Polarimetry in X-rays

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You can download this presentation from **ftp://ftp.iasf-roma.inaf.it/muleri/**

Outline

Introduction

Polarimetry in High Energy Astrophysics

- Linear polarization is the most common, it should be produced whenever there is some "preferred direction" in the system:
  - polarized by scattering in aspherical geometries
  - intrinsically polarized
  - polarized because of radiative transfer in a strong gravitational/magnetic field
- Basically all classes of X-ray sources should emit partially polarized radiation at a few % level:
  - Pulsar Wind Nebulae (PWNe)
  - Pulsar (PSR);
  - Isolated Neutron Stars (INS);
  - X-ray binaries (XRB);
  - MicroQuasar (μQSO);
  - Reflection Nebulae (RN);
  - Active Galactic Nuclei (AGN);
  - Cataclysmic Variables (CVs);
  - Gamma Ray Bursts (GRBs);
  - etc...

Polarimetry in High Energy Astrophysics

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- etc...

Polarimetry in High Energy Astrophysics - II

- Unfortunately, polarimetry in X-rays is still in its early age.
  - Only a high statistics measurement
  - However, **linear** polarization at the level of **1%** will be within the reach of instrumentation in the next future

- Why should we care about polarization *also* in X-rays?
  - ➥ access to peculiar characteristics of sources
  - ➥ access to fundamental physics

We will see in the following a few representative examples of what could be achieved in the next few years.

Polarimetry in High Energy Astrophysics - II

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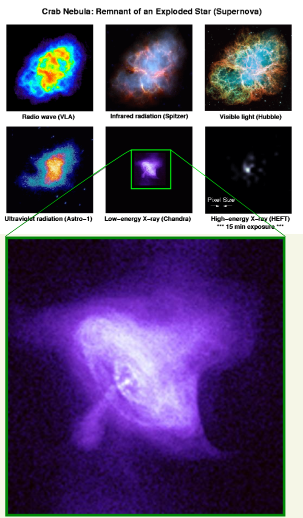
Science objectives

Pulsar Wind Nebulae: the Crab Nebula



- Supernova Remnant powered by a young pulsar
- Large part (99%) of rotational energy by means of a relativistic and magnetized wind which is confined by the surrounding matter
- X-ray power law spectrum, $\frac{\mathrm{d}N}{\mathrm{d}E} = E^{-\alpha}$, with $\alpha \sim 1.5 - 2.2$.
- PWNe emission is due to synchrotron, which is highly polarized!

$$\mathcal{P}_L = \frac{\alpha + 1}{\alpha + 7/3} \qquad \text{for ultrarelativistic electrons}$$

For $\alpha = 2 - 3$, $\mathcal{P}_L = 70 - 75\%$.

- X-rays are the ideal energy band (shorter lifetime of the emitting particles);

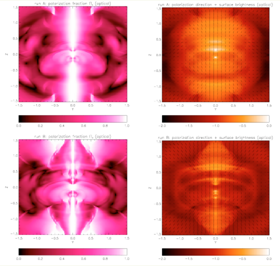
Pulsar Wind Nebulae: the Crab Nebula - II

X-ray polarization of the Crab nebula+PSR

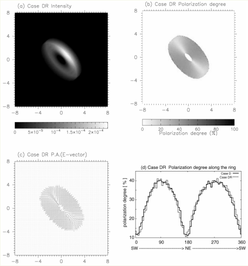
- **OSO-8** $\mathcal{P}_L$=(19.22±0.92)%, angle 155.8°±1.4° @ 2.6 keV + 5.2 keV
  [Weisskopf et al., 1978]
- **INTEGRAL** $\mathcal{P}_L$=(46±10)%, angle 123°±11° @ 0.1-1.0 MeV
  [Dean et al., 2008]

➥ Definitive proof of the synchrotron origin of the emission

➥ Study of the magnetic field and particle acceleration in the nebula



[Del Zanna et al., 2006]



[Nakamura and Shibata, 2007]

Pulsar Wind Nebulae: the Crab Nebula - II

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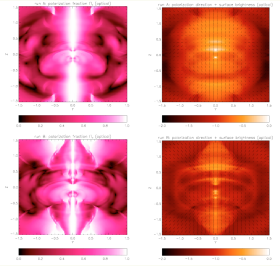

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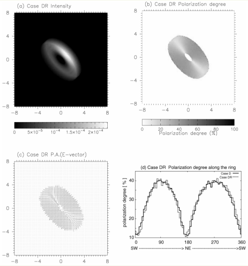


[Nakamura and Shibata, 2007]

Polarimetry to probe quantum gravity theories

- Probe for quantum gravity theories

In some cases, e.g. quantum loop gravity, the vacuum is birefringent [Gambini and Pullin, 1999; Mitrofanov, 2003]

$$v_{\pm} = c\left[1 \pm \chi\left(\frac{E}{E_{\mathrm{QG}}}\right)^{n}\right]$$

A rotation is expected of the plane of polarization which increases with

- distance
- energy

For n=1:

$$\Delta\phi(E) \approx 10^{4}\chi\left(\frac{E}{0.1\ \mathrm{MeV}}\right)^{2} D_{\mathrm{ly}}$$

From the lack of rotation from optical to X-rays in the case of the Crab Nebula, $\chi < 10^{-4}$ [Kaaret, 2004]

