La missione spaziale IXPE

Una nuova finestra osservativa sull'Universo

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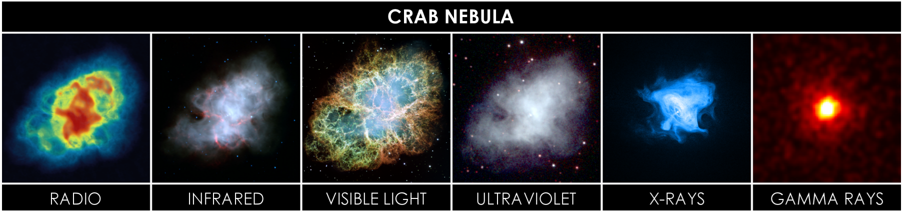
Outline

- IXPE stands for Imaging X-ray Polarimetry Explorer.
  - Recently selected by NASA as the next SMall EXplorer (SMEX) mission for a launch in late 2020.
  - Coronation of a 20-year long R&D activity entirely carried out in Pisa under the lead of Ronaldo Bellazzini.

- Introduction
- The science case for X-ray polarimetry.
- Conventional techniques of X-ray polarimetry.
- Photoelectric X-ray polarimetry: the Gas Pixel Detector (GPD).
- The IXPE mission.

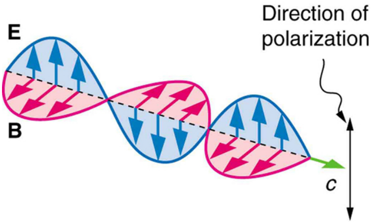
The four facets of light

Four different ways to look at the electromagnetic Universe



- Light carries four different types of information:
  - direction;
  - energy;
  - time;
  - polarization.
- Imaging, spectroscopy, timing and polarimetry are routine observational techniques across the entire electromagnetic spectrum.
- High-energy (X-ray and γ-ray) polarimetry is possibly the most notable exception.

And what is polarization, after all?



- EM waves are oscillations of electric and magnetic fields propagating at the speed of light (in vacuum).
  - Polarization has to do with the orientation of the fields and its complete description is non trivial.
- $\vec{E}$, $\vec{B}$ are mutually perpendicular and perpendicular to the direction of propagation $\vec{k}$, i.e., ($\vec{E} \perp \vec{B} \perp \vec{k}$).
- When the E direction is fixed, the wave is linearly polarized.
  - The orientation of the E field is the polarization angle.
  - The superposition of many different wave trains (of photons), can exhibit an arbitrary polarization degree from 0 to 1.
  - (And linear polarization is all we'll be dealing with today.)

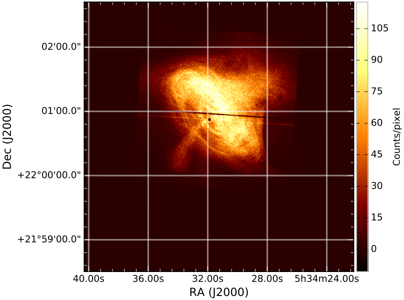
Is X-ray polarization interesting? Yes!

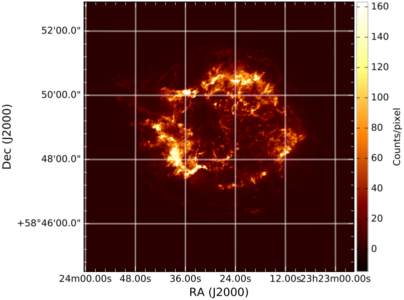
And especially in conjunction with the other observables

- Significant X-ray linear polarization expected in a variety of astronomical X-ray source classes.
  - Acceleration phenomena and non-thermal emission processes.
  - Geometry/propagation (e.g., scattering in aspherical geometries).
- X-Ray polarimetry would add two parameters to the phase space where models are confronted with observations:
  - polarization degree;
  - polarization angle.
- Direct information on the geometry of the source and the configuration of the magnetic field.
- Study of systems under extreme conditions and implications for fundamental Physics:
  - strong gravitational fields;
  - strong magnetic fields and QED effects;
  - photon propagation over cosmological distances.
- Potential for an otherwise inaccessible wealth of information on a wide variety of galactic and extra-galactic sources.

