X-RAY POLARIMETRY AND NEW PROSPECTS IN HIGH-ENERGY ASTROPHYSICS

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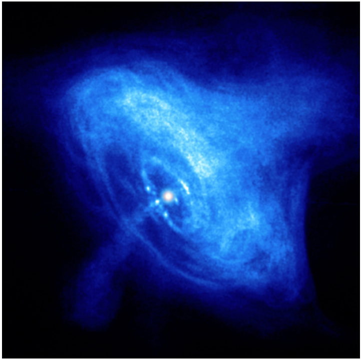
Frascati, March 31, 2016

A new exploration window: X-Ray polarimetry

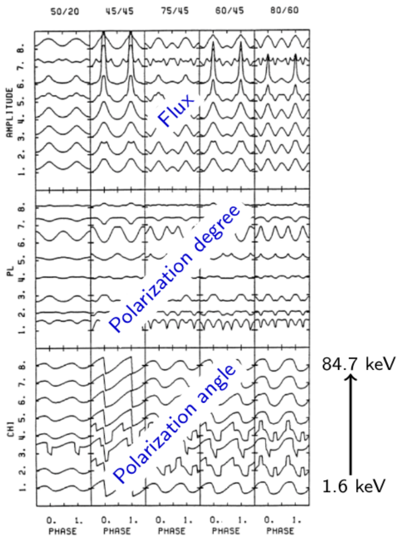
- Spectroscopy, imaging and timing are routine techniques in X-ray astronomy
  - Unlike polarimetry, they underwent continuous development over the last four decades
- Polarimetry is potentially adding two parameters to the phase space:
  - (linear) polarization degree
  - polarization angle (phase)
- 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)
    - Quantum gravity and Lorentz-invariance violation

Acceleration phenomena: PWNe

Image: Crab Nebula observed by the Chandra X-ray observatory

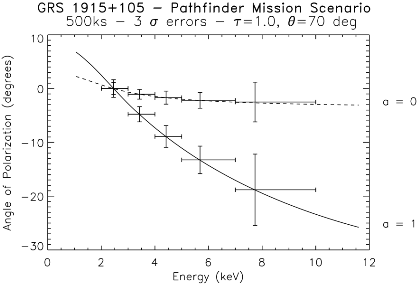


- High-confidence X-ray polarization measurement for the Crab
  - Polarization degree of $19.2 \pm 1.0\%$ (Weisskopf et al. 1978)
  - Measurement averaging out many different emission regions
- Well ordered magnetic field in the PWN
  - Emission locally highly polarized in optical and radio
  - Pulsar emission also polarized
- Spatially resolved X-ray polarization would allow to map the magnetic field orientation and the jet at various distances from the pulsar

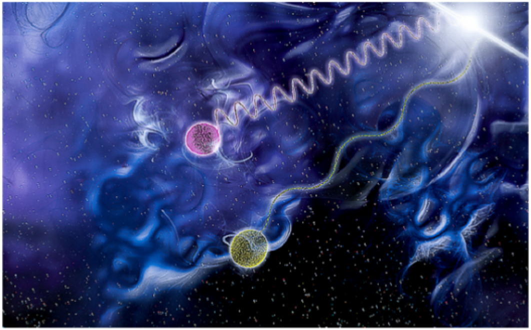


from Meszaros, et al. (1988), ApJ 324, 1056

- The geometry of the system determines the polarization pattern
  - Adding 2 more panels to the phasogram!
  - The phase swing of the polarization angle is a direct measure of the angle between the rotation and the magnetic dipole axis
- In accreting X-ray pulsars, strong (up to 70%) linear polarization is expected
  - Depending on the geometry of the system and the viewing angle



- Thermal emission from the accretion disc around a BH can be polarized
  - Mainly via Thomson scattering
  - Polarization angle can be modified by General Realtivity effects
- The proximity of the BH 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 polarization of the rotation angle increases with energy
- Here an example from a candidate test source: the microquasar GRS 1915+105 (from Dovciak et al. 2008)



- Loop quantum gravity can accommodate a small vacuum birefringence at the Planck scale.
  - Violate Lorentz invariance.
  - Introduce a rotation of the polarization angle as photons propagate from the source to us:
$$\Delta\phi = \xi D \times E^2$$
- Compare the polarization angle in optical and X-rays (e.g., for the Crab).
- Detecting any linear polarizazion from cosmological distances would allow to put fairly strong limits on LIV.

