Transforming our understanding of the X-ray Universe: the Imaging X-ray Polarimetry Explorer (IXPE)

Frédéric Marin
Quizz:

Who can tell me the name of a past/current mission dedicated to X-ray astronomy (spectroscopy, timing, polarimetry, imaging ...) ?
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ASCA, AGILE, Chandra, Granat, NuSTAR, Rosat, Suzaku, XMM-Newton ...
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Who can tell me the name of a past mission dedicated to X-ray polarimetry?
INTRODUCTION

Quizz:

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ASCA, AGILE, Chandra, Granat, NuSTAR, Rosat, Suzaku, XMM-Newton ...

Who can tell me the name of a past mission dedicated to X-ray polarimetry?

Aerobee rockets, Ariel V, OSO-8
X-ray polarimetry is the least known/used method in X-ray astronomy

Why so?
X-ray polarimetry is the least known/used method in X-ray astronomy

Why so?

- **1895**: Discovery of X-ray radiation by Wilhelm Röntgen
- **~1940**: Sun observations
- **1962**: Sco X-1 observation
- **1960s**: Ariel Program, Hakucho, HEAO, Venera Program, ISEE-3, OSO, SAS, Aryabhata, Salyut-4, ANS, Skylab, Copernicus, TD-1A, Cosmos Series, Vela 5A/B and 6A/B
- **1970s**: Granat, Phobos, Kvant-1, Ginga, Spacelab, Spartan-1, EXOSAT, Astron, Tenma, Venera Program
- **1980s**: XMM, Chandra, Beppo, SAX, RXTE, Wind, ALEXIS, ASCA, DXS, EURECA, BBXRT, Ulysses, ROSAT
- **1990s**: RXTE, Chandra, XMM, Swift, Suzaku (ASTRO-E2), MAXI, NuSTAR
- **2000s**: RXTE, Chandra, XMM, Swift, Suzaku (ASTRO-E2), MAXI, NuSTAR
- **2010s**: Today
X-ray polarimetry is the least known/used method in X-ray astronomy

Why so?

1895  
*Discovery of X-ray radiation*  
Wilhelm Röntgen

1962  
*Sco X-1 observation*

1960

1970

1980

1990

2000

2010

2018  
*TODAY*

1968  
*Aerobee rockets*

Bragg-crystal X-ray polarimeters

Galactic sources polarization

1969  
*Intercosmos I*

Dniproptevsk Spoutnik satellite

Solar flares polarization

1974  
*Ariel V*

1975  
*OSO-8*

Galactic sources polarization

1974  
*Ariel Program, Hakuch, HEAO, Venera Program, ISEE-3, OSO, SAS, Aryabhata, Salyut-4, ANS, Skylab, Copernicus, TD-1A, Cosmos Series, Vela 5A/B and 6A/B*

1975  
*Granat, Phobos, Kvant-1, Ginga, Spacelab, Spartan-1, EXOSAT, Astron, Tenma, Venera Program*

1990  
*XMM, Chandra, Beppo, SAX, RXTE, Wind, ALEXIS, ASCA, DXS, EURECA, BBXRT, Ulysses, ROSAT*

2000  
*RXTE Chandra XMM Swift Suzaku (ASTRO-E2) MAX *

2018  
*RXTE, Chandra, XMM, Swift, Suzaku (ASTRO-E2), MAXI, NuSTAR*
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Why so?

1962 Sco X-1 observation

~1940 Sun observations

1895 Discovery of X-ray radiation

Wilhelm Röntgen

1968 Aerobee rockets
Bragg-crystal X-ray polarimeters
Galactic sources polarization

1969 Intercosmos I
Dnipropetrovsk Spoutnik satellite
Solar flares polarization

1974 Ariel V
Galactic sources polarization

1975 OSO-8

1978: HEAO-2 (Einstein)
X-ray optics and instruments (grazing incidence telescopes) no longer needed rotation
End of compatibility with X-ray polarimeters
X-ray polarimetry is the least known/used method in X-ray astronomy

Why so?

