Current Status of X-ray polarimetry

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with a large team of collaborators, IXPE and eXTP consortia

IXPE report on behalf of the IXPE Science Team

https://ixpe.msfc.nasa.gov/partners_sci_team.html

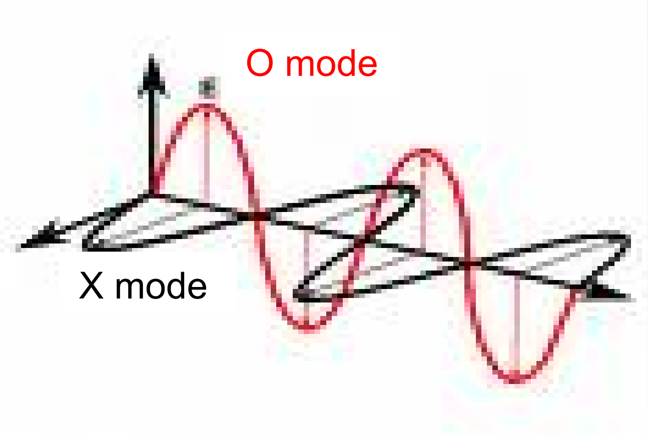
CTAO
Bologna, Italy
15-18 April 2024

With slides on courtesy of Giorgio Matt and Paolo Soffitta

INTRODUCTION: X-ray Polarimetry

Information on celestial (extra-solar) sources are mostly provided by electromagnetic radiation.

They can be obtained by studying the spatial, spectral, timing and *polarization* properties of the observed radiation.



In particular, the polarization properties give us information on *geometry* (in a broad sense: geometry of the emitting matter but also of magnetic and gravitational fields, of space-time, etc.). The polarization degree depends on the level and type of symmetry of the system, the polarization angle indicates its orientation.

Our knowledge of the emission from a celestial source in any energy band is therefore incomplete without polarimetry.

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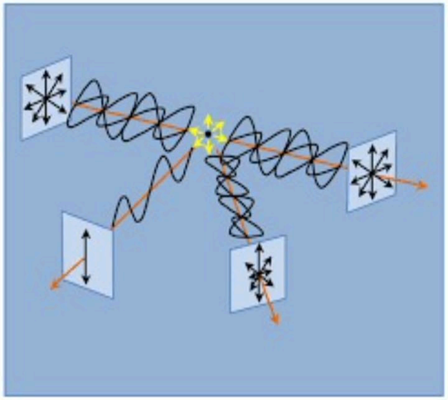
X-ray polarimetry

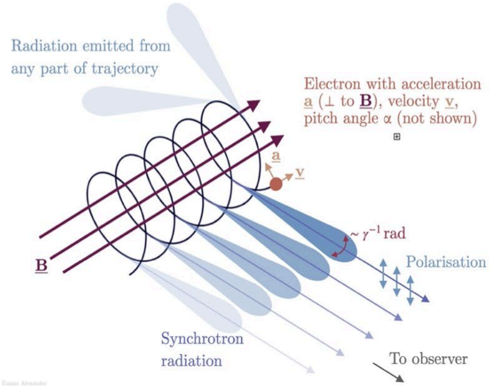
Polarization is a (pseudo) vector → measures geometry (of the emitting matter, the radiation field, the magnetic field, the space-time, …)

Scattering / reflection



EVPA perpendicular to scattering plane

Synchrotron radiation



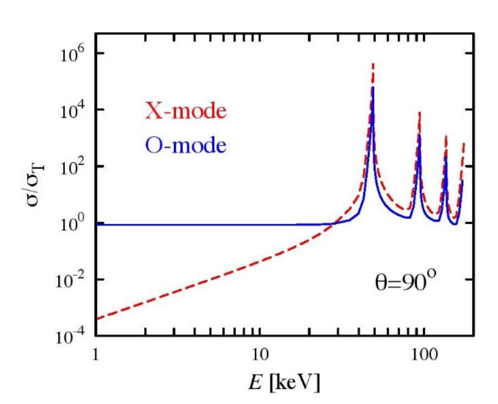
EVPA perpendicular to magnetic field lines

General relativity

$$\nabla_k f = 0$$

EVPA changes

Highly magnetized plasma



EVPA parallel or perpendicular to magnetic field lines depending on the dominant mode

EVPA = electric vector position angle

However, polarimetric information were basically missing in the X-ray band before IXPE!

THE CRAB NEBULA

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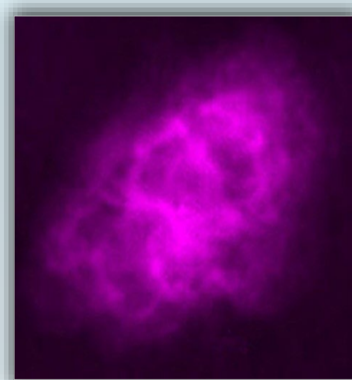
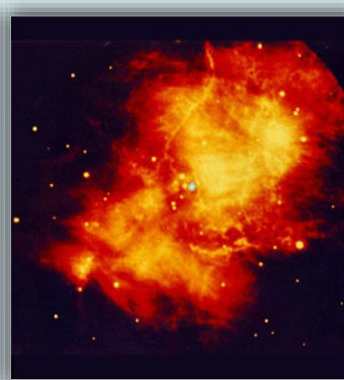
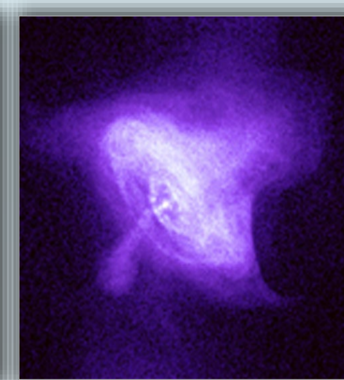


Radio (VLA)

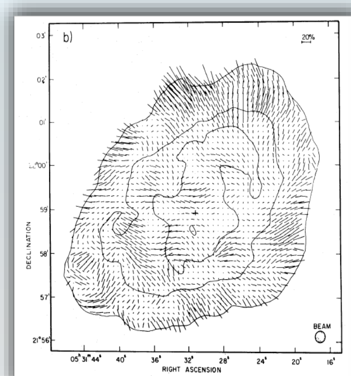


Infrared (Keck)

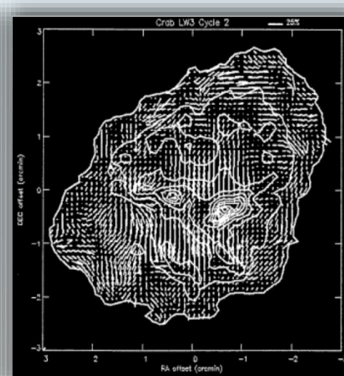
Optical (Palomar)



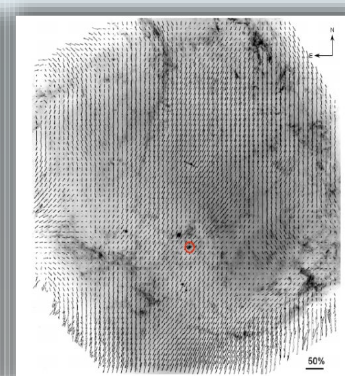
X-rays (Chandra)