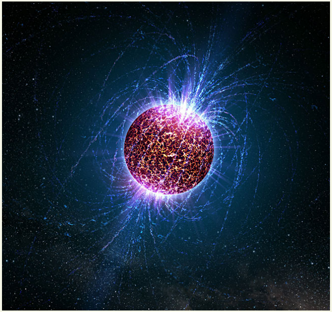
➥ More stringent upper limits derived by other measurements [e.g., Maccione et al., 2008; Toma et al., 2012]

Neutron stars

Neutron stars are a kind of compact remnant produced as a result of Supernova explosions

- Mass $\sim$1.4–2.0 solar masses
- High magnetic field: $10^8 - 10^{14}$ Gauss
  1 Gauss=10^{-4} T
- Radius $\sim$10 km

Provide a laboratory for testing General Relativity and Quantum Electrodynamics



Very different manifestation in X-rays:

➥ in system binaries, powered by accretion

➥ isolated, powered by magnetic field or thermal cooling

High polarization expected

Propagation of electromagnetic waves in magnetized plasmas

The magnetic field of NS is strong enough to constrain the movement of the electrons along the field lines and quantizes that orthogonally to the magnetic field.

This reduces the cross section when the electric field of the wave is orthogonal to $\vec{B}$ [Canuto, 1970].

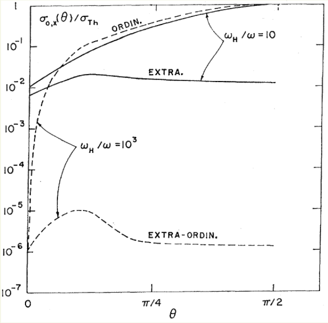
$$\vartheta \approx 0 \begin{cases} \sigma_X(\vartheta) \simeq \sigma_T \left[\frac{\omega^2}{(\omega_B - \omega)^2} + \frac{1}{2}\sin^2\vartheta\right] \\ \sigma_O(\vartheta) \simeq \sigma_T \left[\frac{\omega^2}{(\omega_B + \omega)^2} + \frac{1}{2}\sin^2\vartheta\right] \end{cases}$$

$$\vartheta \approx \frac{\pi}{2} \begin{cases} \sigma_X(\vartheta) \simeq \sigma_T \left[\frac{\omega^2}{(\omega_B - \omega)^2} + \frac{1}{2}\cos^2\vartheta\right] \\ \sigma_O(\vartheta) \simeq \sigma_T \sin^2\vartheta \end{cases}$$

where σ_T is the Thomson cross section and

$$\omega_B = \frac{eB}{m_e} \simeq 10\ B_{12}\ \text{keV}.$$

The opacity is different for the two modes



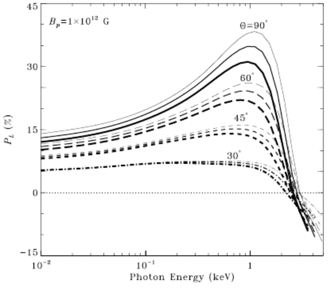
[Canuto et al., 1971]

X-mode can escape from deeper layers of the atmosphere

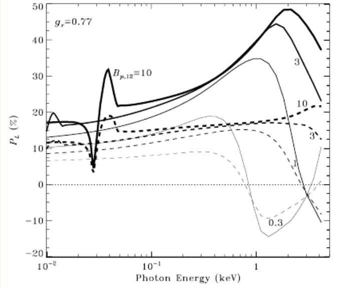
Emission from the surface of isolated neutron stars

Main ingredients

- X-mode escapes from deeper (and then hotter) layers of the atmosphere
  Expected a very strong linear polarization orthogonal to the magnetic field
- Gravitational bending
  Sensitivity to the M/R ratio of the NS



$g_r = 0.90, 0.77, 0.66$, from thick to thin



vs B

$$g_r = \sqrt{1 - 2GM/c^2R}$$

[Pavlov and Zavlin, 2000]

Emission from the surface of isolated neutron stars - II

Different features if including

- **Vacuum polarization**: Resonance in the spectrum [Ventura et al., 1979] and polarization [Lai and Ho, 2003]

  With reasonable assumptions, flip of the angle of polarization at a few keV for "normal" neutron stars but not for magnetar (B$\gtrsim 10^{13}$ G)

- **Vacuum birefringence**:
  - circular polarization is removed
  - linear polarization reduced of a factor $|\cos\phi|$

    ϕ is angle between the direction of polarization and the projection of the magnetic field on the plane orthogonal to the direction of propagation

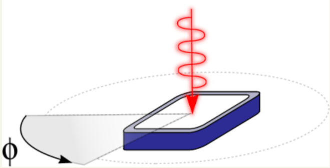
Measurements in X-rays

Fundamentals

Procedure of measurement

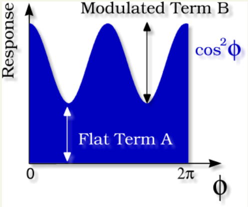
- Only linear polarization is accessible today in High Energy Astrophysics.