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Discovery of X-ray radiation
Wilhelm Röntgen

1960
Sco X-1 observation
1962
Aerobee rockets
Bragg-crystal X-ray polarimeters
Galactic sources polarization

1968
Intercosmos I
Dnipropetrovsk Spoutnik satellite
Solar flares polarization

1969
Vela 5A/B and 6A/B, Cosmos Series, OSO Series, ESRO-2B, OGO

1970
Ariel Program, Hakumo, HEAO, Venera Program, ISEE-3, OSO, SAS, Aryabhata, Salyut-4, ANS, Skylab, Copernicus, TD-1A, Cosmos Series, Vela 5A/B and 6A/B

1974
Ariel V
Granat, Phobos, Kvant-1, Ginga, Spacelab, Spartan-1, EXOSAT, Astron, Tenma, Venera Program

1975
OSO-8
XMM, Chandra, Beppo, SAX, RXTE, Wind, ALEXIS, ASCA, DXS, EURECA, BBXRT, Ulysses, ROSAT

1990
RXTE
Chandra
XMM
Swift
Suzaku (ASTRO-E2), MAX

1997
INTEGRAL
Soft γ-ray polarization measurement of the Crab
... dubious ...

2002
RXTE, Chandra, XMM, Swift, Suzaku (ASTRO-E2), MAXI, NuSTAR

2018
TODAY

INTRODUCTION

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1940 Sun observations


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1975 XMM, Chandra, Beppo, SAX, RXTE, Wind, ALEXIS, ASCA, DXS, EURECA, BBXRT, Ulysses, ROSAT


1975 Intercosmos I

2002 INTEGRAL
Soft γ-ray polarization measurement of the Crab ...
... dubious ...

2002 RXTE Chandra XMM Swift Suzaku (ASTRO-E2) MAX

2018 TODAY

2018 RXTE, Chandra, XMM, Swift, Suzaku (ASTRO-E2), MAXI, NuSTAR

2018 PoGO+

Hard X-ray measurement of the Crab and Cyg X-1.
There is a clear lack of X-ray satellites mounted with an X-ray telescope

→ Polarimetry is more complicated than photometry, spectroscopy or timing

**Reminder on polarization**

Polarization is intrinsically connected with the **transverse nature of light**

The electric and magnetic field vectors oscillate **perpendicularly** (or right angled) to the direction of energy transfer

E.g.: light, transverse seismic waves, waves in a guitar string
Reminder on polarization

By definition, the electric vector oscillates randomly (natural light is unpolarized)

However, during the measurement time, if the temporal evolution of the tip of its transverse (electric) vector is found to be stationary, the wave is said to be polarized

→ vectorial nature of light (Young 1801, Fresnel 1821)

For this reason, polarization phenomena are inexistent for longitudinal waves

Polarization is thus an important information encoded in spatially asymmetric electromagnetic waves (along with intensity, frequency and phase)
Reminder on polarization

How to produce/modify/cancel polarization?
- Intrinsic polarization
- Absorption / re-emission
- Magnetic effects (Faraday rotation, Zeeman effect …)
- Scattering (Thomson, Mie, Compton …)
- General relativity
- Dilution by starlight

+ polarization sensitive to geometry and composition!

How do we measure polarization?

Polarization degree
A quantity used to describe the portion of an electromagnetic wave which is polarized
Perfectly polarized wave = 100%, unpolarized wave = 0%

Polarization angle
Orientation of the plane of vibration of the electric vector (for linear polarization)
The problem of X-ray polarization

Due to the high photon energies and short wavelengths involved, optical elements used at longer wavelengths become transparent at high energies.

X-ray polarimetry can be based on any of three distinct physical effects:
- Bragg diffraction
- Scattering polarimeters
- Photoelectron tracking
The problem of X-ray polarization

Due to the high photon energies and short wavelengths involved, optical elements used at longer wavelengths become transparent at high energies.

X-ray polarimetry can be based on any of three distinct physical effects:
- Bragg diffraction
- Scattering polarimeters
- **Photoelectron tracking**: the direction of the initial K-shell photoelectron is determined by the electric vector and the direction of the incoming photon.

Gas Pixel Detector (Costa et al. 2001, Bellazzini et al. 2006, 2007)
The problem of X-ray polarization

Due to the high photon energies and short wavelengths involved, optical elements used at longer wavelengths become transparent at high energies.