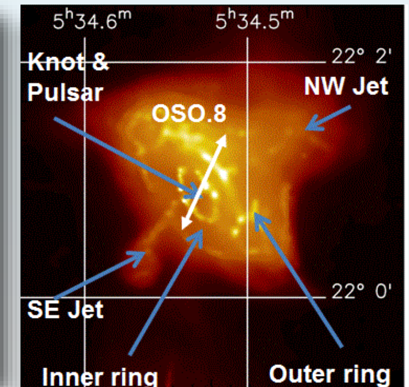
Radio polarisation



IR polarisation



Optical polarisation



X-ray polarisation

Only one positive measurement (Crab Nebula: 19%) in the X-ray band, dating back to the 70s (OSO-8)

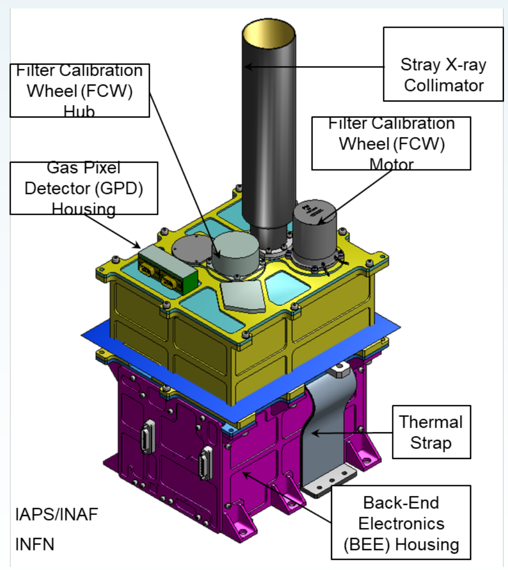
No X-ray polarimeters onboard X-ray satellites after OSO-8, due to lack of sensitive enough detectors

X-rays probe freshly accelerated electrons and their acceleration site

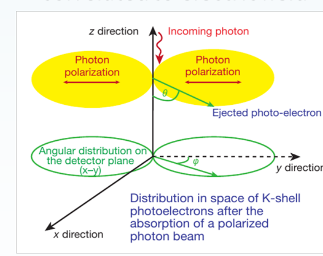
The lack, for many decades, of significant technical improvements implied that no polarimeters were put on board of X-ray satellites.

The situation has changed dramatically with the advent of polarimeters based on the photoelectric effect.

Such detectors, on the focal plane of a X-ray telescope, may provide meaningful measurements for hundreds of (bright) sources (remember that polarimetry is a photon hungry technique...).



- **Gas Pixel Detector (GPD)**
  - Polarization sensitive
    - Initial photoelectron direction correlated to electric field

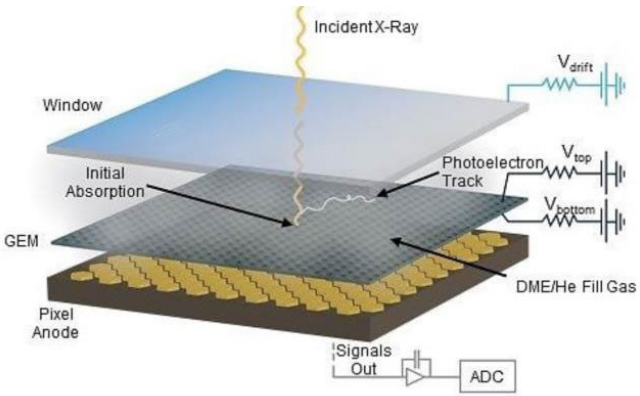


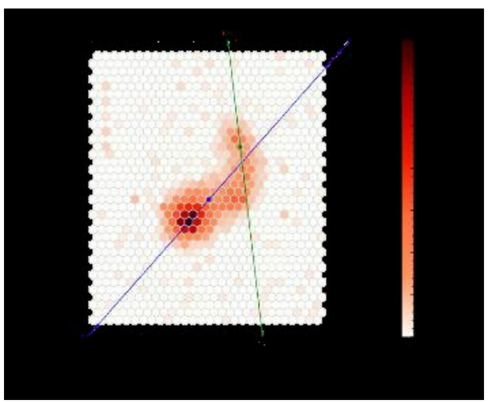
$$\frac{\partial\sigma}{\partial\Omega} = r_0^2 \frac{Z^5}{137^4}\left(\frac{mc^2}{h\nu}\right)^{7/2} \frac{4\sqrt{2}\sin^2(\theta)\cos^2(\varphi)}{(1-\beta\cos(\theta))^4}$$

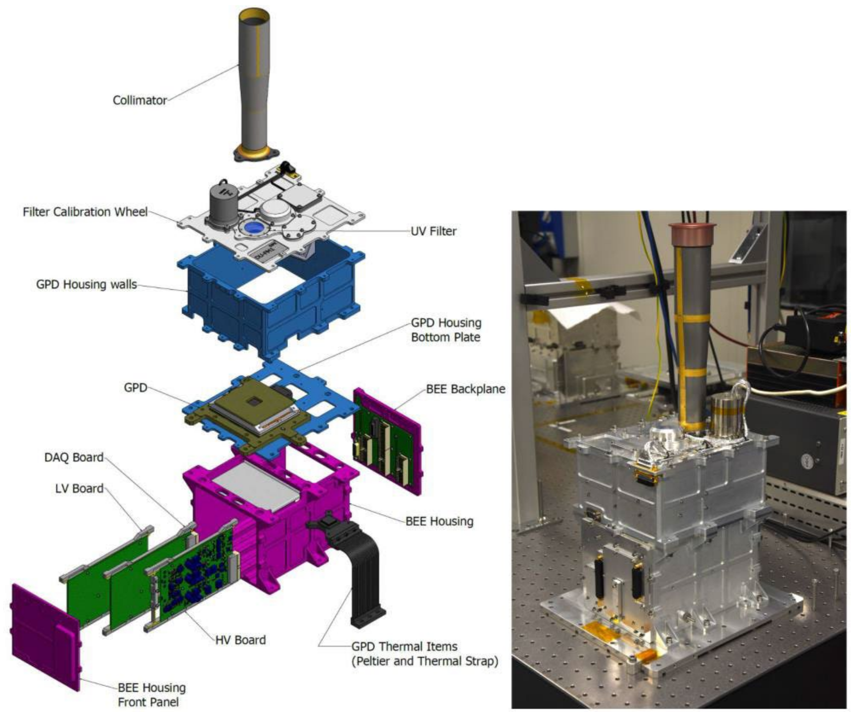
Pisa – INFN, IASF Rome (INAF)

Polarization Detection Principle

The detection principle is based on the photoelectric effect





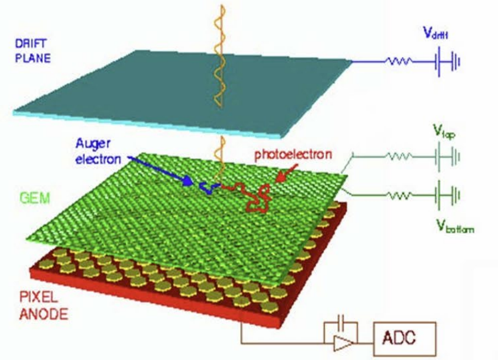


(a) (b)