A polarimeter has an azimuthal response which depends on the polarization:

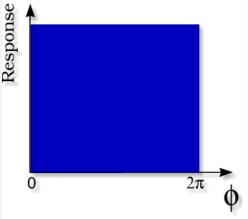


The azimuthal response is used to construct the **modulation curve**:

Polarized radiation



Unpolarized radiation



Procedure of measurement - I

1. Collection of data & construction of the modulation curve
   - conceptually, measure the intensity while rotating the Polaroid filter

2. Fit the modulation curve with the function:

$$\mathcal{M}(\phi) = A + B\cos^2(\phi - \phi_0)$$

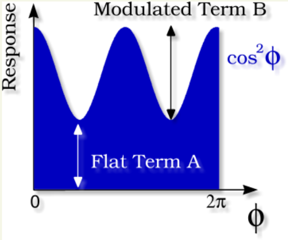
   - ϕ_0 is related to the angle of polarization

3. Calculate the amplitude modulation:

$$M = \frac{\mathcal{M}_{\max} - \mathcal{M}_{\min}}{\mathcal{M}_{\max} + \mathcal{M}_{\min}} = \frac{B}{B + 2A}$$

   - the degree of polarization is related to M, but it is also convolved with the "quality" of the instrument.

The modulation factor μ is defined as the amplitude of the modulation for 100% polarized photons



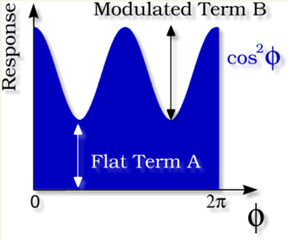
Procedure of measurement - III

4. Rescale the measured modulation with the modulation factor to derive the polarization:

$$\mathcal{P} = \frac{M}{\mu} = \frac{1}{\mu}\frac{B}{B+2A}$$

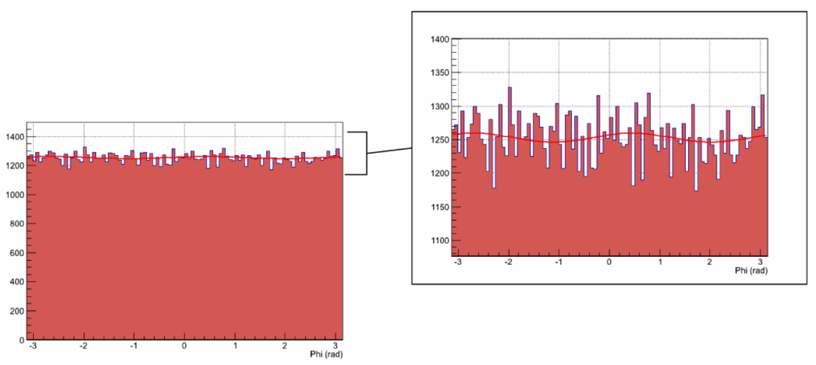
   This is equivalent to say $\mathcal{P} = I_{\rm pol}/I_{\rm tot}$ and rescaling for μ

5. If incident radiation is unpolarized? Can $\mathcal{P}$ be zero?



Sensitivity

The measurement of a cosine square modulation is a definite positive quantity

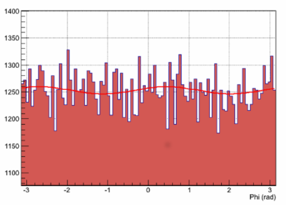


Real data from the Gas Pixel Detector

A modulation of a certain amplitude is always detected because of statistical fluctuations on the content of each bin of the modulation curve.

Sensitivity - II

- The polarization degree associated to the amplitude of such a statistical modulation at a certain confidence level is called Minimum Detectable Polarization (MDP).



- Assuming that the content of the bin of the modulation curve is Poisson-distributed, at the 99% confidence level the MDP is calculated as [Weisskopf et al., 2010]

$$\mathrm{MDP} = \frac{4.29}{\epsilon \mu F}\sqrt{\frac{B + \epsilon F}{ST}}$$

ϵ : efficiency $\quad$ F, B: Source and background counting rate

S: collecting area $\quad$ T: observation time

- By definition, there is a probability <1% that a polarization higher than the MDP as calculated above is measured by accident

- The MDP is used to express and compare the statistical sensitivity of X-ray polarimeters.

Sensitivity - III

- $\mathrm{MDP} = \frac{4.29}{\epsilon\mu F}\sqrt{\frac{B+\epsilon F}{ST}}$

  ϵ : efficiency $\quad$ F, B: Source and background counting rate
  S: collecting area $\quad$ T: observation time

- If the background is negligible,

$$\mathrm{MDP} \approx \frac{4.29}{\epsilon\mu F}\sqrt{\frac{\epsilon F}{ST}} = \frac{4.29}{\mu\sqrt{N}} \propto \frac{1}{q}$$

where $q = \mu\sqrt{\epsilon}$ is a quality factor of the instrument

  - the sensitivity of a polarimeter depends "more" on μ than ϵ
  - To reach MDP=1% with $\mu = 0.5$ (a very good instrument), $N = 7.36 \times 10^5$ counts.

Source	**detection**	> 10 counts
	spectrum	$> 10^2$ counts
	polarimetry	$> 10^5$ counts

Relation with Stokes parameters

- Standard fit function: $\mathcal{M}(\phi) = A + B\cos^2(\phi - \phi_0)$
- With some algebra we can obtain:

$$\mathcal{M}(\phi) = A + \frac{B}{2} + \frac{B}{2}\left[\cos(2\phi)\cos(2\phi_0) + \sin(2\phi)\sin(2\phi_0)\right]$$

- Let us assume that $C = A + \frac{B}{2}$, $D = \frac{B}{2}\cos(2\phi_0)$, $E = \frac{B}{2}\sin(2\phi_0)$, so that

$$\mathcal{M}(\phi) = C + D\cos(2\phi) + E\sin(2\phi)$$

- Placing: $Q = \frac{D}{\mu}$ and $U = \frac{E}{\mu}$

Angle of Polarization: $2\chi = \arctan\frac{U}{Q} = \arctan\frac{E}{D} = \arctan(\tan(2\phi_0)) = 2\phi_0$