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Measure of polarization using modulation

Fit function: \( M(\phi) = A + B \cos^2(\phi - \phi_0) \)

Modulation: \( \frac{M_{\text{max}} - M_{\text{min}}}{M_{\text{max}} + M_{\text{min}}} = \frac{B}{B + 2A} \)

Polarization:
\[
\text{Polarization} = \frac{B}{\mu B + 2A}
\]
\( \mu \) is the modulation factor.

Very sensitive in the 1 – 40 keV range
No rotation
Imaging
A MAJOR LIMIT

Even with the best technology, X-ray polarimetry is facing a big limit

- Source detection >10 photons
- Source spectra >100 photons
- Source polarimetry >100000 photons

X-ray polarization is photon hungry!

In polarimetry the sensitivity is a matter of photons
To describe the capability of rejecting the null hypothesis (no polarization) at 99% confidence, we use the Minimum Detectable Polarization:

\[
MDP = \frac{4.29}{\mu R_S} \sqrt{\frac{R_S + R_B}{T}}
\]

- \(R_S\) is the source rate, \(R_B\) is the background rate,
- \(T\) is the observing time, \(\mu\) is the modulation factor
- (the modulation of the response of the polarimeter to a 100% polarized beam)

Examples to reach a MDP of 1%:
- Crab (PWN) > 10 ks
- X-ray binary > 100 ks
- Active Galactic Nuclei ~ 1 Ms
IXPE: the forthcoming mission!

In 2014 NASA issued an AOO for a Small Explorer Mission (budget of ~ 175 M$) → Deadline Dec 2014

On July 30th 2015, NASA selected 3 missions for phase A study
1) IXPE: X-ray Polarimetric mission based on GPD; P.I. Martin Weisskopf
2) Praxys: X-ray Polarimetric mission based on TPC
3) SPHEREx: All Sky Survey with Near IR spectroscopy

Phase A accomplished in July 2016. Site Visit at MSFC the 17th Nov 2016. On January the 3rd 2017, NASA selected IXPE

Launch in 2021

SPECTROSCOPY
IMAGING
POLARIZATION

2 – 8 keV
2 years duration
100+ targets
Future instruments

IXPE: the forthcoming mission!

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Quantity</th>
<th>Scientific driver</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Payload requirements</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total collecting area</td>
<td>&gt;1100 cm$^2$ at 3 keV</td>
<td>See Req-Sci-010</td>
</tr>
<tr>
<td>Modulation factor</td>
<td>&gt;30% at 3 keV</td>
<td>See Req-Sci-010</td>
</tr>
<tr>
<td>Detector efficiency</td>
<td>&gt;10% at 3 keV</td>
<td>See Req-Sci-010</td>
</tr>
<tr>
<td><strong>Scientific requirements</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polarimetric sensitivity</td>
<td>MDP&lt;10% for 100ks observation of source with flux 2x10^{-11} erg/s/cm$^2$ (1 mCrab) in the 2-8 keV band</td>
<td>NGC1068, GC, ...</td>
</tr>
<tr>
<td>Spurious polarization</td>
<td>&lt;0.5%</td>
<td>GRS1915, Cyg X-1</td>
</tr>
<tr>
<td>Angular resolution</td>
<td>&lt;30 arcsec</td>
<td>Crab, jet in CenA, SNR, GC, ...</td>
</tr>
<tr>
<td>Field of View</td>
<td>&gt;10 arcmin</td>
<td>PWNe, SNRs, ...</td>
</tr>
<tr>
<td>Spectral resolution</td>
<td>&lt;20% at 5.9 keV</td>
<td>Black hole spin</td>
</tr>
<tr>
<td>Timing resolution</td>
<td>8 μs</td>
<td>Accreting millisecond pulsars</td>
</tr>
<tr>
<td>Timing synchronization with the Universal Time</td>
<td>10 μs</td>
<td>Accreting millisecond pulsars</td>
</tr>
<tr>
<td>Dead time for one telescope</td>
<td>&lt;100 μs</td>
<td>Crab Nebula, Cyg X-1, ...</td>
</tr>
<tr>
<td>Mission duration</td>
<td>3 yr</td>
<td>Core program and population studies</td>
</tr>
<tr>
<td>TOO</td>
<td>Repointing &lt;12 hr during working hours</td>
<td>Bursters</td>
</tr>
<tr>
<td>Sky accessibility</td>
<td>1/3 of the sky accessible at any time</td>
<td>Observation of galactic and extragalactic sources</td>
</tr>
<tr>
<td>Forbidden directions</td>
<td>None over one year</td>
<td>Core program and population studies</td>
</tr>
</tbody>
</table>
What can we do with X-ray polarimetry?

