

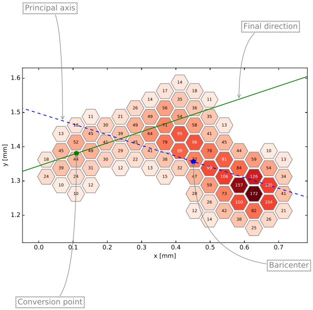


- ▷ Self-triggering, with ROI definition
- ▷ Metal top layer acting as a charge collecting anode
- ▷ Integrating preamplifier, shaper, S/H, multiplexer
- ▷ Serial readout via external 14 bits ADC

Event reconstruction

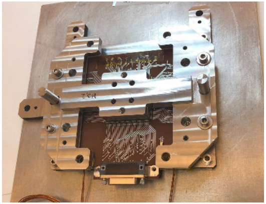
A typical 5.9 keV track (Fe55)

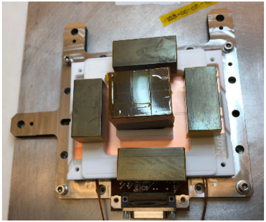


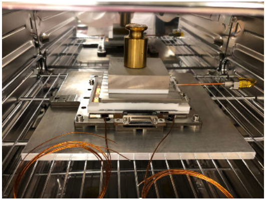


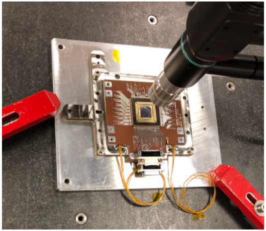
- Clustering stage to identify main track
- Moments analysis to get the ellipsoide of inertia of the charge distribution
- Exploit the Bragg peak to identify conversion point
- A second, weighted moments analysis, to improve direction estimate (especially helpful for high-energy events)

DU construction: GPD assembly @INFN Pisa



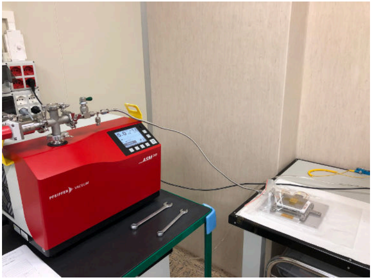


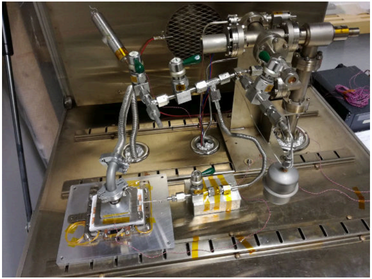


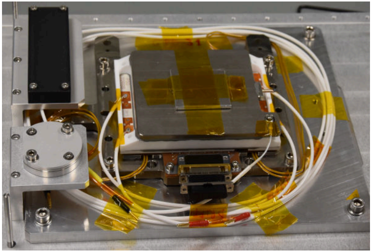


- Hard challenge, due to strict time schedule:
  - Less than 3 years from mission approval to delivery of the last DU
  - 17 GPDs assembled, 9 of flight quality, 3 of which (+1 spare) selected for the mission.
- Requirement on leak rate: $< 1 \cdot 10^{-9}$ mbar l/s
  - Careful design of the entire process
  - Patiently tuned by trial-and-error
- Several gluing steps ($\sim$ 1 day each), with CMM alignment verification

GPD filling and testing

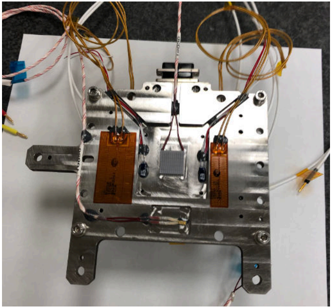


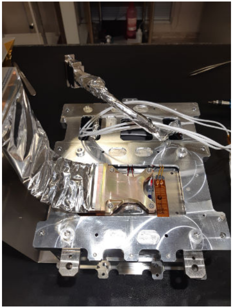




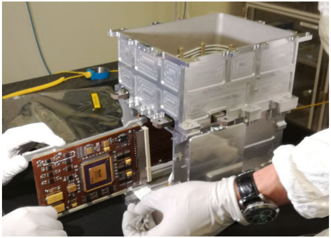
- Final leak test with He at INFN-Pisa
- Bake-out and filling at Oxford Instrument (OIT) in Finland
  - A 2 weeks bake-out at 100 °C
  - Filling with DME at 0.8 bar is done in the same facility
  - Finally GPD is permanently sealed by crimping the filling tube
- Back to Pisa for electrical and functional tests with Fe55 source