Linear Polarization: $\mathcal{P}_L = \frac{\sqrt{Q^2 + U^2}}{I} = \frac{\sqrt{\frac{D^2+E^2}{\mu^2}}}{C} = \frac{\frac{B}{2\mu}}{A + \frac{B}{2}} = \frac{1}{\mu}\frac{B}{B + 2A}$

Measurements in X-rays

Techniques

Bragg diffraction at 45°

Bragg diffraction

- Light can be diffracted by repetitive structures of the dimensions of the wavelength λ
- Constructive interference occurs when

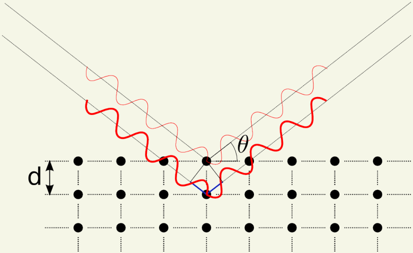
$$n\lambda = 2d \sin\theta$$

or

$$E_B(\theta) = \frac{nhc}{2d\sin\theta} = \frac{12.4\ \mathrm{keV}}{2d\sin\theta}$$

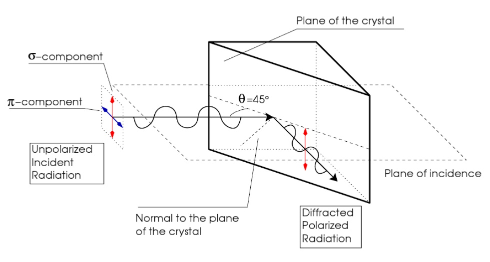
where n is an integer

- Diffraction direction and energy are related except for the diffraction order n

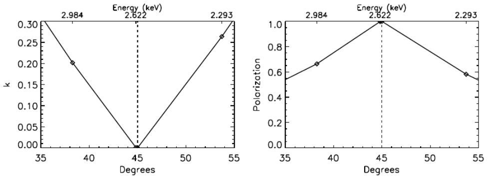


▶ X-rays do not make exception, but requires “structures” at the Å level, e.g. crystals

Polarization characteristics of Bragg diffraction at 45°



Graphite crystals:



The intensity of diffracted flux depends on the polarization

- Integrated reflectivity

$$R_E = \int_0^{\frac{\pi}{2}} P_E(\vartheta)\, d\vartheta$$

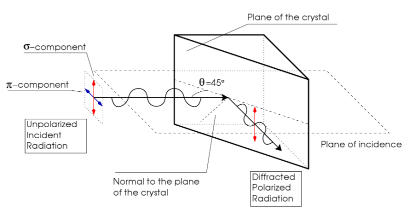
  - P_E is the rocking curve, that is the ratio between the diffracted and incident intensity

    Strongly peaked at $\theta_{\rm out} = \theta_{\rm in}$
  - $R_E \lesssim 2 \times 10^{-3}$
- $\mathcal{P} = \dfrac{1-k}{1+k}$, with $k = R_E^{\pi}/R_E^{\sigma}$

Polarization “uses” of Bragg diffraction at 45°

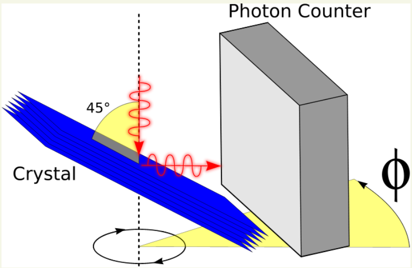
- **Calibration sources**

  The diffracted flux is polarized in the direction orthogonal to the plane of incidence



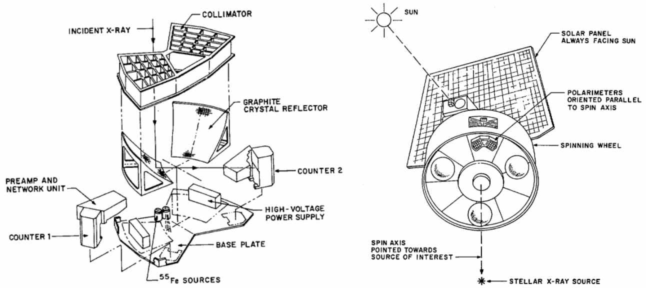
- **X-ray polarimeter**

  If the incident photons are partially polarized, the diffracted flux is modulated while the crystal is rotated around the incident direction



The Bragg polarimeter on-board OSO-8

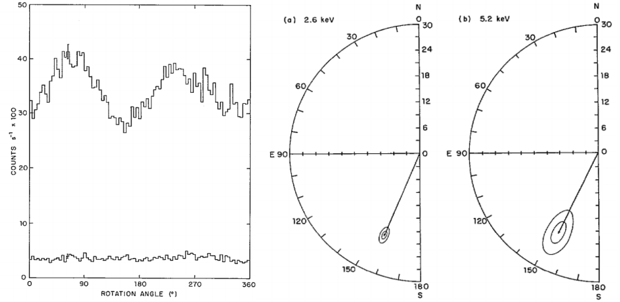
The first (out of two) dedicated polarimeter ever flown was that on-board OSO-8, which was based on Bragg diffraction on Graphite crystals