A new view on the galactic cosmic-ray accelerators

Potential for spatially resolved X-ray polarimetry

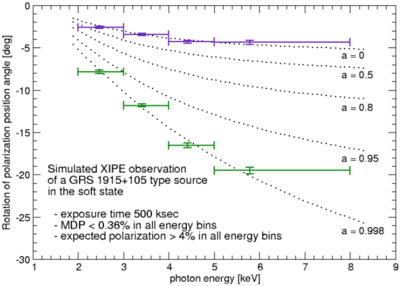




- ▷ Pulsar wind nebulæ: ordered magnetic field, high degree of linear polarization guaranteed.
- ▷ Shock fronts in supernova remnants: candidate cosmic-ray acceleration sites, turbulent magnetic field.
- ▷ Can we map the polarization degree and angle in these objects on meaningful spatial scales?
- ▷ Additionally, can we isolate the central pulsar and study the polarization pattern as a function of the pulse phase?

Black-hole systems and general relativity effects

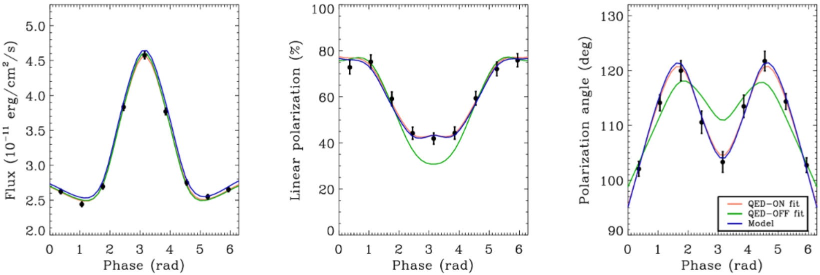
Potential for energy-resolved polarimetry



- In systems with accretion disks the thermal (unpolarized) primary emission can acquire linear polarization via Compton scattering.
  - About $\sim$ 12% for a thick disk viewed on edge (Chandrasekhar limit).
- When the central object is a black hole general-relativity comes into play.
  - The proximity of the black hole causes a rotation of the polarization angle of the radiation emitted from the disk.
  - As the temperature of the disk decreases with the radius, the rotation of the position angle increases with energy.
- Effective way to measure the black hole spin a.

Systems with strong magnetic fields and QED effects

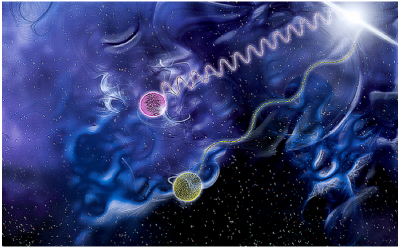
Potential for time- (or phase-) resolved polarimetry



- Magnetars are magnetized neutron stars with B up to 10^{12}–10^{15} G.
- In the strong-field regime the index of refraction of the vacuum depends on the field intensity.
  - Different for the ordinary and the extraordinary modes (aka vacuum polarization, predicted by Heisenberg and Euler in 1936).
- Photon propagation is influenced, and the polarization angle and degree are modified.
- Tiny effect on the intensity, measurable effect on the polarization degree and angle.

Photon propagation over large distances

Study of fundamental physics in space



- Distant astronomical sources are a terrific laboratory to study fundamental physics over length scales not accessible on Earth.
  - Do photons of different energy travel at the same speed c?
- X-ray polarimetry allows to test a possible (small) birefringence of the vacuum.
  - Rotation of the polarization angle for nearby sources.
  - Destroy any linear polarization from sources at cosmological distances.
- On the other hand: are there plausible mechanisms that can induce polarization through propagation?
  - What if see evidence of linear polarization where we don't expect it (e.g., galaxy clusters)?

Great expectations, meager results...