- State of the art in the soft X-ray regime is a single source (Crab Nebula), measured in the '70s
  - Weisskopf et al., ApJ 220, 1978 (L117)
  - Technology is the key factor
- A few more suggestive measurements and interesting initiatives in the Compton regime
  - INTEGRAL/SPI
  - SGD onboard Astro-H.
  - Polarized Gamma-ray Observer (PoGOLite), with a pathfinder flight in 2013

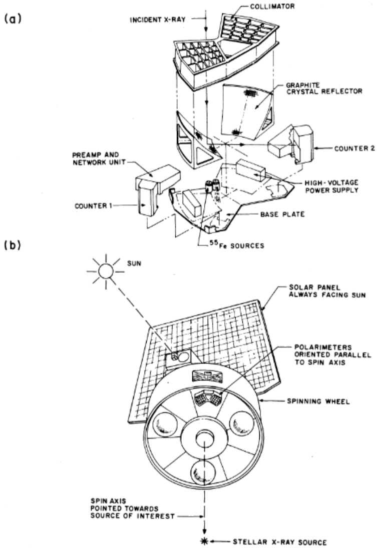
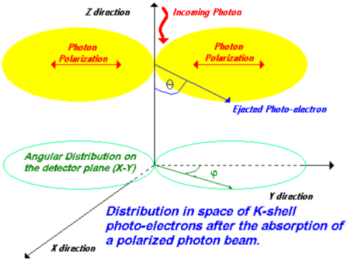


Fig. 1.—(a) Exploded view of the OSO-8 polarimeter assemblies. (b) Location of the polarimeters in the satellite.



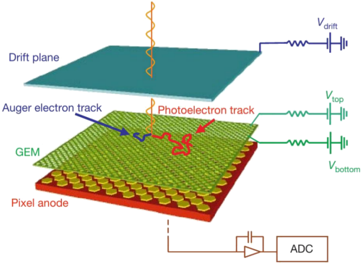
- Dominant interaction process at a few keV
- The distribution of the direction of emission of a K-shell photoelectron is 100% modulated if the incident radiation is 100% linearly polarized:

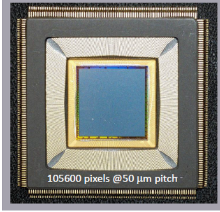
$$\frac{d\sigma_C^k}{d\Omega} \propto Z^5 E^{-\frac{7}{2}} \frac{\sin^2\theta\cos^2\phi}{(1+\beta\cos\theta)^4}$$

  - e^- preferentially emitted orthogonally to the incidence direction
  - Denominator accounting for a slight bending in the forward direction
- Technical challenges:
  - Small photoelectron range (typically less than 1 mm in gas)
  - Multiple Coulomb scattering

The Gas Pixel Detector

- Basic components: absorption gap, Gas Electron Multiplier (GEM), finely pixelized readout anode (ASIC top layer)



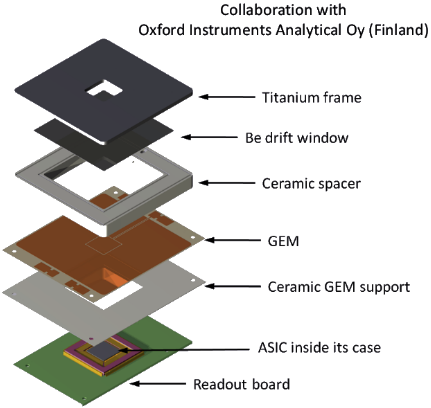


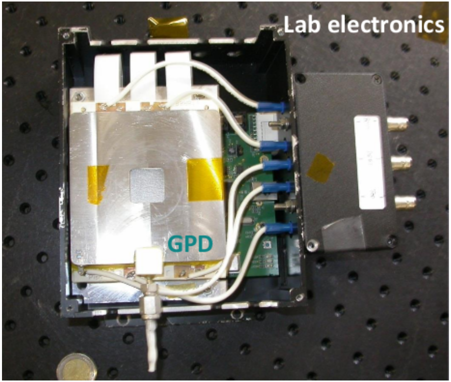
ASIC CHARACTERISTICS

- Peaking time: 3-10 microseconds, externally adjustable;
- Full-scale linear range: 30000 electrons;
- Pixel noise: 50 electrons ENC;
- Read-out mode: asynchronous or synchronous;
- Trigger mode: internal, external or self-trigger;
- Read-out clock: up to 10MHz;
- Self-trigger threshold: 2300 electrons (10% FS);
- Frame rate: up to 10 kHz in self-trigger mode (event window);
- Parallel analog output buffers: 1, 8 or 16;
- Access to pixel content: direct (single pixel) or serial (8-16 clusters, full matrix, region of interest);
- Fill fraction (ratio of metal area to active area): 92%