DU integration

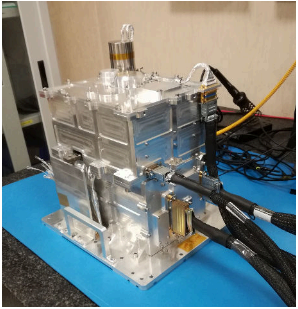


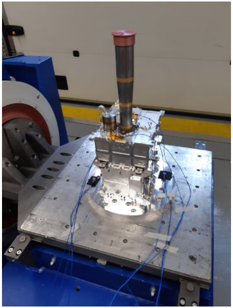


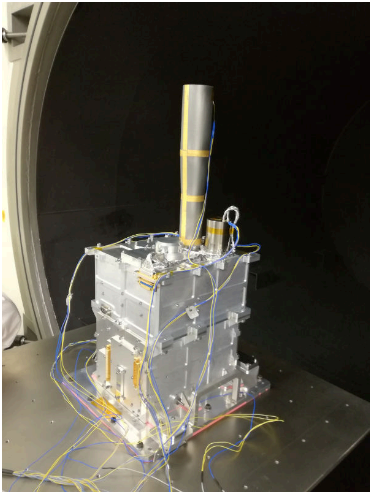
- ▷ DU Intergation performed in-house
- ▷ Installation of thermal items and cabling
- ▷ Integration of BEE boards, FCW, UV filter and collimator



DU FM tests

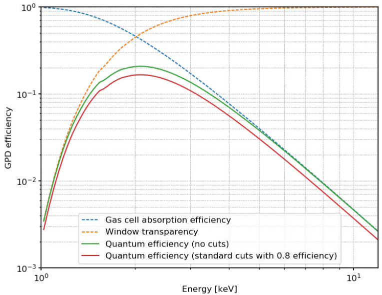


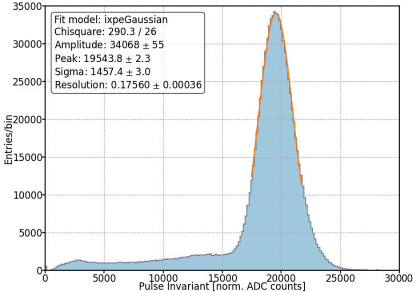




- Full functional tests and metrology @INFN-Pisa
- Vibration test @BPS (FM1) and SERMS
  - Followed by a functional test
- TVAC tests and calibration with X-ray beams @IAPS, Rome

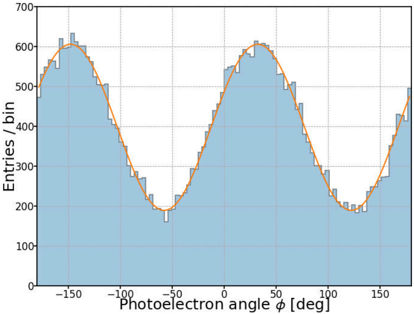
Performance of the GPD

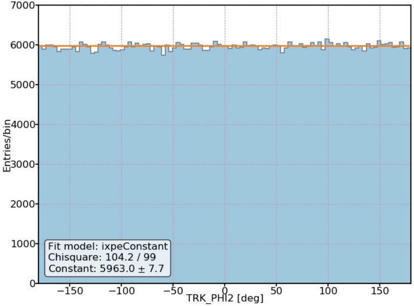




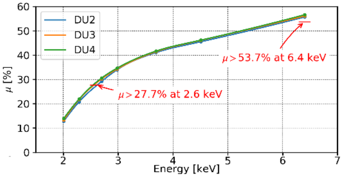
- Quantum efficiency: 20% (3%) at 2.7 keV (5.9 keV)
- Energy resolution: $\sim$ 17% at 5.9 keV.
  - Better than our mission requisite (25%)
  - Enough to perform energy-resolved polarimetry in a few bins
  - Left tail: photons converting in GEM or Be window
- Spatial resolution: $\sim$ 90 μm at 5.9 keV
  - Subdominant compared to the blurring introduced by the optics
- Temporal resolution: $\sim$ a few μs.
  - Allows phase-resolved polarimetry for pulsars

Performance of the GPD





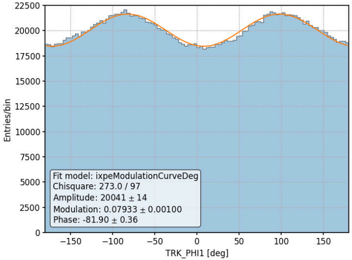
- ▷ Modulation factor: 0.3 (0.55) at 2.7 (6.4) keV.
  - ▷ Fully meet scientific requirements
- ▷ Flat response to unpolarized radiation at 5.9 keV
- ▷ What about lower energies?