Weisskopf et al., ApJ **220**, 1978 (L117)

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

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

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Received 1977 November 15; accepted 1977 December 22

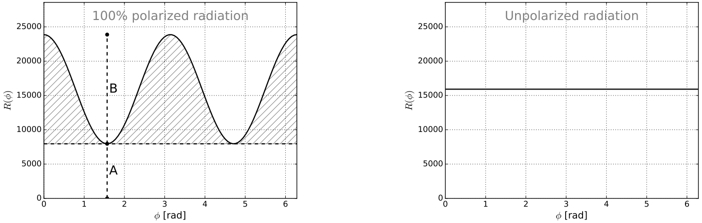
ABSTRACT

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

- This is all great, but where do we stand?
- A crystal X-ray polarimeter flown onto the OSO-8 satellite in 1975.
  - $\sim 20\,\sigma$ measurement averaged over the Crab nebula.
  - Still the state of the art in the soft X-ray band.
- Polarimetry still largely underdeveloped, compared to the other branches of X-ray astronomy.
  - No soft-X-ray polarimeter flown in the last 40 years.

Basic formalism

What is a polarimeter and why polarimetry is photon-greedy?



- Any polarimeter ultimately measures an azimuthal modulation around the polarization angle ϕ_0 of the incident photon beam:

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

- Modulation factor: response to 100% polarized radiation:

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

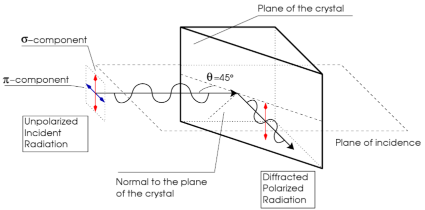
- Minimum Detectable Polarization (MDP)[1] with no background:

$$\mathrm{MDP} = \frac{4.29}{\mu\sqrt{N}} \quad (99\% CL)$$

[1] Need 184,000 photons to reach a MDP of 1% even for $\mu = 1$!

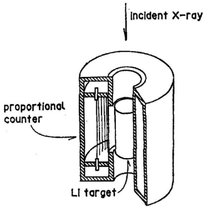
Conventional techniques of X-ray polarimetry

—Bragg diffraction at 45°



- ✓ Excellent modulation factor.
- ✓ Energy-resolved (discrete harmonics).
- ✘ Limited to low energies.
- ✘ Low efficiency (narrow band-pass).
- ✘ Dispersive (one angle at a time).
- ✘ Needs rotation.

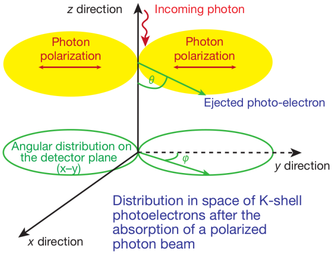
—Thomson scattering around 90°



- ✓ Suitable for hard X-rays.
- ✓ Decent efficiency and modulation factor.
- ✓ Decent energy resolution.
- ✘ Limited at low energy.
- ✘ Background can be important.
- ✘ Rotation to reduce systematics.

Photoelectric X-ray polarimetry

Why such an obvious thing is so hard to implement?

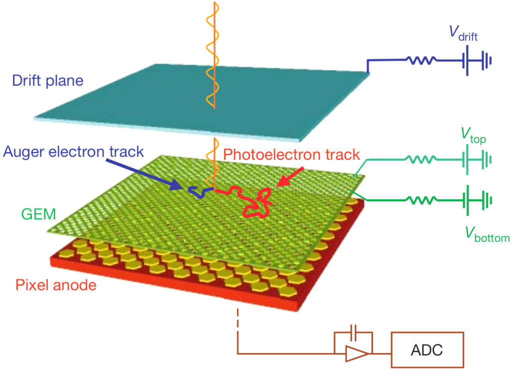


- Dominant interaction process at low energy (< 10 keV).
- Distribution of the direction of emission of a K-shell photoelectron 100% modulated for linearly polarized radiation:

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

- In principle this is the perfect polarization analyzer, but. . .
  - Need to reconstruct the direction of emission of the photoelectron, i.e., a granularity significantly smaller than the typical range.
  - The range for a 5 keV photoelectron is a few μm in a solid—main driver for choosing a gaseous detection medium.

