The Imaging X-ray Polarimetry Explorer (IXPE)

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Imaging X-ray Polarimetry Explorer
- Imaging and polarimetry in the 2–8 keV band
- The observation technique and the mission were made possible by the introduction of a polarization-sensitive detector developed at INFN-Pisa
  - 2 order of magnitude increase of sensitivity wrt previous measurements
- Recently selected by NASA as the next SMall EXplorer (SMEX) mission
  - Launch in early 2021
- International partnership:
  - X-ray Mirror by NASA/MSFC
  - X-ray Instruments by INFN, IAPS/INFN and ASI
  - Spacecraft, payload structure and integration by Ball Aerospace
Spectroscopy, imaging and timing are routine techniques in X-ray astronomy.

Polarimetry adds two parameters to the phase space:
- (linear) polarization degree
- polarization angle (phase)

Significant X-ray linear polarization expected in most classes of non-thermal X-ray sources:
- Emission processes
  - Synchrotron radiation and Inverse Compton
  - Acceleration phenomena (supernova remnants, pulsar wind nebulae, jets)
- Geometry
  - Photon scattering in aspherical geometries (accretion disks, X-ray reflection nebulae)
  - Photon propagation in magnetized plasmas (accreting pulsars, magnetars)
- Fundamental physics
  - Quantum electrodynamics (photon propagation in strong magnetic fields)
  - General relativity (photon propagation in strong gravitational fields)
Map magnetic field of bright extended source

Example: Cassiopeia A (Cas A) Supernova Remnant (SNR)

- Probe sites of cosmic-ray acceleration
  - Lines and thermal continuum dominate 1-4 keV
  - Non-thermal emission dominates 4-6 keV
- 1.5 Ms simulated IXPE observation
- See poster by Melissa Pesce-Rollins
Phase-resolved polarimetry

Example: Crab Pulsar

- Isolated pulsar in pulsar wind nebula (PWNe)
- 34-ms period
- 140 ks of simulated observation
  - IXPE expectation (in blue)
  - visible-band profile (in gray)
- The geometry of the system determines the polarization pattern
  - Adding 2 more panels to the phasogram
- Magnetar is a neutron star with magnetic field up to $10^{15}$ Gauss
- Non-linear QED predicts birefringence in magnetized vacuum
  - Impacts polarization and position angle as functions of pulse phase
- 250 ks simulated IXPE observation to exclude QED-off
Measure Black-hole spin
Example: GRX1915+105

- Microquasar in accretion-dominated state
  - Scattering polarizes the thermal disk
  - Polarization rotation is greatest for emission from inner disk
    - Inner disk is hotter, producing higher energy X-rays
- 200 ks simulated IXPE observation
Three identical telescopes, each including polarization-sensitive detector and grazing-incidence optics

Equatorial circular orbit at $\geq 540$ km altitude

2-year baseline mission, 1 year extension
Mirror Module Assembly (MMA)

**MMA Properties**

- **Number of MMAs**: 3
- **Number of shells per MMA**: 24
- **Focal length**: 4000 mm
- **Shell length**: 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 (CBE)
- **Effective area per MMA**:
  - 210 cm² (2.3 keV)
  - >230 cm² (3–6 keV)
- **Angular resolution**: ≤ 25 arcsec HPD
- **Field of view (detector-limited)**: 12.9 arcmin
**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
The Gas Pixel Detector (GPD)
Invented by Ronaldo Bellazzini at INFN-Pisa

- Distribution of the direction of emission of a K-shell photoelectron 100% modulated for linearly polarized radiation:

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

- Need to reconstruct the direction of emission of the photoelectron, i.e., a granularity significantly smaller than the typical range

- Detector concept
  - X-ray absorption in a gas gap
  - Signal amplification via a Gas Electron Multiplier (GEM)
  - Finely pixelized ASIC as readout anode

- Sensitive down to very low energy (∼ 2 – 8 keV)