- 2× parabolic crystals
- 2.4-2.8 keV & 4.8-5.6 keV
- μ=0.93
- spin period 10 s

The Bragg polarimeter on-board OSO-8 - II

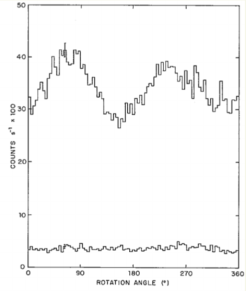
The first measurements in X-ray polarimetry: Crab Nebula, $\mathcal{P} = 19.22 \pm 0.92\%$, $\phi_0 = 155^\circ.79 \pm 1^\circ.37$

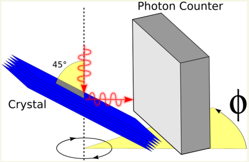


- 12 days of observation in 2 years
- 71.2 hours of good data, 71.3 hours of background
- signal to noise 10 at 2.6 keV, 2 at 5.2 keV
- the modulation curve was not a cosine square!

A small digression

- We have seen that a certain degree of polarization is always measured also for unpolarized photons for statistical reasons.
  - Such a polarization is called Minimum Detectable Polarization (MDP)
  - The MDP basically depends on the number of counts and on the modulation factor
- Real instruments are also affected by instrumental systematic effects
  - Ultimately, such effects are due to the fact that the azimuthal response is not exactly uniform because of misalignments, non-uniformities in the photon detection, etc..
- It is **much easier** to obtain a modulated signal for polarized photons than a spurious modulation compatible with the statistics!





Bragg diffraction - summary

PROs:

- ✓ High modulation factor;
- ✓ Energy resolved polarmetry;

CONs:

- ✗ Limited to low energies
- ✗ Very low efficiency (R_E is small!)
- ✗ Dispersive (one angle a time)
- ✗ Needs rotation

Today proposed only for very soft X-ray polarimetry ($<$1 keV), but requires an X-ray telescope + grating spectrometer [Marshall, 2008].

Compton scattering

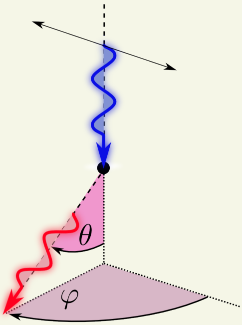
Compton scattering

Photon scattering on atomic electrons:

- Klein-Nishina cross section:

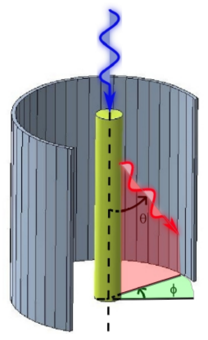
$$\frac{d\sigma}{d\Omega} = \frac{{r_0}^2}{2}\frac{{E'}^2}{E^2}\left[\frac{E}{E'} + \frac{E'}{E} - 2\sin^2\theta\cos^2\phi\right]$$

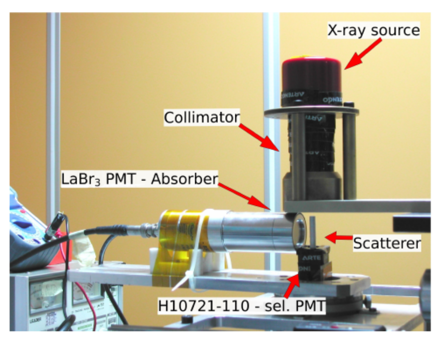
- $r_0 = \frac{1}{4\pi\epsilon_0}\frac{e^2}{mc^2}$ is the classical electron radius
- θ is the angle of scattering
- ϕ is the azimuthal angle of scattering, *measured from the electric field direction*
- in case of polarized radiation, the number of photons scattered in the ϕ direction is modulated as $\cos^2\phi$, the peak is orthogonal to the direction of polarization
- modulation decreasing with energy
- maximum modulation only for scattering at 90°



X-ray polarimetry with Compton scattering

The direction of scattering is distinguished by the knowledge of the first scattering position and by the detection of a second interaction.

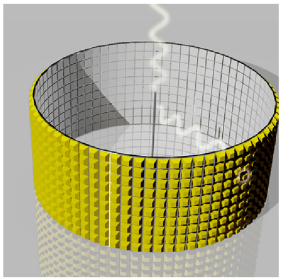




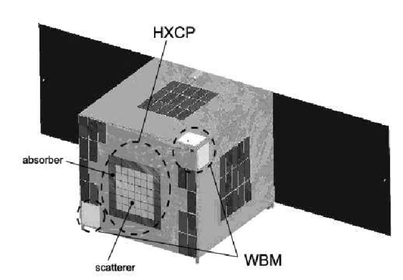
Very different designs [Krawczynski et al., 2011]

Compton scattering polarimeter designs - I

Other designs: **Focal plane or large area instruments**



[Soffitta et al., 2010]



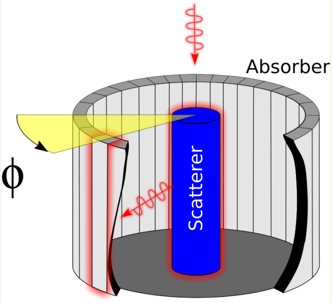
[Toizumi et al., 2011]

- ✓ High sensitivity
- ✓ Lower background
- ✗ Higher costs: multilayer telescopes