1 – Acceleration phenomena

Supernova remnants (SNR) are believed to be the acceleration sites of cosmic rays up to very high energies
   → diffusive shock acceleration

To achieve the observed multi-TeV energies, the magnetic field must be amplified well above the adiabatic compressed magnitude (Amato 2014)
   → amplified magnetic field likely highly turbulent

High resolution imaging X-ray polarimetry:
   - unique constraints on the magnetic field amplification mechanisms
   - localize the regions of shock acceleration
   - measure the strength and the orientation of the magnetic field at the emission sites (Vink 2012).

Figure 2. Simulated maps of polarized synchrotron emission in a random magnetic field at 0.5 keV. Intensity, $I(R, t, \nu)$, is shown with a linear colour scale in the left-hand panel. The central panel shows the product of intensity and polarization degree. The right-hand panel shows the degree of polarization indicated by the colour bar. The stochastic magnetic field sample has $\sqrt{B^2} = 3 \times 10^{-5}$ G and spectral index $\delta = 1.0$.
What can we do with X-ray polarimetry?

1 – Acceleration phenomena

Magnetic fields in pulsar wind nebulae (PWN) are rather well ordered, so the emission is locally highly polarized in the radio and optical bands (up to 60%, close to the theoretical limit)

X-ray emitting electrons have a synchrotron lifetime far shorter than that of particles which emit at longer wavelengths,

→ X-rays are produced in the regions close to where the electrons are accelerated and therefore provide a much cleaner view of the inner regions than optical

Detailed and spatially-resolved X-ray polarization measurements will allow to determine the magnetic field orientation in the torus, the jet and at various distances from the pulsar

This is of significant interest because, compared to the total synchrotron emission, polarized emission is a more sensitive probe of the plasma dynamics in these nebulae
Accreting sources

What can we do with X-ray polarimetry?

2 – Emission in strong magnetic fields

Phase-resolved polarimetry can distinguish between “pencil” and “fan” radiation patterns
→ the degree of linear polarization is maximal for emission perpendicular to the magnetic field,
the flux and degree of polarization are in-phase for fan beams, but out-of-phase for pencil beams

Meszaros et al. (1988)
What can we do with X-ray polarimetry?

3 – Scattering in aspherical geometries

Demonstrating past activity from Sgr A* through polarization measurements of the X-ray flux from nearby molecular clouds

Sgr A* has a very low accretion rate $\sim 10^{-8} \, M_{\odot} \, y^{-1}$ near the event horizon (Baganoff et al. 2003)

$\rightarrow$ X-ray luminosity of the order $2 \times 10^{33} \, \text{erg s}^{-1}$

(Baganoff et al. 2001; Quataert 2002)

Pure reflection spectra ($L_X \sim 10^{35} \, \text{erg s}^{-1}$) ... but no nearby sources bright enough!
What can we do with X-ray polarimetry?

3 – Scattering in aspherical geometries

Demonstrating past activity from Sgr A* through polarization measurements of the X-ray flux from nearby molecular clouds

- the degree of polarization is related to the source-cloud-observer (scattering) angle

- the position angle is perpendicular to the source direction
What can we do with X-ray polarimetry?

3 – Scattering in aspherical geometries

Active galactic nuclei (AGN) are scaled up version of galactic black holes (micro-quasars)
- black hole
- accretion disk
- winds
- jets (sometimes)

At first order: 
axisymmetry

Unresolvable scattering regions
→ polarization as a tracer of any asymmetry

Goosmann & Matt (2011)
Vacuum birefringence

What can we do with X-ray polarimetry?

4 – Fundamental physics

X-ray polarimetry of NS emission gives the opportunity to observe a QED effect predicted nearly 80 years ago (Heisenberg & Euler 1936) but still to be experimentally confirmed

Photons propagating in strong magnetic fields are subject to a phenomenon called the "vacuum birefringence" where refractive indices of two physical modes both deviate from unity and differ from each other

→ significant change in the dependence on the phase and the energy of the polarization

→ a strong test of the magnetar paradigm and a probe of strong-field QED
**Strong gravity effects**

What can we do with X-ray polarimetry?