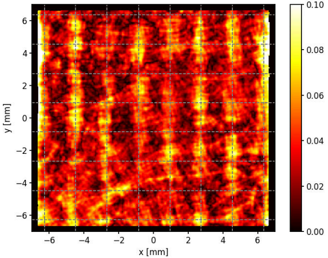


The spurious modulation puzzle

An unexpected behaviour

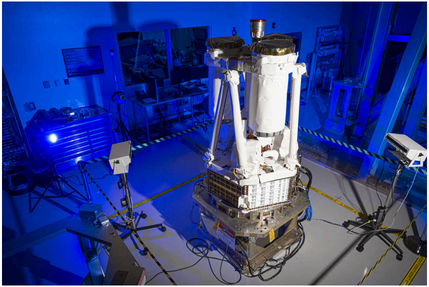
- Spurious modulation signal detected during tests with low-energy pencil X-ray beams
- Orientated vertically ($\sim 90^\circ$), quickly decreasing with energy: up to $\sim$ 10% at 2.7 keV, essentially absent at 5.9 keV
- Large variations on relatively small (sub-mm) spatial scale: calibration is time consuming





- A mix of different causes:
  - Coherent noise effects in the ASIC (small and easily removed by off-line analysis)
  - Spatial variation due to GEM
- Solution: observatory dithering along the line of sight + calibration of the residual effect

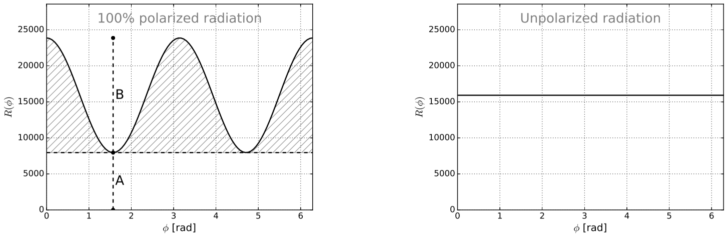
Status and Conclusions



- IXPE will open a new observative window on the Universe
- Expected to observe for the first time X-ray polarization in the soft X-ray band (2-8 keV) for many tens of sources, with unprecedented sensitivity
- Production and delivery of flight DUs completed
- Satellite integration at Ball Aerospace (Colorado) completed
- Currenlty undergoing final vibration and TVAC tests at spacecraft level
- Launch scheduled in November 2021... science coming soon!

BACKUP SLIDES

Basic polarimetry formalism



- A polarimeter essentially measures the azimuthal modulation around the polarization direction ϕ_0 of the incident photon beam:

$$R(\phi) = A + B\cos^2(\phi - \phi_0)$$

- Modulation factor: Response to 100% polarized radiation

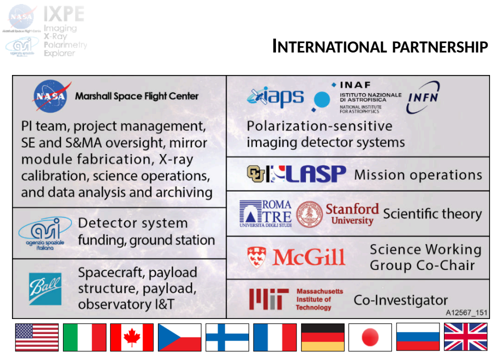
$$\mu = \frac{R_{\max} - R_{\min}}{R_{\max} + R_{\min}} = \frac{B}{B + 2A}$$

- Minimum Detectable Polarization (MDP):

$$MDP_{99\%} = \frac{4.29}{\mu\sqrt{N}}$$

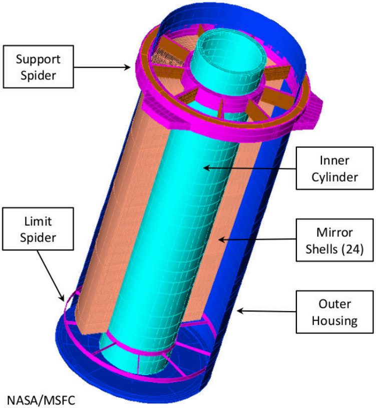
The IXPE mission

Overview



- ▷ 2 years of on-orbit operations + 1 years extension
- ▷ Point-and-stare observation mode towards predefined targets
  - ▷ Long duration - from days to week(s)
  - ▷ Data are made public after validation
  - ▷ No-repointing, but Targets of Opportunity possible in a few days
- ▷ Equatorial orbit (0.1°inclination), 600 Km nominal altitude
  - ▷ Minimize charged particle background
  - ▷ $\sim$ 13% off-time due to South Atlantic Anomaly