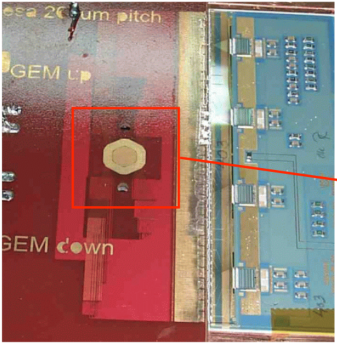
The Gas Pixel Detector (GPD) as a polarimeter



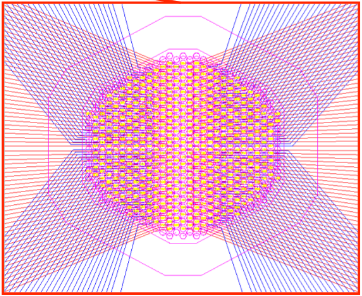
- Basic components:
  - gas-filled absorption gap acting as detection medium;
  - Gas Electron Multiplier (GEM) providing gas amplification;
  - finely pixelized readout anode for signal collection.
- Sensitive down to very low energy ($\sim$ 1 keV).
- Fully two-dimensional (imaging).
- Highly azimuthally symmetric (no need of rotation).

The proof of concept for the readout plane

Circa 2000 (and, incidentally, the subject of my master thesis)



- 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 $\sim 200\ \mu$m pitch.
- High input capacitance to the preamplifier (high noise).
- Cross-talk between adjacent lines.

Photoelectric X-Ray polarimetry gets attention

Costa et al., Nature **411**, 662–665 (2001)

letters to nature

An efficient photoelectric X-ray polarimeter for the study of black holes and neutron stars

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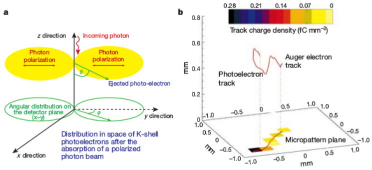
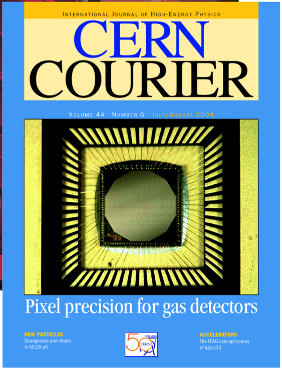
The study of astronomical objects using electromagnetic radiation involves four basic observational approaches: imaging, spectroscopy, photometry (accurate counting of the photons received) and polarimetry (measurement of the polarizations of the observed photons). In contrast to observations at other wavelengths, a lack of sensitivity has prevented X-ray astronomy from making use of polarimetry. Yet such a technique could provide a direct picture of the state of matter in extreme magnetic and gravitational fields[1–6], and has the potential to resolve the internal structures of compact sources that would otherwise remain inaccessible, even to X-ray interferometry[7]. In binary pulsars, for example, we could directly 'see' the rotation of the magnetic field and determine if the emission is in the form of a 'fan' or a 'pencil' beam[1,8]. Also, observation of the characteristic twisting of the polarization angle in other compact sources would reveal the presence of a black hole[9–12]. Here we report the development of an instrument that makes X-ray polarimetry possible. The factor of 100 improvement in sensitivity that we have achieved will allow direct exploration of the most dramatic objects of the X-ray sky.

The main advantage of the proposed polarimeter is its capability of investigating active galactic nuclei (quasars, blazars and Seyfert galaxies) for which polarization measurements have been suggested, crucial to understand the geometry and physics of emitting regions. We can separate synchrotron X-rays from jets[13,14] from the emission scattered by the disk corona or by a thick torus. The effects of relativistic motions and of the gravitational field of a central black hole have probably been detected by iron line spectroscopy on the Seyfert-1 galaxy MCG-6-30-15 (ref. 15) but this feature is not ubiquitous in active galactic nuclei. Polarimetry of the X-ray continuum provides a more general tool to explore the structure of emitting regions[16,17], to track instabilities and to derive direct information on mass and angular momentum[12] of supermassive black holes.