4 – Fundamental physics

Disk illuminated by a hot corona (geom., temp., … ?)
→ soft X-rays: absorption + reemission
→ hard X-rays: Compton scattering

Scattering = polarization

Strong gravity fields affect the polarization of scattered radiation (Connors et al. 1980)

→ the polarization angle as seen at infinity is rotated due to aberration (SR) and light bending (GR) effects

The rotation is larger for smaller radii and higher inclination angles and it depends on the spin of the BH!
What can we do with X-ray polarimetry?

4 – Fundamental physics

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First balloon-borne results

Accretion geometry of the black-hole binary
Cygnus X-1 from X-ray polarimetry

M. Chauvin\textsuperscript{1,2}, H.-G. Florén\textsuperscript{3}, M. Friis\textsuperscript{1,2}, M. Jackson\textsuperscript{1,9}, T. Kamae\textsuperscript{4,5}, J. Kataoka\textsuperscript{6}, T. Kawano\textsuperscript{7}, M. Kiss\textsuperscript{1,2}, V. Mikhalev\textsuperscript{1,2}, T. Mizuno\textsuperscript{7}, N. Ohashi\textsuperscript{7}, T. Stana\textsuperscript{1}, H. Tajima\textsuperscript{8}, H. Takahashi\textsuperscript{7}*, N. Uchida\textsuperscript{7} and M. Pearce\textsuperscript{1,2}

Black hole binary (BHB) systems comprise a stellar-mass black hole and a closely orbiting companion star. Matter is transferred from the companion to the black hole, forming an accretion disk, corona and jet structures. The resulting release of gravitational energy leads to the emission of X-rays. The radiation is affected by special/general relativistic effects, and can serve as a probe for the properties of the black hole and surrounding environment, if the accretion geometry is properly identified. Two competing models describe the disk-corona geometry for the hard spectral state of BHBs, based on spectral and timing measurements\textsuperscript{1,2}. Measuring the polarization of hard X-rays reflected from the disk allows the geometry to be determined. The extent of the corona differs between the two models, affecting the strength of the relativistic effects (such as enhancement of the polarization fraction and rotation of the polarization angle). Here, we report observational results on the linear polarization of hard X-ray emission (19–181keV) from a BHB, Cygnus X-1*, in the hard state. The low polarization fraction, \(<8.6\%\) (upper limit at a 90\% confidence level), and the alignment of the polarization angle with the jet axis show that the dominant emission is not influenced by strong gravity. When considered together with existing spectral and timing data, our result reveals that the accretion corona is either an extended structure, or is located far from the black hole in the hard state of Cygnus X-1.
**Conclusions**

X-ray polarization will rebirth from its ashes in 2021!

Despite the difficulty to measure X-ray polarization, numerous missions have been proposed and many of them are already accepted.

**A new observable window**
- High energy cosmic sources
- Considerations for stellar/solar polarimetry too

IXPE will explore a new observational window after 42 years from the last positive space measurement, with a dramatic improvement in sensitivity: from 1 to 100+ sources!

In the violent X-ray sky, polarimetry is expected to have a much greater impact than in most other wavelengths.
Additional material
The problem of X-ray polarization

Due to the high photon energies and short wavelengths involved, optical elements used at longer wavelengths become transparent at high energies.

X-ray polarimetry can be based on any of three distinct physical effects
- Bragg diffraction

Light with sufficiently short (less than a few nanometers) wavelength falling onto a crystal is reflected by the crystal according to Bragg’s law: \( n \lambda = 2dsin\theta \) (\( n = 1, 2, 3, \ldots \))

“d” : distance between two consecutive atomic layers
”\( \theta \)” : angle of incidence
“n” : order of diffraction

Bragg diffraction polarimetry was the method used for the X-ray polarimeters implemented in Ariel V and OSO-8 satellites (and rockets)

ROTATION OF THE CRYSTAL IS NECESSARY
The problem of X-ray polarization

Due to the high photon energies and short wavelengths involved, optical elements used at longer wavelengths become transparent at high energies.