Mirror modules

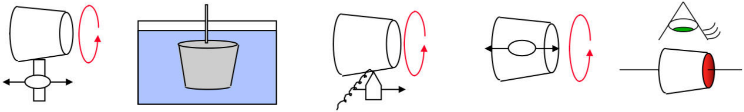


Property	Value
Number of MMAs	3
Mirror shells per MMA	24
Focal length	4000 mm
Shell length (P+S combined)	600 mm
Inner–outer shell diameter	162–272 mm
Inner–outer shell thickness	0.18–0.26 mm
Shell material	Nickel–Cobalt alloy
Mass per MMA	30 kg (current best estimate)
Effective area per MMA	210 cm^2 (2.3 keV) > 230 cm^2 (3–6 keV)
Angular resolution	≤ 25 arcsec HPD
Field of view (detector-limited)	12.9 arcmin

Mirror modules assembly

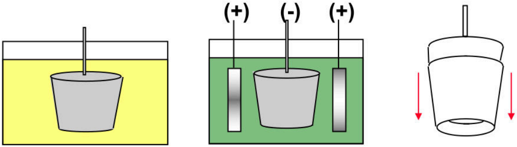
Mandrel fabrication

1. Machine mandrel from aluminum bar
2. Coat mandrel with electroless nickel (Ni–P)
3. Diamond turn mandrel to sub-micron figure accuracy
4. Polish mandrel to 0.3-0.4 nm RMS
5. Conduct metrology on the mandrel



Mirror-shell forming

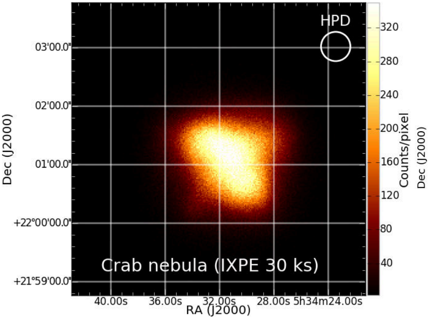
6. Passivate mandrel surface to reduce shell adhesion
7. Electroform Ni–Co shell onto mandrel
8. Separate shell from mandrel in chilled water

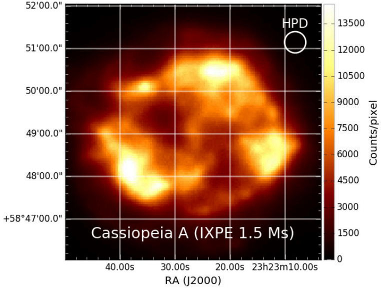


Ni–Co electroformed mirror shells

A novel view on cosmic-ray accelerators

Space resolved polarimetry

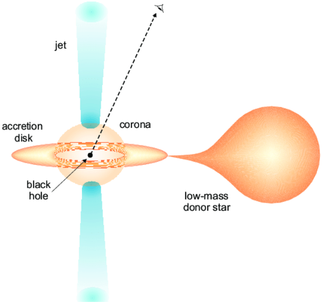


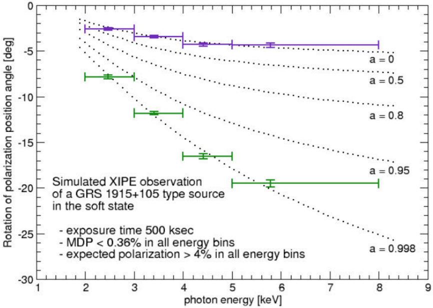


- Pulsar wind nebulæ: ordered magnetic field, high polarization degree expected
  - IXPE imaging capabilities will separate the jet and axis components
  - Will also separate pulsar from the brighter nebula emission
- Shock front in supernova remnant: candidate for comsic rays acceleration, turbolent magnetic fields
  - What is the orientation of the magnetic field at the site of acceleration?
  - How ordered is it (i.e. level of turbulence)?

Black-holes system and general relativity effects

Energy resolved polarimetry

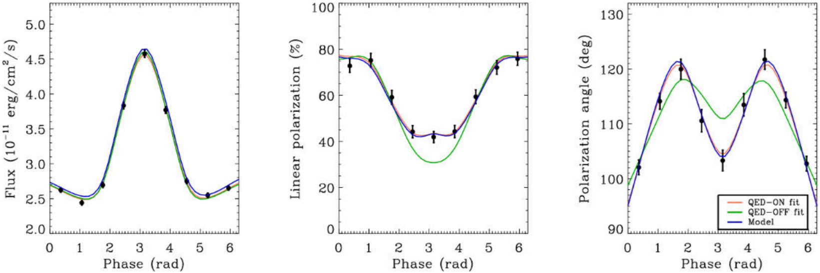




- Thermal emission from the accretion disk can become polarized (up to $\sim$ 12%) by Compton scattering on the Corona
- Including general relativity effects:
  - Black-hole proximity causes a rotation of the polarization angle;
  - Since the disk temperature decreases with the radius, the phase rotation increases with energy.
- An independet technique for measuring the black hole spin *a*