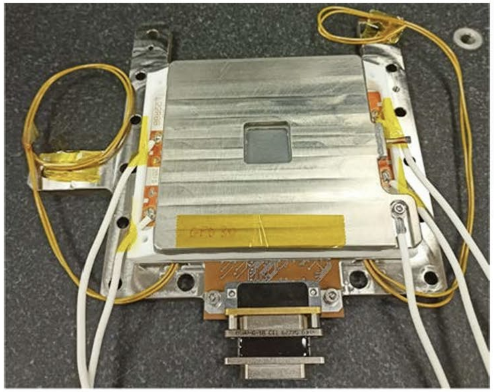
The distribution of the photoelectron initial directions determines the degree of polarization and the position angle

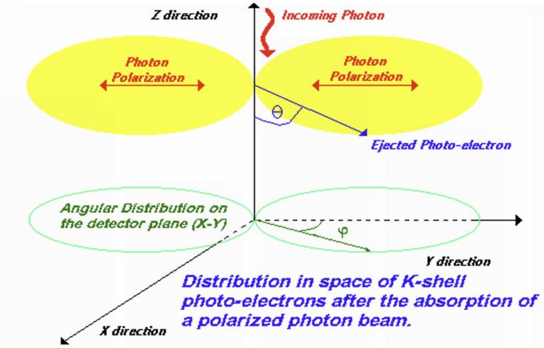
Proposed missions to date

Mission	Date	PI
XMM	Late 80'	G.W. Fraser (UK)
SXRP /SRG	Late 80' Early 00'	R.Novick (USA)
XEUS/IXO	2007-2012	R. Bellazzini (IT)
POLARIX	2007-2008	E. Costa (IT)
IXPE (OLD)	2007	M. Weisskopf (USA)
HXMT	2007-2009	E. Costa (IT)
NHXM	2011	G. Tagliaferri (IT)
LAMP	2013	H. Feng (China)
XIPE (Small)	2014	E. Costa (IT)
ADAELI+	2014	F. Berrilli (IT)
SEEPE (ESA-CAS)	2014	S.Liu-P. Soffitta
XIPE M4	2014-2017	P. Soffitta (IT)
IXPE	**2017+**	**M. Weisskopf (USA)**



Costa et al., 2001, Bellazzini et al, 2005,2006, Baldini et al., 2021, Soffitta et al. 2022





The Imaging X-ray Polarimetry Explorer (IXPE), selected in the NASA SMEX launched on 9 Dec 2021

IXPE can perform spectrally-, spatially- and time-resolved polarimetry of many cosmic sources. A breakthrough in astrophysics and fundamental physics

Equatorial Orbit 600 km altitude

IXPE mission description

- A NASA + ASI mission within the NASA’s Small Explorer Program (SMEX)
- Launch December 9, 2021 on a Falcon 9 from KSC

* 600-km circular orbit at a nominal 0° inclination
* 2-year baseline mission, optional extension with GO program
* Point and stare (with dither) at pre-selected targets
* Malindi ground station - primary (Singapore - secondary)
* Mission Operations Center (MOC) at the University of Colorado, Laboratory for Atmospheric and Space Physics (LASP)
* Sciences Operations Center (SOC) at MSFC
* Data archiving at NASA's HEASARC
    * During the first 3 months of the mission, including one month of orbital checkout, all IXPE data shall be made publicly available at the HEASARC within 30 days of the end of an observation, which is defined as when data for 90% of the scheduled observation time are received by the MOC.
    * After the first 3 months of the mission, data shall be made available to the HEASARC within 1 week of the end of an observation, which is defined as when data for 90% of the scheduled observation time are received by the MOC.

IXPE Team

Principal Investigator: M. C. Weisskopf (MSFC) Now Phil Kaaret

Co-Investigators: *Luca Baldini, Wayne Baumgartner, Stephen D. Bongiorno, Ronaldo Bellazzini, Enrico Costa, Jeffery Kolodziejczak, Luca Latronico, Herman Marshall, Giorgio Matt, Fabio Muleri, Stephen L. O'Dell, Brian D. Ramsey, Roger W. Romani, Paolo Soffitta, Allyn Tennant*

NASA Marshall Space Flight Center
PI team, project management, SE and S&MA oversight, mirror module fabrication, X-ray calibration, science operations, and data analysis and archiving

asi agenzia spaziale italiana
Detector system funding, ground station

Ball
Spacecraft, payload structure, payload, observatory I&T

iaps, INAF Istituto Nazionale di Astrofisica, National Institute for Astrophysics, INFN, OAC, OHB Italia
Polarization-sensitive imaging detector systems

CU, LASP
Mission operations

Roma Tre Università degli Studi, Stanford University
Scientific theory

McGill
Co-Investigator

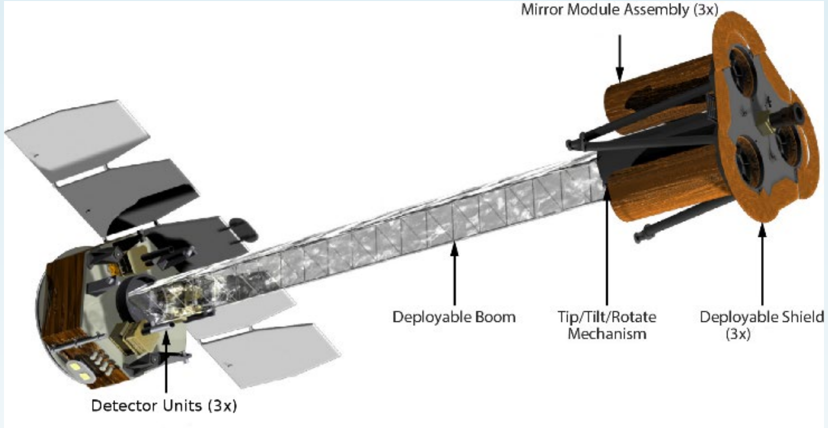
MIT Massachusetts Institute of Technology
Co-Investigator

Science Advisory Team

SAT currently comprises > 100 scientists from 12 countries

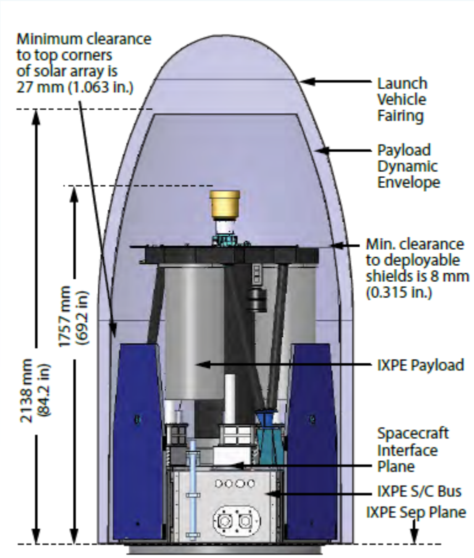
3x Telescopes

- 3x Mirror Units (MUs) + 3x Detector Units (Dus)
- A Detectors Service Unit (DSU) with built-in redundancy
- 4 m focal length, deployable boom and X-ray shield