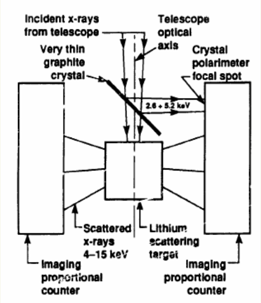
- ✓ Cheaper
- ✗ High background

Compton scattering polarimeter designs - II

Other designs: **Active or passive scatterer**



Fabiani et al. 2013 in publication



[Kaaret et al., 1994]

✓ Lower background and confidence in double events detection

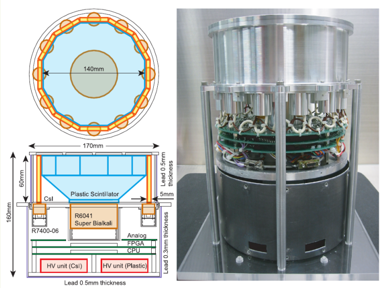
✗ Higher threshold

✓ Lower threshold

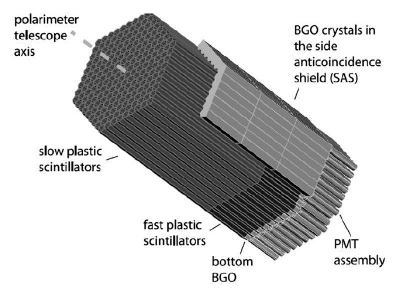
✗ Higher background

Compton scattering polarimeter designs - III

Other designs: **Two phases or One phase**



[Yonetoku et al., 2011a]



[Kamae et al., 2008]

✓ Good energy resolution

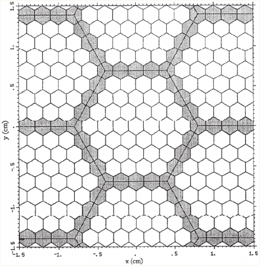
✗ More complexity

✓ Simpler

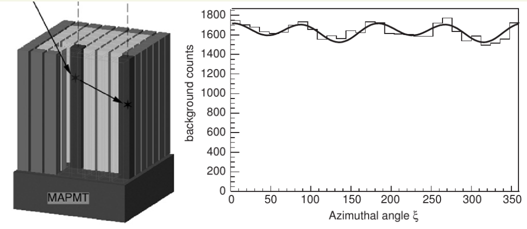
✗ Poor energy resolution

Compton scattering polarimeter designs - IV

Other designs: **Hexagonal Vs Square pixels**



[Costa et al., 1995]



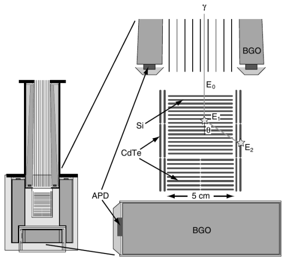
[Bloser et al., 2009; Xiong et al., 2009]

- ✓ Good control of systematics
- ✗ More mechanical complexity

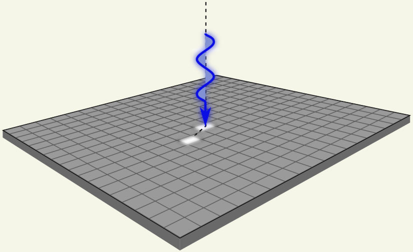
- ✓ Simpler
- ✗ Evident systematics

Compton scattering polarimeter designs - V

Other designs: **Dedicated Vs Non-dedicated instruments**



Two phases [Takahashi et al., 2008]



One-phase [Krawczynski et al., 2011; Lotti et al., 2012]

✓ More possibilities to be launched

✗ Depending on the peculiar design, variable sensitivity to X-ray polarimetry

✗ Depending on the peculiar design, possibly high systematic effects

Compton polarimetry results

Crab Nebula:

- ROCKET 1709 [Novick et al., 1972]: Linear polarization, P=(15.4±5.2)%, angle 156°±10°
- INTEGRAL-SPI [Dean et al., 2008]: Linear polarization (46±10)%, 123°±11° between 0.1-1 MeV, confirmed by INTEGRAL-IBIS Forot et al. [2008]

Cyg X-1:

- INTEGRAL-IBIS [Laurent et al., 2011]: Linear polarization (67±30)%, between 0.4-2 MeV
- INTEGRAL-SPI [Jourdain et al., 2012]: Linear polarization (76±15)%, above 230 keV

Gamma Ray Bursts:

- **GRB021206**, P=(80±20)% (Coburn and Boggs [2003], RHESSI). Not confirmed by Rutledge and Fox [2004]
- **GRB021206**, $\mathcal{P} = 41^{+57}_{-44}\%$ (Wigger et al. [2004], RHESSI)
- **GRB930131**, $\mathcal{P}$ >35% and $\mathcal{P}$ >50% for **GRB960924** (Willis et al. [2005], BATSE)
- **GRB041219a**, $\mathcal{P} = (98 \pm 33)\%$ (Kalemci et al. [2007], INTEGRAL-SPI), $P \sim 60\%$ (McGlynn et al. [2007], INTEGRAL-SPI), Variable polarization (Götz et al. [2009], INTEGRAL-IBIS)
- **GRB061122**, $\mathcal{P}$ <60% (McGlynn et al. [2009], INTEGRAL-SPI)
- **GRB 100826a**, $\mathcal{P} = (27 \pm 11)\%$ (Yonetoku et al. [2011b], IKAROS-GAP)
- **GRB 110301A**, $\mathcal{P} = (70 \pm 22)\%$ and $\mathcal{P} = 84^{+16}_{-28}\%$ for **GRB110721A** (Yonetoku et al. [2012], IKAROS-GAP)

Large uncertainties. For the large part, obtained with non-dedicated instruments.