X-ray polarimetry can be based on any of three distinct physical effects:
- Bragg diffraction
- Scattering polarimeters

Thomson / Compton scattering of photons by electrons is sensitive to the (linear) polarization of the incident photons.

A calorimeter will measure the distribution of scattered radiation:
- In case of no polarization, the distribution of scattered photons will be isotropic.
- If the light is partially polarized, photons will be scattered preferentially perpendicular to the direction of polarization projected onto the xy plane.

Adequate for >10 keV polarimetry; rotation not necessarily needed.
### Why the 1 – 10 keV for the first accepted mission?

<table>
<thead>
<tr>
<th>Scientific goal</th>
<th>Sources</th>
<th>&lt;1 keV</th>
<th>1-10</th>
<th>&gt;10 keV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acceleration phenomena</td>
<td>PWN</td>
<td>yes (but absorption)</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td></td>
<td>SNR</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td></td>
<td>Jet (Microquasars)</td>
<td>yes (but absorption)</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td></td>
<td>Jet (Blazars)</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Emission in strong magnetic fields</td>
<td>WD</td>
<td>yes (but absorption)</td>
<td>yes</td>
<td>difficult</td>
</tr>
<tr>
<td></td>
<td>AMS</td>
<td>no</td>
<td>yes</td>
<td></td>
</tr>
<tr>
<td></td>
<td>X-ray pulsator</td>
<td>difficult</td>
<td>yes (no cyclotron?)</td>
<td>yes</td>
</tr>
<tr>
<td></td>
<td>Magnetar</td>
<td>yes (better)</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td>Scattering in aspherical geometries</td>
<td>Corona in XRB &amp; AGNs</td>
<td>difficult</td>
<td>yes</td>
<td>yes (difficult)</td>
</tr>
<tr>
<td></td>
<td>X-ray reflection nebulae</td>
<td>no</td>
<td>yes (long exposure)</td>
<td>yes</td>
</tr>
<tr>
<td>Fundamental Physics</td>
<td>QED (magnetar)</td>
<td>yes (better)</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td></td>
<td>GR (BH)</td>
<td>no</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td></td>
<td>QG (Blazars)</td>
<td>difficult</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td></td>
<td>Axions (Blazars, Clusters)</td>
<td>yes ?</td>
<td>yes</td>
<td>difficult</td>
</tr>
</tbody>
</table>

[IXPE/XIPE books]

### Secondary Information
- Diffraction on multilayer mirrors
- Photoelectric effect
- Compton scattering
Complex absorption versus strong gravity effects in AGN

Not everybody believes that we are really seeing relativistic reflection in AGN
Complex ionized absorption?

Polarimetry can tell (Marin et al. 2012, 2013)

Absorption scenario – clumpy wind:  
→ constant polarization degree and angle

Reflection scenario:  
→ energy dependent polarization degree and angle
What can we do with X-ray polarimetry?

2 – Radio-loud AGN and ULX

Active galaxies are powered by supermassive BHs with jets
- Radio polarization implies the magnetic field is aligned with jet
- Different models for electron acceleration predict different dependencies in X-ray polarization

Imaging **Centaurus A** allows to isolate other sources in the field (2 ULXs)
Magnetic cataclysmic variables

CV = accreting white dwarf
    = X-ray bright during active states

In magnetized systems, the accretion flow is confined by the magnetic fields near the WD (Warner 1995)

If strong mag. fields, cyclotron cooling is very efficient
    → non isotropic Maxwellian distrib. of electron
    → Bremsstrahlung X-rays intrinsically polarized

If high accretion rate, $\tau$ accretion column is high
    → Compton scattering (polarization)

Photons escaping from the base of the accretion column should be less polarized than those that scatter several times.
Magnetic cataclysmic variables

- $M_{\text{WD}} = 0.5$ Msol
- $r_{\text{acc}} = 10$ g/cm$^2$/s
- Cycl/Brems cooling rate = 0 and 10

Cooling rate unlikely important

Polarization up to 8% (may vary with rotation phase)
  → Sensitive to density structure

McNamara et al. (2008)
Magnetic cataclysmic variables

BL Lac objects, OVV : parsec-scale jets (b ~ 0.995)

X-ray spectrum steeper than optical spectrum
   → X-ray produced by accelerated, high energy e⁻ (base of the jet ? Shocks ?)