- Sensitive down to very low energy ($\sim$ 1 keV)
- Fully 2-dimensional (imaging)
  - 105k hexagonal pixels, 50 μm pitch
- Highly azimuthally symmetric (no need of rotation to control systematics)
- Coupling between the efficiency and the modulation factor
  - Track blurring due to the transverse diffusion of the ionization

The GPD Assembly



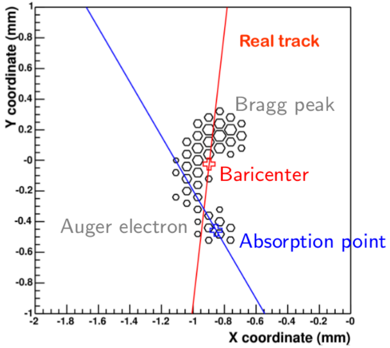


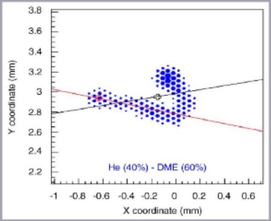
- Sealed detector, prototype tested in lab. and relevant environmental conditions
- Filled with He 20% + DME 80% at 1 bar
- Gas cell thickness 1 cm
- GEM holes 50 μm pitch, 50 μm thick (Scienergy, Japan)

Event reconstruction

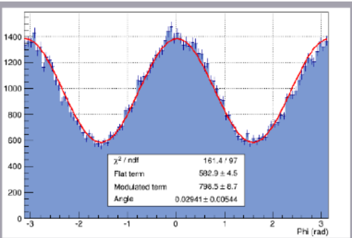
- Event by event acquisition and off-line analysis
- Track projection on the readout plane sampled and digitized
  - Reconstruction as to take into account the effect of the Coulomb scattering and the smearing due to the transverse diffusion

- First pass:
  - track baricenter
  - track direction through a 2-d moments analysis
  - skewness of the longitudinal profile
- Second pass:
  - absorption point
  - new weighted moments analysis
  - refined direction and absorption point estimates

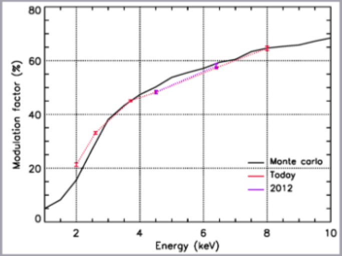




Reconstruction of a real photoelectron track

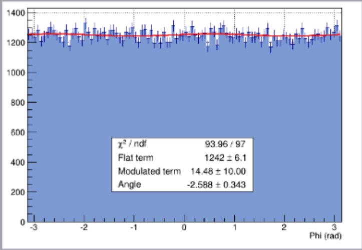


Real modulation curve derived from the measurement of the emission direction of the photoelectron



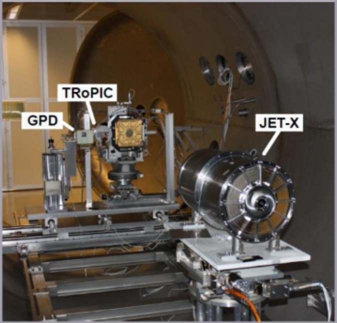
Modulation factor as a function of energy