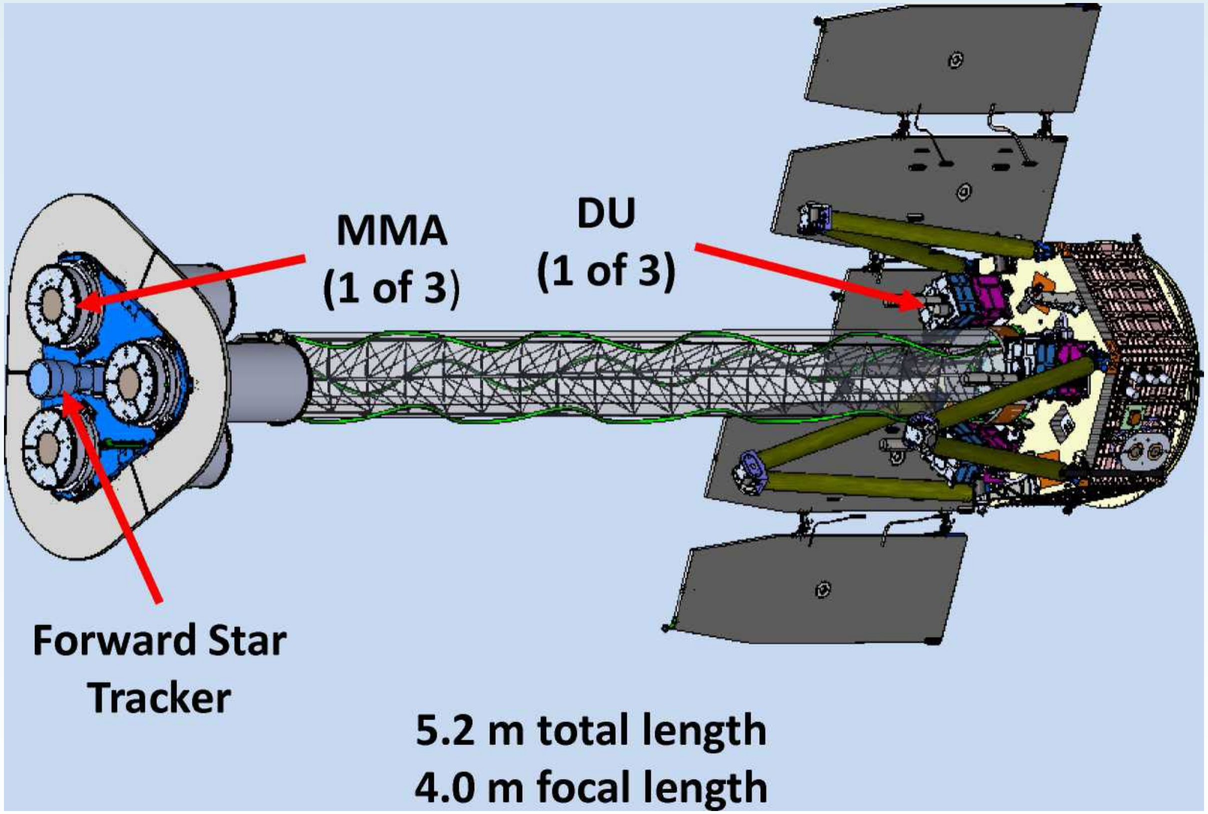


Performance

- Polarization sensitivity: $MDP_{99\%}$<5.5% in 1 day for flux of 10^{-10} ergs/cm^2/sec
- Energy range: 2-8 keV
- Limit polarization: 0.5% (degree), 1 degree (angle)
- Angular resolution: better than 30 arcsec, field of view larger than 9 arcmin
- UTC synchronization: better than 250 μs
- Energy resolution: better than 25%



IXPE deployed



Science Advisory Team (chaired by Giorgio Matt and Roger Romani) Coordinates science activities required for planning, analyzing, interpreting, and reporting IXPE observations

Organized into seven *Topical Working Groups*:

- *TWG1 Pulsar Wind Nebulae, led by Niccolò Bucciantini (INAF-Arcetri)*

  Obtain polarimetric imaging to constrain the magnetic-field geometry of the nebula and the phase-dependent polarization of the pulsar
- *TWG2 Supernova Remnants, led by Pat Slane (CfA)*

  Obtain spectral polarimetric imaging of Supernova Remnants (SNR) to constrain the magnetic-field structure of the X-ray emitting regions
- *TWG3 Accreting Black Holes, led by Michal Dovčiak (CAS-ASU)*

  Obtain spectral polarimetry of microquasars to constrain the value of the black-hole spin parameter (if in soft state), or constrain the geometry of the corona (if in hard state)
- *TWG4 Accreting Neutron Stars, led by Juri Poutanen (Turku)*

  Obtain phase-dependent polarimetry of accreting X-ray pulsars (high-magnetic-field binaries) to constrain models and geometries for the pulsing emission. Obtain polarimetry of non pulsating accreting NS to constrain the geometry of the system
- *TWG5 Magnetars*, led *by Roberto Turolla (Uni Padua)*

  Obtain phase-dependent polarimetry of magnetars to constrain the effects of vacuum polarization (birefringence in a strong magnetic field)
- *TWG6 Radio-Quiet AGN & Sgr A, led by Frédéric Marin (Strasbourg)*

  Obtain polarimetry of RQ AGN to constrain the geometry of the emitting regions
- *TWG7 Blazars & Radio Galaxies, led by Alan Marscher (Boston U)*

  Obtain polarimetry of Blazars and RG to study jet emission

>60 sources observed

		Number of objects
TWG -1	5 PWNe and isolated pulsars	Crab PWN, Vela PWN, MSH 15-52, PSR B0540-69, G21.5
TWG-2	6 SNR	Cas A, Tycho's, NE SN 1006,RCW 86, RX J1713.7-3946, Vela Jr.
TWG-3	11 Accreting stellar-BH	Cyg X-1, 4U 1630-472, Cyg X-3, LMC X-1, 4U 1957-115, SS 433 Lobes, LMC X-3, SWIFT J1727.8-1613, 4U 1957+115, Swift J0243.6+6124, Swift J1727.8-1613
TWG-4	19 Accreting NS & WD	Cen X-3, Her X-1, GS1826-67, Vela X-1, Cyg X-2, GX 301-2, Xpersei, GX 9-9, 4U 1820, GRO J1008-57, XTE 1701-46, EXO 2030+375, LS V+44 17, GX 5-1, 4U 1624-49, Sco X-1, Cir X1, GX13+1, SMC X-1
TWG-5	4 Magnetars	4U 0142+61, 1RXS J170849, SGR 1806-20, 1E 2259+586
TWG-6	5 Radio-quiet AGN & 1 Sgr A*	MCG 5-23-16, Circinus Galaxy, NGC 4151, IC 4329 A Sgr A* Complex, NGC 1068
TWG-7	15 Blazars & radio galaxies	Cen A, S5-0716-714, 1ES 19-59-650, Mrk 421, BL Lac, 3C 454, 3C 273, 3C 279, Mrk 501,1ES 1959-650, BL-Lac, 1ES 0229-200, PG 1553 -113, S4 0954+65, 1E 2259+586,

Some sources have been revisited
Mrk 421, Mrk 501, BL Lac, Vela X1, Her X-1, MCG 5-23-16, Crab, MSH 15-52, Cyg X-1, Sgr A (complex), ….

About 50 % of the observed celestial sources displayed a polarization with at least 6 σ significance in the Quick Look Analysis (Integrating in time, energy and position performed for the first 2 years by Fabio Muleri) . Resolved analysis showed polarization on a much larger number of sources.