In spite of this wealth of expectations, the important but only positive result until now is the measurement, by the Bragg technique, of the polarization of the Crab nebula[18,19]. The Stellar X-ray Polarimeter[20] (SXRP) represents the state of the art for conventional methods based on Bragg diffraction and Thomson scattering. However, Bragg polarimetry[21] is dispersive (one angle at one time) and very narrow-band. Thomson polarimetry[22] is non-imaging and band-limited (>5 keV). This limits the sensitivity of SXRP to a few bright, galactic sources only.

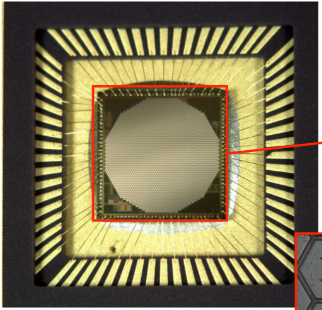
The photoelectric effect is very sensitive to polarization. The electron is ejected from an inner shell with a kinetic energy which is the difference between the photon energy and the binding energy. The direction of emission is not uniform but is peaked around that of the electric field of the photons (see Fig. 1a). This photoelectron

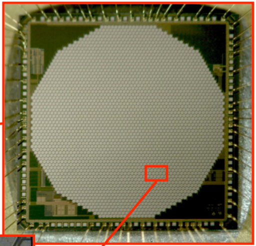


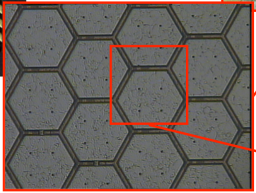


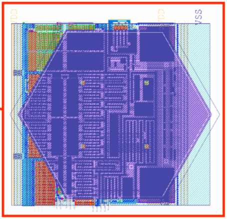
The turning point: a dedicated readout VLSI ASIC

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



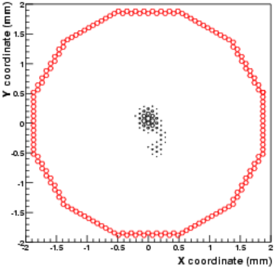


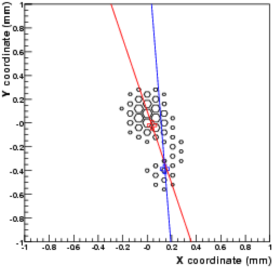


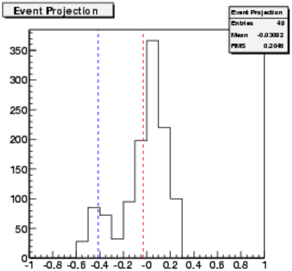


- 2101 hexagonal pixels.
- 80 μm pitch.
- Metal top layer acting as a charge collecting anode.
- Integrating preamplifier, shaper, S/H, multiplexer.
- Serial readout via external ADC.