3 scenarios: disk/Compton, CMB or SSC ?
   → constrains on the directionality of the magnetic field

<table>
<thead>
<tr>
<th>i</th>
<th>P (per cent)</th>
<th>Average number of scatterings per photon</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(E = 1–10 keV)</td>
<td></td>
</tr>
<tr>
<td>10°</td>
<td>3.2</td>
<td>3.0</td>
</tr>
<tr>
<td>45°</td>
<td>14.0</td>
<td>2.8</td>
</tr>
<tr>
<td>80°</td>
<td>20.6</td>
<td>2.8</td>
</tr>
</tbody>
</table>

Relativistic jet
- central BH 10⁶ Msol
- jet Lorentz factor 5
- jet opening angle 11°
- Accr. rate 0.1 Msol/yr
- z = 2
- 50% conversion accr/jet

McNamara et al. (2009)
Magnetic cataclysmic variables

BL Lac objects, OVV: parsec-scale jets (b ~ 0.995)

X-ray spectrum steeper than optical spectrum
  → X-ray produced by accelerated, high energy e⁻ (base of the jet? Shocks?)

3 scenarios: disk/Compton, CMB or SSC?
  → constrains on the directionality of the magnetic field

<table>
<thead>
<tr>
<th>( i )</th>
<th>( P(\text{per cent}) ) ((E = 1-10 \text{ keV}))</th>
<th>( \text{Average number of scatterings per photon} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>10°</td>
<td>4.2</td>
<td>3.2</td>
</tr>
<tr>
<td>45°</td>
<td>16.5</td>
<td>2.6</td>
</tr>
<tr>
<td>80°</td>
<td>23.9</td>
<td>3.2</td>
</tr>
</tbody>
</table>

Relativistic jet
- central BH \(10^8\) Msol
- jet Lorentz factor 5
- jet opening angle 11°
- Accr. rate \(0.1\) Msol/yr
- \( z = 2 \)
- 50% conversion accr/jet

\[ \text{McNamara et al. (2009)} \]
Magnetic cataclysmic variables

BL Lac objects, OVV: parsec-scale jets ($b \sim 0.995$)

X-ray spectrum steeper than optical spectrum
  $\rightarrow$ X-ray produced by accelerated, high energy $e^-$ (base of the jet? Shocks?)

3 scenarios: disk/Compton, CMB or SSC?
  $\rightarrow$ constrains on the directionality of the magnetic field

Relativistic jet
- central BH $10^8$ Msol
- jet Lorentz factor 5
- jet opening angle 11°
- Accr. rate 0.1 Msol/yr
- $z = 2$
- 50% conversion accr/jet

**Figure 6.** Polarization degree $P$ of SSC photons with energies between 1 and 10 keV plotted as a function of the inclination angle $i$. The solid line is for the case where the seed photons are emitted uniformly throughout the jet (uniform $\zeta$). The dashed and dotted lines are for the cases where the seed photons are emitted at the jet base ($\zeta = 0$) and in the middle of the jet ($\zeta = 0.5$).

McNamara et al. (2009)
What can we do with X-ray polarimetry?

2 – Emission in strong magnetic fields

Isolated neutron stars and X-ray binaries are perfect targets since they are bright sources.

The radiation emergent from atmospheres of neutron stars with strong magnetic fields is expected to be strongly polarized (~10% – 30%).

Depends on:
- photon energy
- effective temperature
- magnetic field

Polarimetry is more sensitive than spectroscopy to magnetic fields!

The shape of polarization pulse profiles depends on the orientation of the rotational and magnetic axes.