TOOs

IXPE is not a Swift like mission

- Time for a TOO is not earlier than about 3 working days after the proposal
- GRB 221009A was indeed a special case TOO was requested on 10-10-2022 at 16:48 UTC and started on 10-11-2023 at 23:34:28 UTC
- We expect to trigger about one TOO per months.
- After a ToO started, the object that was in the long term planning is somewhat 'lost' and there is some discretion if it will be recovered later in the schedule.

TOO (18 requested 11 performed)

- Cyg X-1 (TWG 3)
- 4U 1630-472 (TWG 3)
- XTE 1701-46 (TWG 4)
- GRB 221009A No TWG
- EXO 2030 + 375 (TWG 4)
- Cyg X-3 (TWG 3)
- LS V + 44 17 (TWG 4)
- 4U 1630-47 (TWG 3)
- Swift J0243.6+6124 (TWG 4)
- 1ES 1959+650 (TWG 7)
- Swift J1727.8-1613 x 2 (TWG 3)

Mission	Allowed Sun Angle (deg)
HST	60-180 (+/-30 deg)
IXPE	65-115 (+/-25deg)
NICER	45-180
NuSTAR	43-180
SWIFT	47-180
XMM	70-110 (+/-20deg)

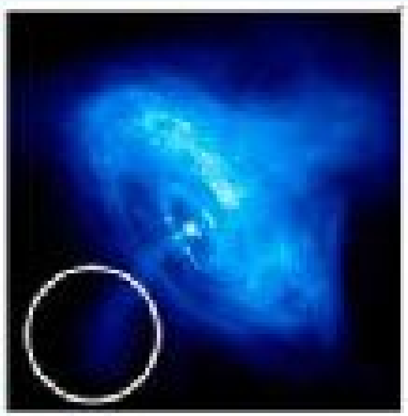
From HEASARC tools website

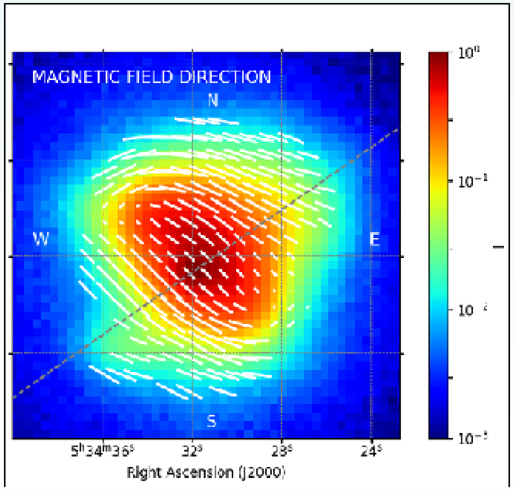
IXPE new allowed Sun Angle increased up to +/- 35 deg (50 % of accessible sky at any time)

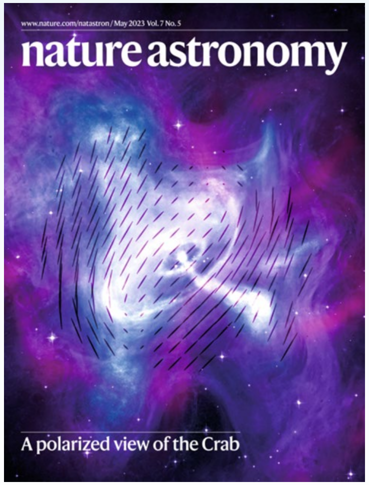
Pulsar Wind Nebulae

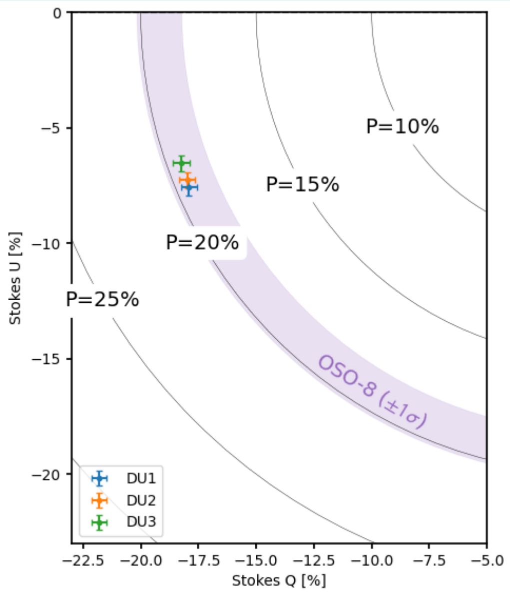
IXPE observations of PWN (Crab, Vela) confirmed they are highly polarized (very high in certain regions, close to the synchrotron limit) *(Bucciantini et al. 2022, Xei et al. 2022).*

Crab result consistent with OS0-8, when integrated over the entire nebula. However, polarization map shows a complex pattern, not surprisingly given the Chandra image

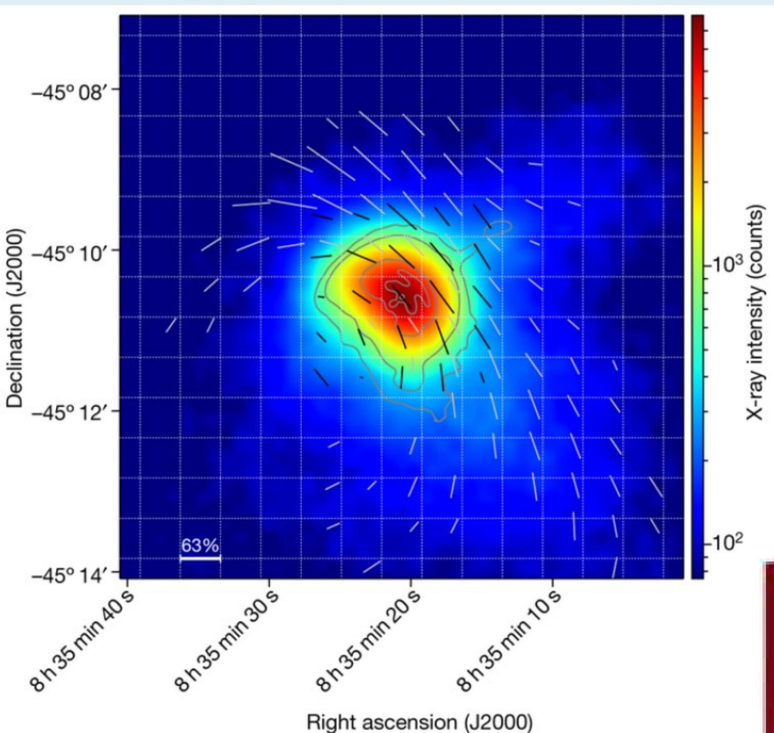








The Vela PWN

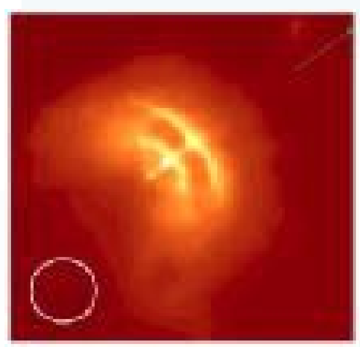


Average polarization of 45%, larger than 60% is some, small regions → close to the Synchrotron limit!

High polarization suggests B less turbulent than expected.

Polarization consistent with radio, but X-rays sample regions closer to the site of acceleration.