And the first light from the ASIC

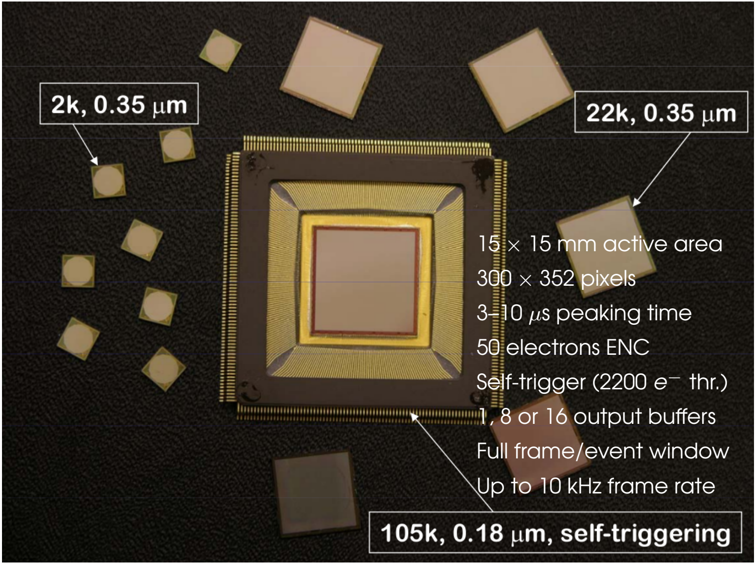






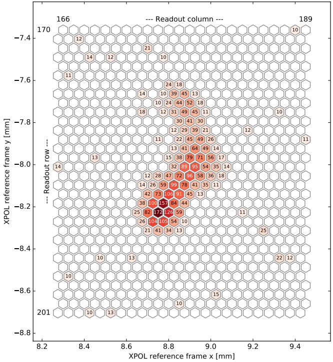
Event Number:	157
Number of Clusters:	1
Cluster Size (largest):	49
Pulse Height:	1197.1
Signal to Noise:	87.0
Baricenter:	0.04 -0.02
Conversion Point:	0.14 -0.39
Phi (iteration 1)	1.8872
Phi (iteration 2)	1.6490
Second Mom Max:	0.0419
Second Mom Min:	0.0077
Shape (ratio of moments):	5.42
Third Mom Max:	8.1e-03

Three generations of ASICs



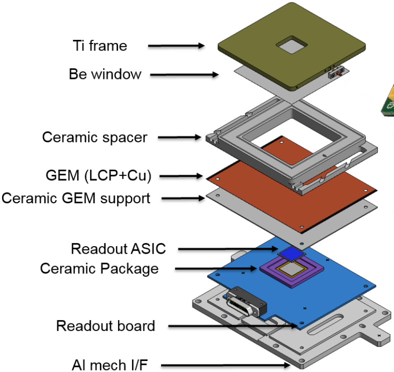
Salient features of the ASIC

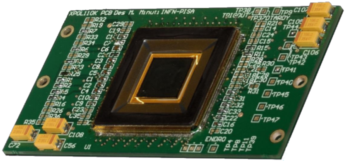
Image: real 5.9 keV photoelectron track

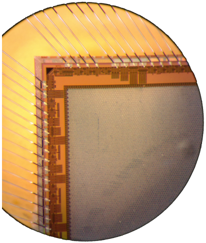


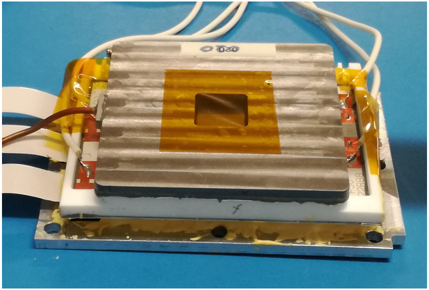
- ▷ Self-triggering.
- ▷ Internal definition of the region of interest for the event readout.
  - ▷ Typical window size $<$ 1 k pixels.
  - ▷ Multiple window readout for event-by-event pedestal subtraction.
- ▷ Serial readout via an external ADC.

The GPD assembly



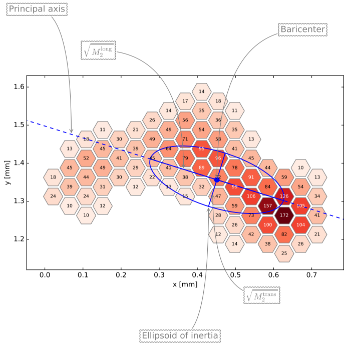


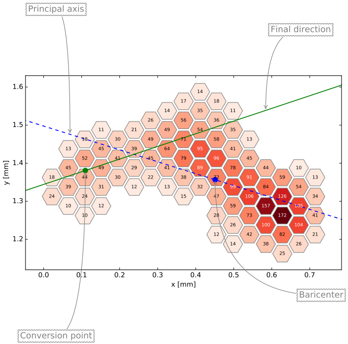




Event-level analysis basics

Real 5.9 keV photoelectron track, colors indicate the pulse height

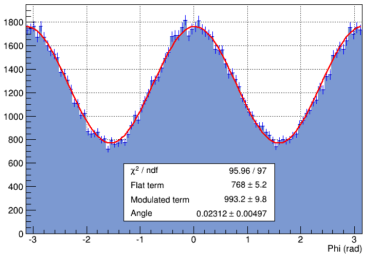


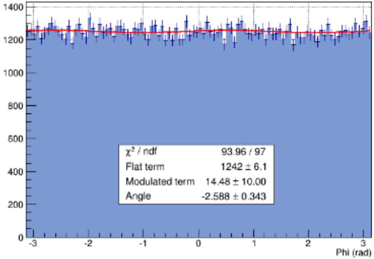


- Analysis is done event-by-event.
- Track reconstruction:
  - First pass: baricenter, basic moments analysis, skewness of the longitudinal projection to identify the Bragg peak.
  - Second pass: determination of the absorption point and weighted moments analysis for a refined estimate of the direction of emission.
- Rich morphological information available.