High magnetic field systems and QED effects

Phase-resolved polarimetry



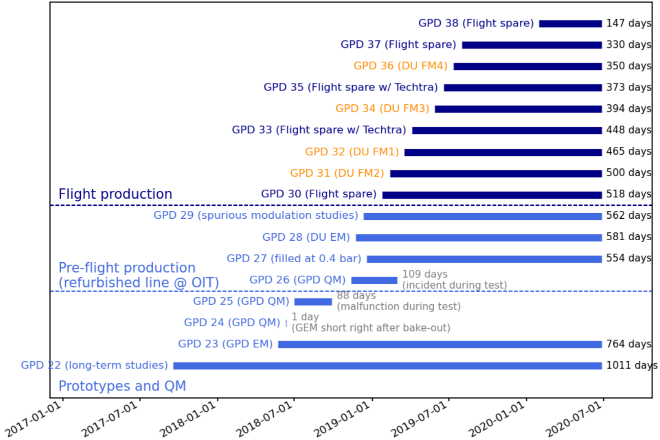
- Magnetar are ultra-magnetized neutron stars with B $\sim 10^{13}$–10^{15} G.
- In this regime the refraction index of the vacuum depends on the mangnetic field intensity:
  - Vacuum polarization, predicted by Heisenberg e Euler in 1936;

$$n_{\parallel} - n_{\perp} = \frac{\alpha_{QED}}{30\pi} \left(\frac{B}{B_{QED}} \right)^2 \sin\theta^2$$

$$B_{QED} = \frac{m_e^2 c^3}{he} = 4.4 \times 10^{13} G$$

- Negligible effect on the flux, measurable using polarimetric quantities

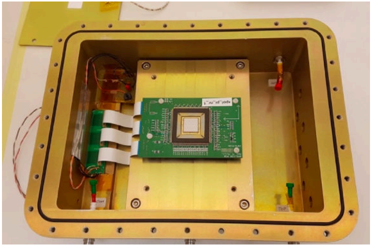
GPD production

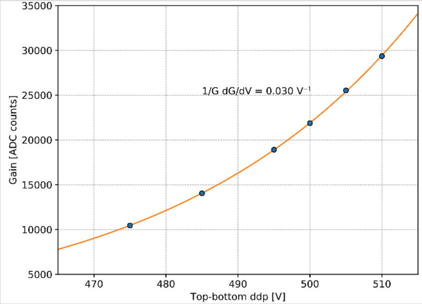


▷ 17 GPDs: 9 FMs, 4 QM, 4 EM. 3 FMs (+1 spare) selected for the mission

GEM testing

- Thorough electrical and performance testing of each production batch performed in Pisa
- Dedicated set-up, reproducing the detector environement (ASIC + DAQ) with fluxed Ar/CO_2 gas mixture
- Asserting gain unformity, gain stability, etc...

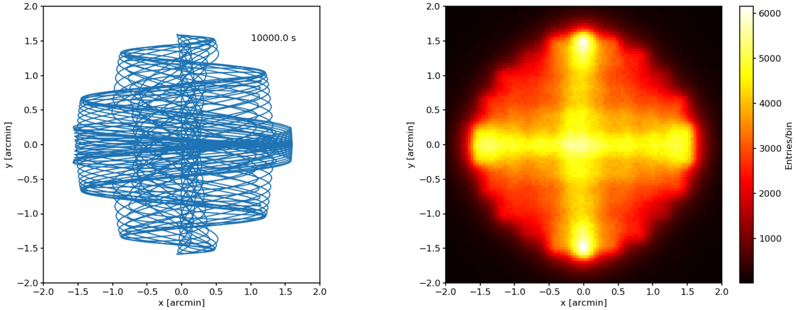




- Typical operating voltages 400 - 500 V
- Effective gain ~200 (including collection efficiency)
- Experimental data well in agreement with simple exponential gain model

$$\frac{1}{G}\frac{dG}{dV} = \gamma \quad [\mathrm{V}^{-1}]$$

Dithering



- Dithering of the Observatory along the line of sight
  - Decrease the average spurious modulation amplitude (partial cancellation due to phase incoherence)
  - Make it possible to calibrate the rest of the effect