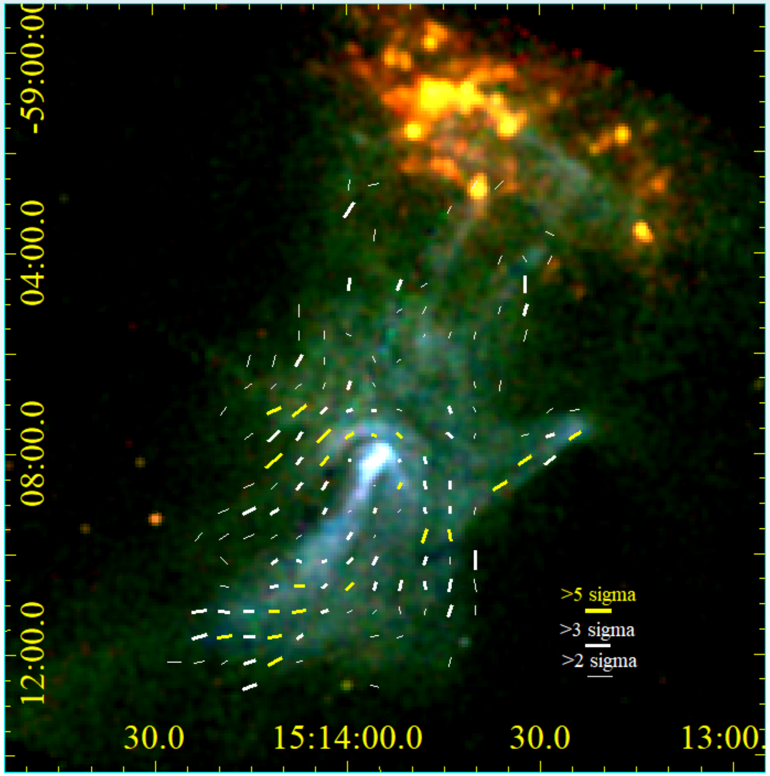
(Xie et al. 2022)



PWN: MSH 15-52 (Cosmic Hand)

Highly significant polarization in arcs and at the end the jet,with PD>70% *(Romani et al. 2023)*

Smaller polarization at the base of the jet, indicating a more complex magnetic field.



SuperNova Remnants

SNR much less polarized than PWN (not surprisingly, as emission is mostly thermal).

Analysis done in pixels and assuming circular symmetry.

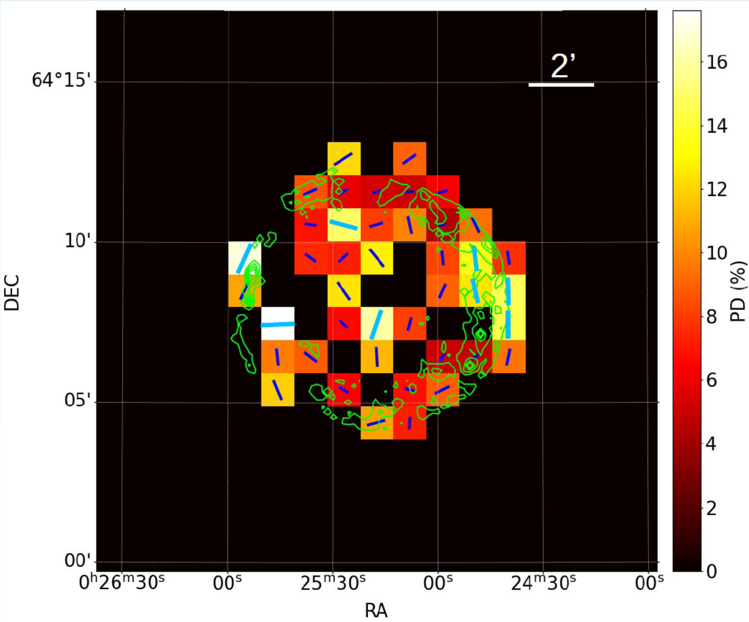
Corrected for thermal emission, PD are quoted for synchrotron component.

Both Cas A *(Vink et al. 2022)* and Tycho *(Ferrazzoli et al. 2023)* show radial magnetic fields near the shock.

Cas A has PD = (4.5±1.0)% near forward shock.

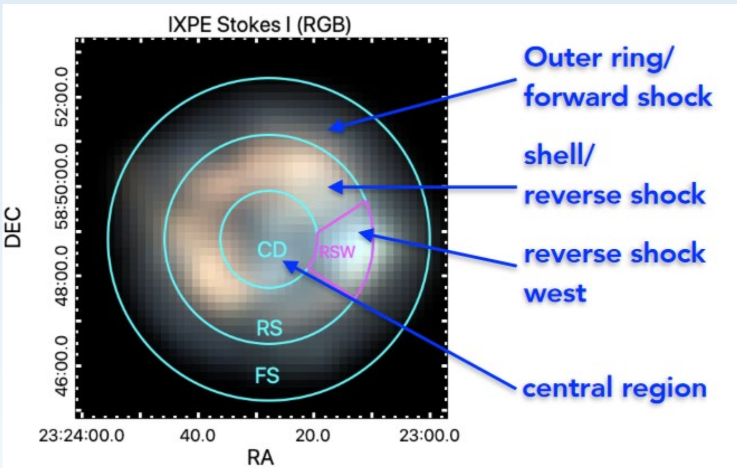
Tycho has PD = (12±2)% in rim. Tycho has factor 2 variations, (23±4)% in the west.

Compatible with turbulent, radial magnetic field near the shock.

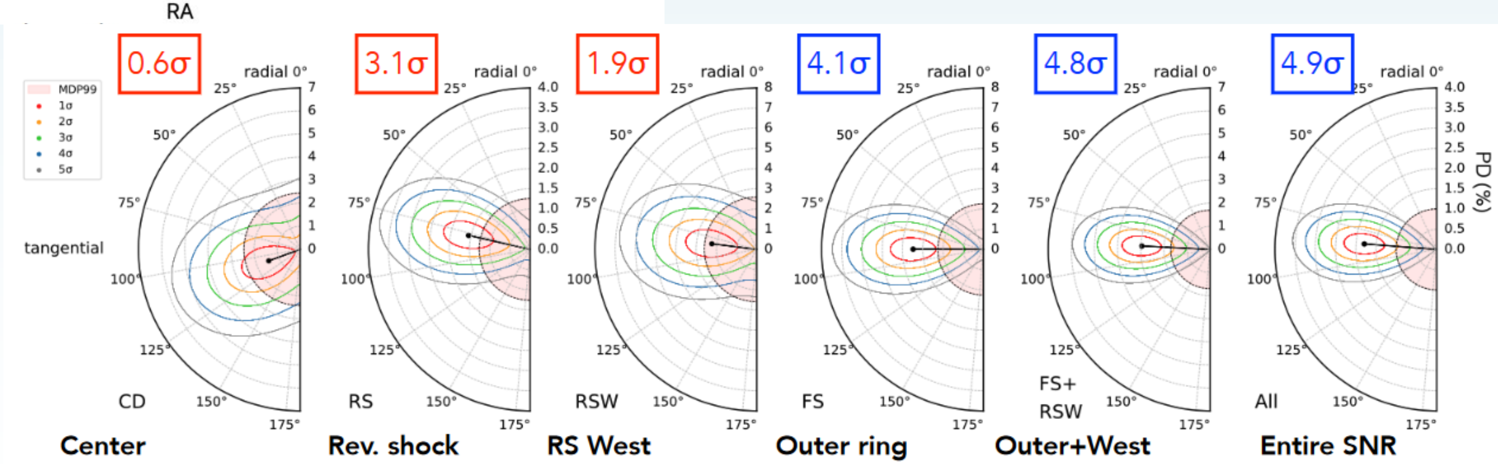


Ferrazzoli et al. 2023

SNR: Cas A



Polarization in the non-thermal emission is low
→ Turbulent magnetic field



SNR: Tycho

Qualitatively similar results for Tycho (i.e. radial magnetic field), but with larger polarization degrees, up to 23±4 % in the west region *(Ferrazzoli et al. 2023)*