- Fully two-dimensional (imaging)
The core of the detector: the ASIC

Properties

<table>
<thead>
<tr>
<th>Properties</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixels organization</td>
<td>300×352 pixels in hexagonal pattern</td>
</tr>
<tr>
<td>Pixel pitch</td>
<td>50 µm</td>
</tr>
<tr>
<td>Active area</td>
<td>15×15 mm²</td>
</tr>
<tr>
<td>Shaping time</td>
<td>3-10 µs</td>
</tr>
<tr>
<td>Pixel Noise</td>
<td>~ 50 electrons ENC</td>
</tr>
<tr>
<td>Trigger</td>
<td>internal, with definition of a region of interest</td>
</tr>
<tr>
<td>Output</td>
<td>analog (external ADC required)</td>
</tr>
<tr>
<td>Technology</td>
<td>CMOS 0.18 µm</td>
</tr>
</tbody>
</table>
The GPD assembly

- Ti frame
- Be window
- Macor spacer
- GEM
- PCB with ASIC
- Mech. I/F

- Sealed detector
  - No gas system needed
- Gas cell thickness 1 cm
  - Gas based on DME (small lateral diffusion)
  - Optimized in the 2-8 keV range
- A Ti frame acts as “drift” electrode
- X-ray window in Be, 50 µm thick
- GEM holes 50 µm pitch, 50 µm thick
- ASIC in a standard package mounted on a custom PCB
- A Ti frame for mechanical and thermal interface
Event reconstruction

- Event by event reconstruction
- Rich morphological information available
- Iterative moment analysis to reconstruct relevant information
  - Interaction point: imaging
  - Photoelectron direction: polarimetry
  - Trigger output: timing
  - Pixel charge content: spectroscopy
Performance of the GPD as a focal-plane polarimeter

- **Modulation factor**: 0.2 (0.7) at 2 (8) keV
  - Stability over ~3 years demonstrated with a sealed detector
- Residual modulation for unpolarized radiation <0.5%
- ~90 μm **spatial resolution** at 5.9 keV, measured (≪track length)
  - Good match for a ~25 arcsec-type X-ray optics with ~4 m focal length
- <20% **energy resolution** (FWHM) at 5.9 keV
  - Enough for spectrally-resolved polarimetry (in a few energy bins) when statistics allow it
- **μs-type time resolution**
  - More than adequate for the shortest time scales of interest
Conclusions

- A new NASA mission dedicated to X-ray polarimetry
  - After 40 years from the last polarimeter in orbit
- The IXPE satellite will explore the polarization of celestial sources in the 2-8 keV energy band
- The Gas Pixel Detector will be at the focal plane of a X-ray optics
  - Will allow spatially-resolved polarimetry
- Design of the flight detector is basically concluded
  - Prototypes under construction and test
  - Flight production will begin soon
- Software activity on-going:
  - Event reconstruction
  - Detector simulation
  - Science analysis tools
- On our way for launch in 2021
SPARE SLIDES
Main technical challenge: fan-out from the readout anode to the front-end electronics.

Yet it worked as a proof of principle.

- Maximum number of channels: ≈ 1000 at ≈ 200 $\mu$m pitch.
- High input capacitance to the preamplifier (high noise).
- Cross-talk between adjacent lines.
2101 hexagonal pixels.
80 μm pitch.
Metal top layer acting as a charge collecting anode.
Integrating preamplifier, shaper, S/H, multiplexer.
Serial readout via external ADC.
The Gas Electron Multiplier (GEM)

- Produced by RIKEN and SciEnergy in Japan
- Hexagonal hole pattern, with 50 $\mu$m pitch, 50 $\mu$m thick
The Back-End Electronics (BEE)

> Four PCBs:
  > Data Acquisition board (DAQ)
  > Low Voltage Power Supply, Board (LVPS)
  > High Voltage Supply Board (HVPS)
  > Back Plane (BP)

> FPGA based DAQ, with a 14-bit ADC for GPD data

> Two custom digital interfaces for communication:
  > Command and Control Interface (CCI)
  > Science Data Interface (SDI)

> Event timing via 1-PPS (from spacecraft GPS) and a 1 MHz clock

> Dedicated mechanical frames provide stiffness and thermal control