Compton scattering - Summary

PROs

- ✓ Works up to hard X-rays
- ✓ Optimization allows to reach a good efficiency and modulation factor
- ✓ Good energy resolution for two phases

CONs

- ✗ The sensitivity depends strongly on the design
- ✗ High energy threshold if active scatterer
- ✗ Background may be important, especially in case of a passive scatterer

Photoelectric effect

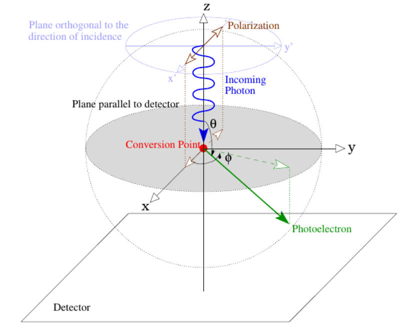
Photoelectric effect

Emission of a photoelectron after the absorption of the photon:

- Differential cross section for the spherical symmetric shells:

$$\frac{d\sigma^K_{ph}}{d\Omega} \propto Z^5 \left(\frac{m_e c^2}{E}\right)^{\frac{7}{2}} \frac{4\sqrt{2}\sin^2\theta\cos^2\phi}{(1+\beta\cos\theta)^4}$$

- ϕ is the azimuthal angle
- θ the polar angle
- In case of polarized radiation, the number of emitted photoelectrons in the ϕ direction is modulated as $\cos^2\phi$, the peak is parallel to the direction of polarization
- modulation constant with energy as long as spherical symmetric shells are involved



Photoelectric polarimetry

- We have to image the path of a few keV photoelectron.
  - The energy range drive the choice of the material
  - The range is inversely proportional to the density
    - in a solid, a few μm; in a gas, a few hundreds μm
- Actually, we have to distinguish the first part of the path...
  - Electron scattering with atomic nuclei: $\sigma_{\rm Ruth} \propto Z^2$
  - Photoelectric efficiency: $\sigma_{\rm Ph} \propto Z^5$
- .. and the pixel must be well smaller than the photoelectron range to avoid systematic effects

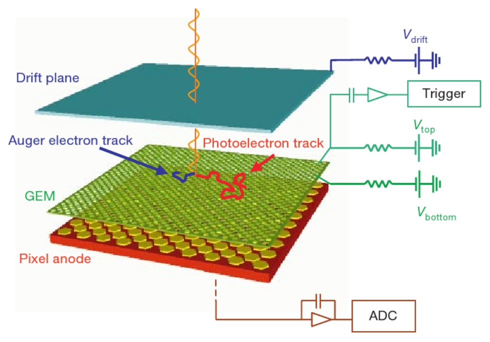
Semiconductor devices, for the moment not so appealing [Tsunemi et al., 1992]

- ✓ high efficiency, compact and robust instruments
- ✓ fast development
- ✗ the pixel size is decreasing, e.g. CCDs with a few μm pixels are already commercially available, but it is still larger than photoelectron range
  - small modulation factor when the efficiency is large [Michel and Durst, 2008]

Gas detectors more mature

Modern gas photoelectric polarimeters

Multiplication and collection of the charge cloud produced by ionization



Charge read-out with

- **Application specific integrated circuit** (ASIC) [Costa et al., 2001; Bellazzini et al., 2006, 2007]
- **Thin-film transistor array** (TFT) [Black et al., 2003]

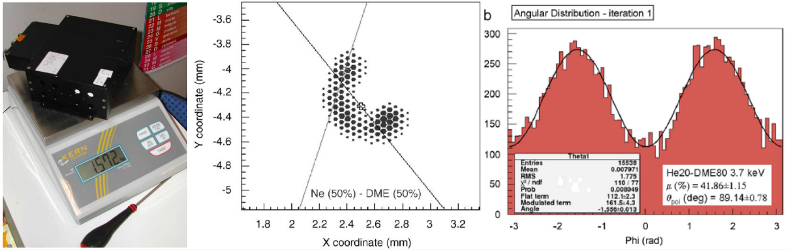
✓ Low energy threshold (<2 keV)

✓ High azimuthal simmetry

✓ Imaging, negligible background

✗ Coupling between modulation factor and efficiency

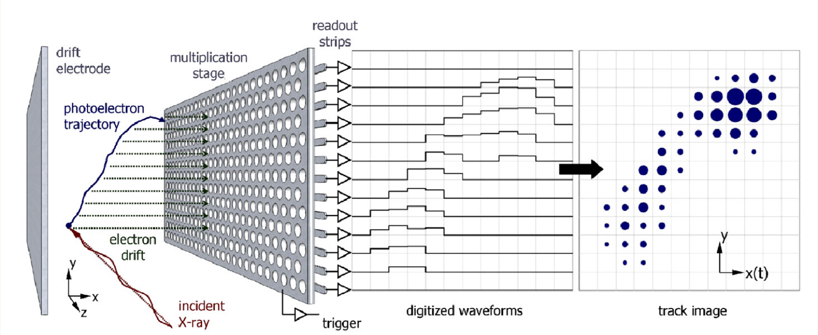
The GPD - current prototype



- ASIC with 15 mm x 15 mm active area 105k pixels, 50 μm pitch
- Autotrigger capabilities
- 1.6 kg, 5 W
- Spectral capabilities: 20% at 6 keV
- Timing capabilities: 8 μs
- Imaging capabilities: 36 μm HEW