→ Less turbulent magnetic field (or a larger maximum turbulence scale)

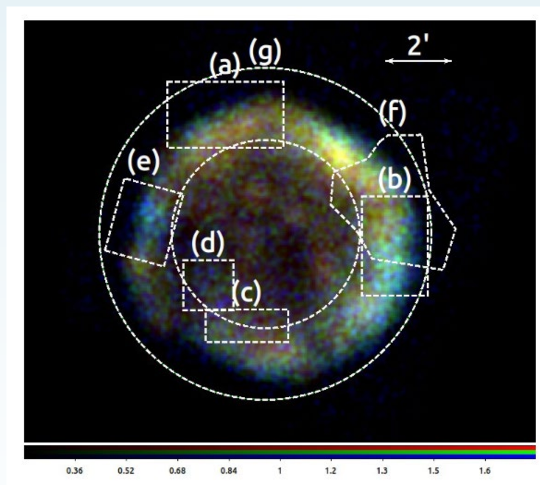
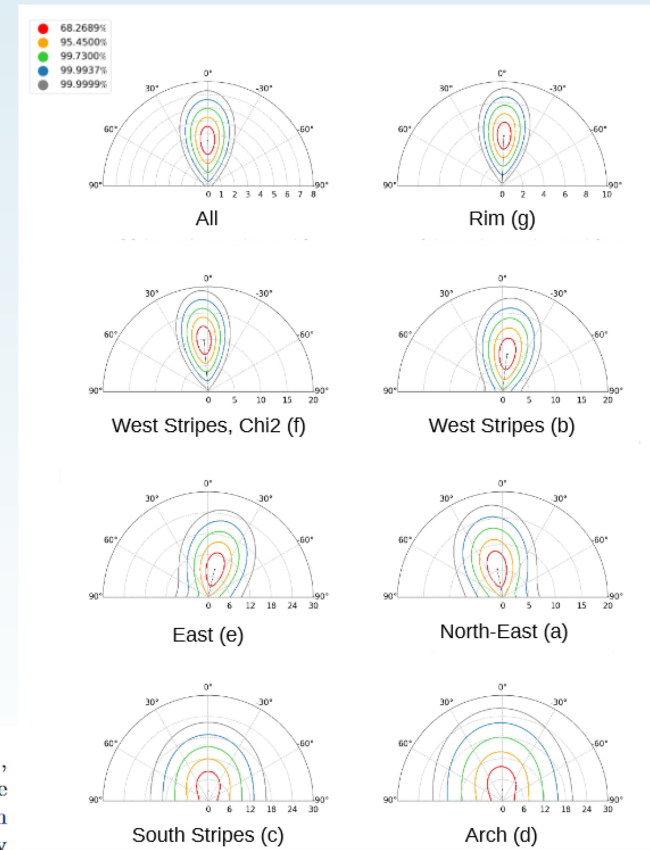


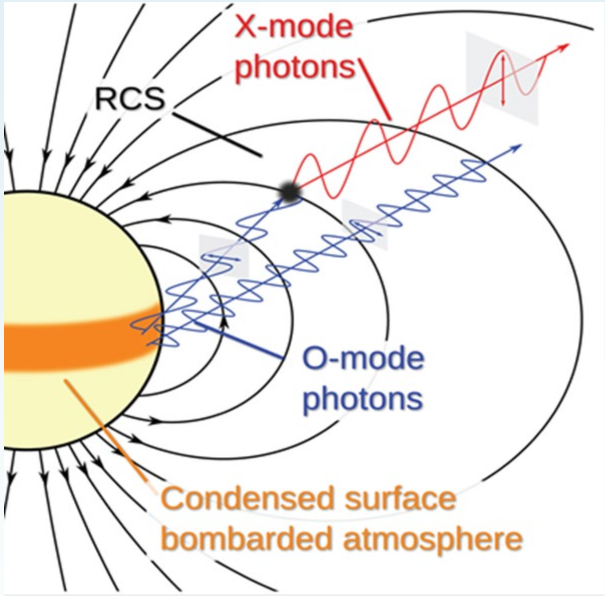
Figure 2. IXPE three color image of Tycho combined from the three detectors based on the 2–3 keV (red), 3–4 keV (green), and 4–6 keV (blue) bands. Superimposed are the regions considered in this work: the northeast (a), the west stripes (b), the south stripes (c), and the Arch (d) are the ones identified by Eriksen et al. (2011). The regions (e) and (f) are, respectively, the east knot and the west region where strong X-ray polarization is detected. Finally the region (g) identifies the rim and the entire SNR.



Magnetars

- **Anomalous X-ray Pulsars and Soft-gamma ray repeaters**
  - $B_{sd} \approx 10^{14} - 10^{15}$ G
  - $L_{X,\mathrm{persist}} \approx 10^{33} - 10^{35}\ \mathrm{erg\ s^{-1}}$ (typically $> \dot{E}_{\mathrm{rot}}$)
  - Bursting activity (short bursts – intermediate/giant flares)
  - Two components (thermal and PL or two thermals) spectra

  - **Powered by their own magnetic energy**



Taverna et al. 2022

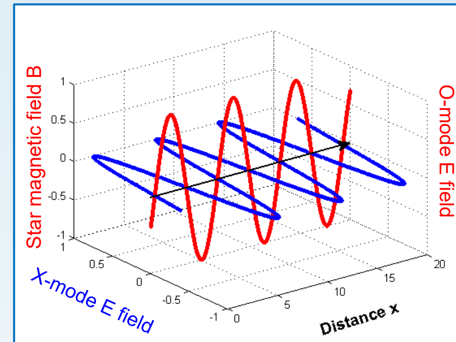
Magnetars

Two modes, with very different opacities

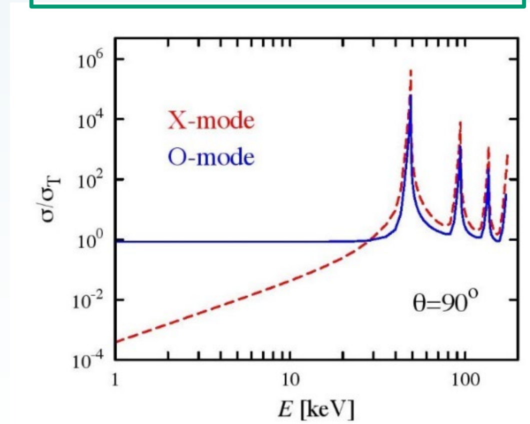
Ordinary mode: E field parallel to the k-B plane