+ polarization substantially modified by general relativistic effects
  → X-ray polarization as a new method for evaluating the mass-to-radius ratio of NS

Pavlov & Zavlin (2000)
**Future instruments**

**enhanced X-ray Timing and Polarimetry (eXTP):**
Chinese + Italian (polarimetric detectors) mission

enhanced version of the XTP mission which, in 2011, has been selected and funded for Phase 0/A as one of the background concept missions in the Strategic Priority Space Science Program of the Chinese Academy of Sciences

Launch > 2025

→ simultaneous spectral-timing-polarimetry studies of cosmic sources in the energy range from 0.5-30 keV (and beyond)
enhanced X-ray Timing and Polarimetry (eXTP):

The scientific payload of eXTP consists of four main instruments:

- **Spectroscopic Focusing Array (SFA):** 9 X-ray optics (total eff. area ~0.9 m² @ 2 keV; 0.6 m² @ 6 keV), equipped with Silicon Drift Detectors offering <180 eV spectral resolution

- **Polarimetry Focusing Array (PFA):** 4 X-ray telescope (total eff. area 250 cm² @ 2 keV) equipped with imaging gas pixel photoelectric polarimeters

- **Large Area Detector (LAD):** a deployable set of 640 Silicon Drift Detectors (total eff. area ~3.4 m², 6 - 10 keV) for spectral resolution better than 250 eV

- **Wide Field Monitor (WFM):** 3 coded mask wide field units, equipped with position-sensitive Silicon Drift Detectors, each covering a 90 degrees x 90 degrees field of view
Polarization Spectroscopic Telescope Array (PolSTAR):
American mission

→ satellite-borne experiment measuring the linear polarization of X-rays in the energy range from 3-50 keV (requirement; goal: 2.5-70 keV)

The mission was proposed to NASA’s 2014 Small Explorer (SMEX) announcement of opportunity … but another polarimetric mission was selected (GEMS)

The PolSTAR design is based on the technology developed for the Nuclear Spectroscopic Telescope Array (NuSTAR) mission launched in June 2012 (same X-ray optics, extensible telescope boom, optical bench, and CdZnTe detectors)
Future instruments

Polarization Spectroscopic Telescope Array (PolSTAR):

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Requirement</th>
<th>Current Best Estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Telescope bandpass (keV)</td>
<td>3-50</td>
<td>2.5-70</td>
</tr>
<tr>
<td>Telescope effective area (effective # of NuSTAR optics)</td>
<td>≥ 0.9</td>
<td>1.1</td>
</tr>
<tr>
<td>Energy resolution (FWHM at 6 keV)</td>
<td>≤ 1 keV</td>
<td>0.45 keV</td>
</tr>
<tr>
<td>Absolute timing accuracy (msec)</td>
<td>≤ 15</td>
<td>2</td>
</tr>
<tr>
<td>Angular resolution (half power diameter; arc-sec)</td>
<td>≤ 80</td>
<td>60</td>
</tr>
<tr>
<td>Pointing, during science portion of orbits (99.7% CL)</td>
<td>≤ 62'' from stick center</td>
<td>17'' from stick center</td>
</tr>
<tr>
<td>Instrument reconstructed pointing knowledge (99.7% CL)</td>
<td>≤ 15''</td>
<td>8''</td>
</tr>
<tr>
<td>Minimum Detectable Polarization (3-15 keV; 25 ks obs’n of 1 Crab source; 99% CL)</td>
<td>≤ 1%</td>
<td>0.5%</td>
</tr>
<tr>
<td>Polarization fraction systematic error (3-15 keV; 99.7% CL)</td>
<td>≤ 1.5%</td>
<td>0.25%</td>
</tr>
<tr>
<td>Polarization angle systematic error (≥ 6% polarized source; 99.7% CL)</td>
<td>≤ 20°</td>
<td>2°</td>
</tr>
<tr>
<td>Bad pixel fraction</td>
<td>≤ 2%</td>
<td>1%</td>
</tr>
<tr>
<td>Instrument mass (kg)</td>
<td>≤ 170</td>
<td>131</td>
</tr>
<tr>
<td>Instrument power (W; orbital avg.)</td>
<td>≤ 45</td>
<td>28</td>
</tr>
</tbody>
</table>
The Polarised Gamma-ray Observer (PoGOLite): Swedish mission

X-ray telescope lifted to an altitude of ~40 km with an enormous helium-filled balloon (one million cubic metres)

→ The PoGOLite balloon experiment is designed to measure the polarization of soft gamma rays in the 20 keV-240 keV energy range (main targets: NS)

Several preliminary flights: 2011 (failure), 2013 (14 days duration was completed)

New design (2017): POGO+
→ With this new design, POGO+ is expected to reduce the MDP from 34.5% to 17.6% for a 6 hour Crab observation