Modern gas photoelectric polarimeters - II

A different implementation of the same idea is that of the Time Projection Chamber



Indirect imaging of the track through temporal delays of charge collection

- ✓ High efficiency, in principle uncorrelated with μ
- ✗ High systematics, rotation required
- ✗ Unidimensional imaging capabilities

Photoelectric polarimetry - Summary

PROs

- ✓ Good efficiency and modulation factor for soft X-rays
- ✓ Works up to a few tens keV
- ✓ Good energy resolution
- ✓ Possibly, imaging

CONs

- ✗ Designed for a focal plane, more expensive
- ✗ Relatively new device, work to do

Measurement techniques: A comparison

	Bragg diffraction	**Compton scattering**	**Photoelectric**
Modulation factor	★★★★★	★★★☆☆	★★☆☆☆
Efficiency	☆☆☆☆☆	★★★★☆	★★★☆☆
Energy range	★☆☆☆☆	★★★★★	★★★☆☆
Low energy threshold	★★★★★	★☆☆☆☆	★★★★☆
Energy resolution	★★★★★	★★★☆☆	★★☆☆☆
Resources required	★★★☆☆	★★☆☆☆	★★★★☆

Perspectives

Some basic considerations

Soft X-rays has to be studied out of the atmosphere

- Satellites or rockets (low value for money)
- Balloons for hard X-rays (>30 keV)

Different mission sizes:

- **Ballons** ∼2 M€, development 2 years
- **Small** ∼100 M€, development 5 years
- **Medium** ∼400 M€, development 10 years
- **Large** ∼1 B€, development 20 years

Cost of the scientific payload ∼30% of the total.

- bus: >15 M€
- launcher: >15 M€
- management: > 10 M€

Cost and weight/volume/complexity are very tightly related.

Some basic considerations - II

- We have seen that a large statistics is required to perform polarimetry
  - ➥ To reach MDP=1% with $\mu = 0.5$ (a very good instrument), $N = 7.36 \times 10^5$ counts.
- A reasonable observation time is of the order of 1 day (∼100 ks)
- X-ray sources are not so bright...
  - ➥ For the Crab nebula, which is one of the brightest, 0.35 $\frac{\mathrm{ph}}{\mathrm{cm}^2\mathrm{s}}$ in the 2-10 keV energy range
- ... and their spectra quickly decrease with energy
  - ➥ X-ray power law spectrum, $\frac{\mathrm{d}N}{\mathrm{d}E} = E^{-\alpha}$, with $\alpha \sim 1.5 - 2.2$.
- BUT Large detectors have a large background
  - ➥ More counts are needed to achieve the same MDP
- AND Polarization from sources typically increase with the energy
  - ➥ For example, scattering is more probable than absorption at higher energy

▶ The perfect instrument does not exist: it is a matter of trade-offs among costs, technical capabilities, scientific objectives, and costs...

Future scenarios

Many attempts of extracting polarization from data of other instruments.

In the meanwhile, a lot of small projects are running in background

- **GAP**, a (very) small Compton polarimeter for Gamma Ray Bursts (GRBs), is currently taking data
- **PoGOLite**, a balloon dedicated to Compton polarimetry, will be launched in summer 2013
- **POLAR**, a Compton polarimeter for Gamma Ray Bursts, should be launched on-board the Chinese Space Station

However, ESA/NASA have already expressed somehow a "declaration" of interest in more demanding missions

- **GEMS**, a small mission dedicated to X-ray polarimetry with TPCs and X-ray telescopes, was selected for the launch but unfortunately last year was canceled for programmatic reasons.
- **XIPE**, a small mission dedicated to X-ray polarimetry with GPDs and X-ray telescopes, was ranked among the firsts in the call of 2012.

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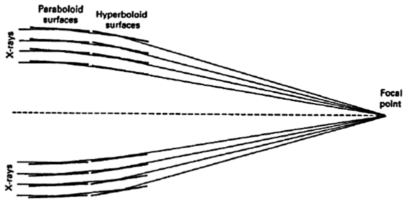
Future scenarios - Soft X-ray polarimetry

- **A small pathfinder satellite mission**
  - Small cluster of telescopes with photoelectric polarimeters in the focus
    - More background but still negligible, lower costs because a certain area is achieved by the replica of the same shells.
    - Short focal length
    - Small and low cost launcher

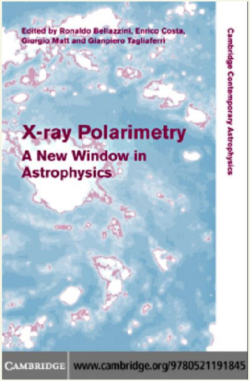


  - Photoelectric polarimeters working in the 2-10 keV energy range
    - both GPD and TPC have a high Technology Readiness Level (TRL)
  - Possibly, a dedicated mission, long pointings to collect enough photons
  - MDP$\sim$10% in 100 ks for 1 mCrab (2.3×10^{-11} erg/cm^2/s)
    - Tens of galactic and a few extragalactic sources accessible with pointings 1-10 days long

For more information on X-ray polarimetry...

X-ray Polarimetry: A New Window in Astrophysics

Edited by R. Bellazzini, E. Costa, G. Matt, G. Tagliaferri



You can download this presentation from **ftp://ftp.iasf-roma.inaf.it/muleri/**

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