Performance of the GPD as a focal-plane polarimeter

Measuring four things at once

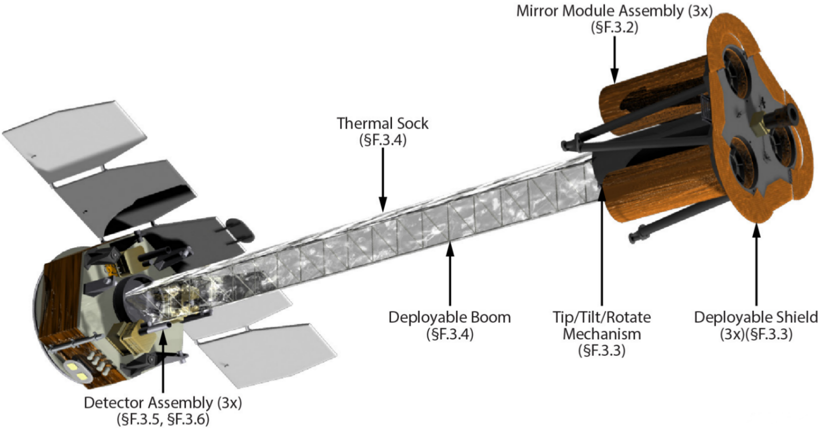




- Modulation factor: 0.2 (0.7) at 2 (8) keV.
  - Stability over $\sim$ 3 years demonstrated with a sealed detector.
- Residual modulation for unpolarized radiation $\sim$ 0.1%.
- $\sim$ 90 μm spatial resolution at 5.9 keV, measured ($\ll$ track length).
  - Good match for a 20 arcsec-type X-ray optics with $\sim$ 4 m focal length.
- $\sim$ 15% 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.

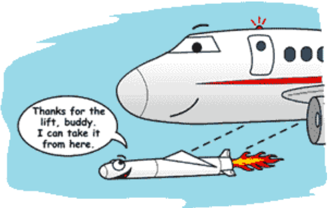
The IXPE mission

Artistic rendering



The IXPE mission

Cheat sheet



- Three identical telescopes, each including GPD and optics:
  - Provide full redundancy, mitigate possible residual systematic effects.
- Mass and power budget (total): $\sim$ 300 kg, $\sim$ 200 W:
  - $\sim$ 15 kg, $\sim$ 20 W for the three detector units;
  - $\sim$ 85 kg for the mirror module assembly.
- Focal length: 4 m (deployable boom).
- Launched in stowed configuration with three critical events:
  - separation from launch vehicle (free-flying spacecraft);
  - solar array deployment (full power available);
  - payload boom deployment (ready for payload commissioning).
- Pegasus launch from Kwajalein on or after November 20, 2020.
  - 2-year mission on a 540 km circular orbit at nominal 0° inclination.
  - One (simple) operation mode: point-and-stare at known targets.

Conclusions

After more than 4 decades, the recent development of the photoelectron tracking gas counter has now enabled a meaningful exploration of X-ray polarimetry within a SMEX envelope.

The physical scales and conditions probed by IXPE require a high-energy polarimetry capability and are not achievable by other current or planned missions.

—Verbatim from the NASA selection debrief package.

- ▷ IXPE will do world-class Science.
  - ▷ "a new observational window on the Universe" = measure polarization for dozens of sources.
- ▷ We introduced the technology that made this possible and we are contributing the most innovative part of the mission concept.
- ▷ If you are a student: this is a unique moment for being involved—you get to pick your own choice among:
  - ▷ hardware: detector, electronics, DAQ;
  - ▷ software: simulation, reconstruction, data processing;
  - ▷ science analysis: modeling, observation simulations, preparation for data analysis.