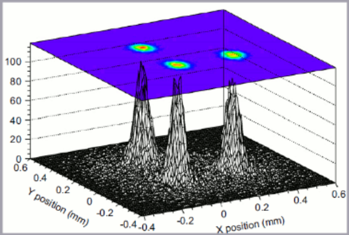
Muleri et al. 2008,2010

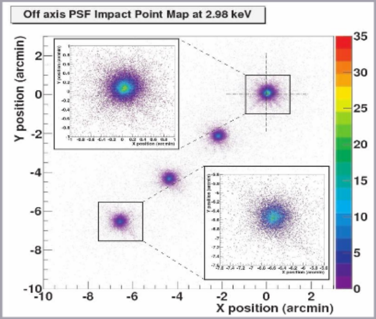


Residual modulation for unpolarised photons

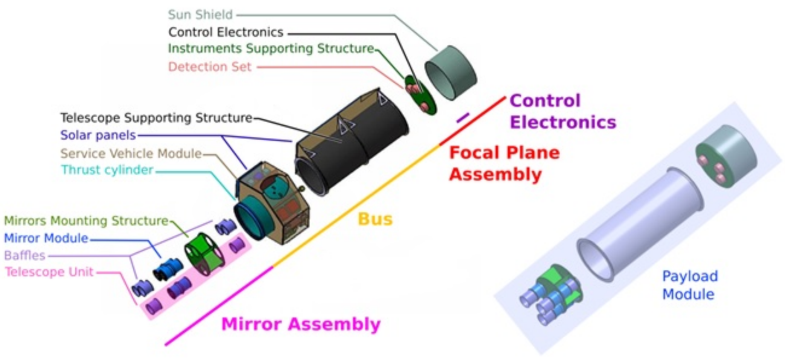
Bellazzini et al. 2012





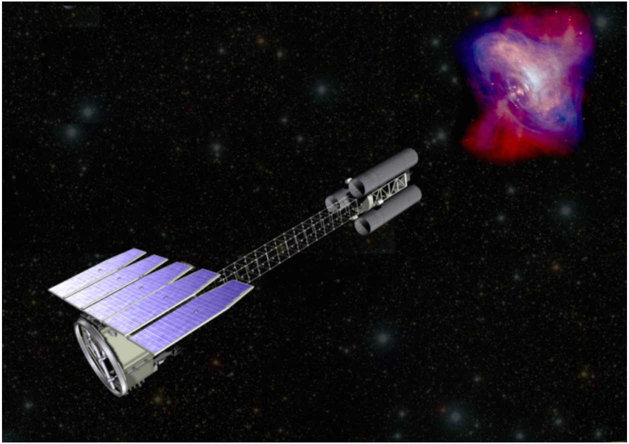


- Good spatial resolution: 90 µm Half Energy Width
- Imaging capabilities on- and off-axis measured @ PANTER with a JET-X telescope *Fabiani et al. 2014*
- Angular resolution for XIPE: < 26 arcsec



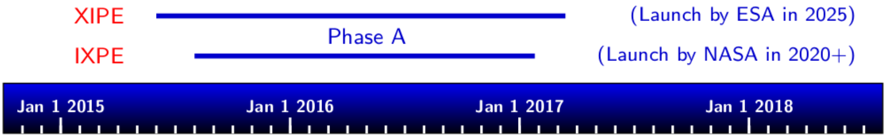
- One of the 3 missions selected in ESA M4 call
  - Final down-selection in April 2017 for a launch in 2025-2026
- Satellite in Low Earth Orbit, 3+2 yr lifetime
- Three identical X-ray grazing incidence mirrors + GPD
  - 27 shells, f=3.5 m
  - on-axis effective area $\sim$ 450 cm^2 @ 3 keV, $\sim$ 200 cm^2 @ 7 keV
  - Angular resolution $<$ 30 arcsec @ 3 keV (including GPD resolution)
- http://www.isdc.unige.ch/xipe/

The Imaging X-ray Polarimeter Explorer



- One of the 3 Astrophysics Small Explorer missions selected by NASA
  - Final down-selection in 2017 for a launch in 2020+
  - Also another mission is devoted to polarimetry, but with a different detector
- Led by M. Weisskopf, Marshall Space Flight Center
- Regular X-ray optics on a extensible bench

Conclusions



- High chance of having a low-energy X-ray polarimeter operational in the next $\sim$ 10 years
  - 3 out of 6 missions considered by ESA/NASA devoted to X-ray polarimetry
- Broad and diverse science case
  - Both astro- and fundamental physics oriented
- The same GPD is at the focal plane of XIPE (ESA) and XIPE (NASA), both now in phase A
- Activity in the next year is to put together the strongest possible design for the final selection(s)
- First XIPE Science Meeting in Valencia, Spain, 24-25 May 2016
  `http://www.isdc.unige.ch/xipe/index.php/first-xipe-science-meeting`