Extraordinary mode: E field perpendicular to the k-B plane

The X-mode from deeper, hotter layers

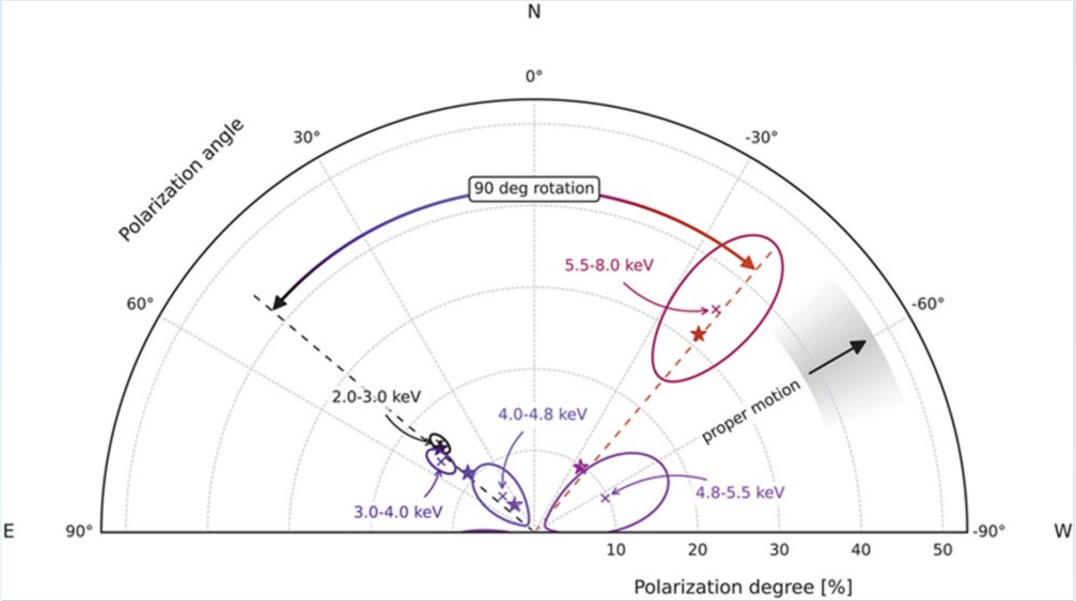


O-mode: the E-field oscillates in the k-B plane
X-mode: the E-field oscillates ⊥ to the k-B plane

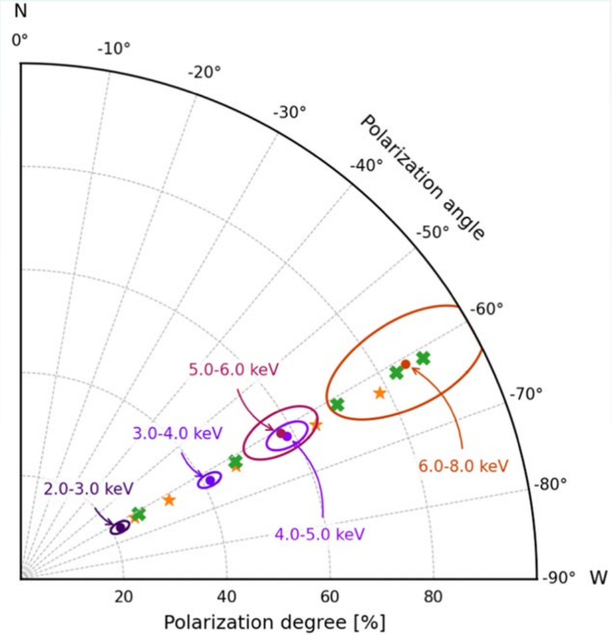


Magnetars

4U0142+61 shows PA swing of 90° (top) *(Taverna et al. 2022).* Two different modes dominate in the two components (Thermal + Resonant Compton Scattering). Low polarization indicates a condensed surface.



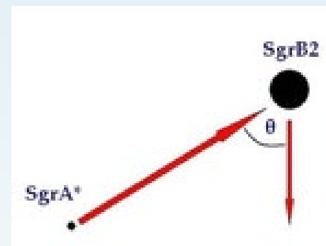
1RXS J170849.0-400910 has constant PA *(Zane et al. 2023).* The same mode is dominating in the two spectral components (both thermal). Pulse-phase-resolved data indicate condensed surface, plus a hotter cup covered by a gaseous atmosphere.

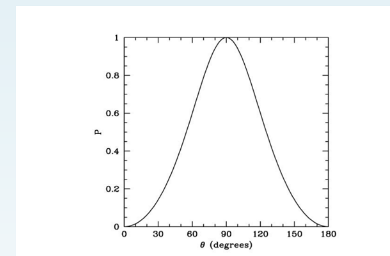


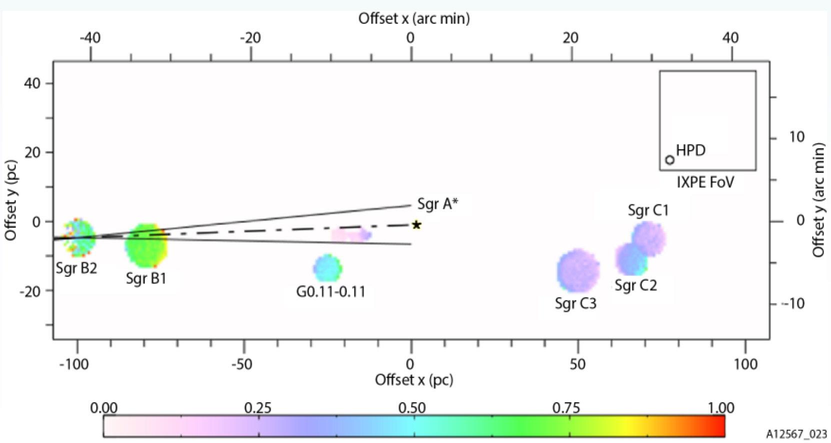
WAS THE GC ACTIVE A FEW CENTURIES AGO?

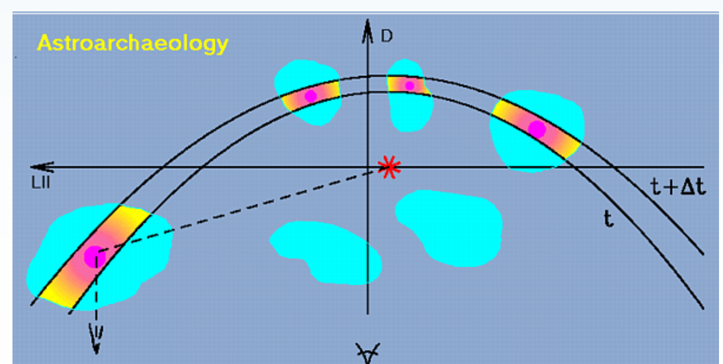
- **Galactic Center molecular clouds (MC) are known X-ray sources**

  - Are MCs reflecting X-rays from Sgr A* ? (supermassive black hole in the GC)
  - Sagittarius B2 (Sgr B2) is a giant molecular cloud of gas and dust that is located about 120 parsecs (390 ly) from the center of the Milky Way.
    - X-radiation would be *highly polarized* perpendicular to plane of reflection and indicates the direction back to Sgr A*
    - Sgr A* X-ray luminosity was 10^6 larger ≈ 300 years ago

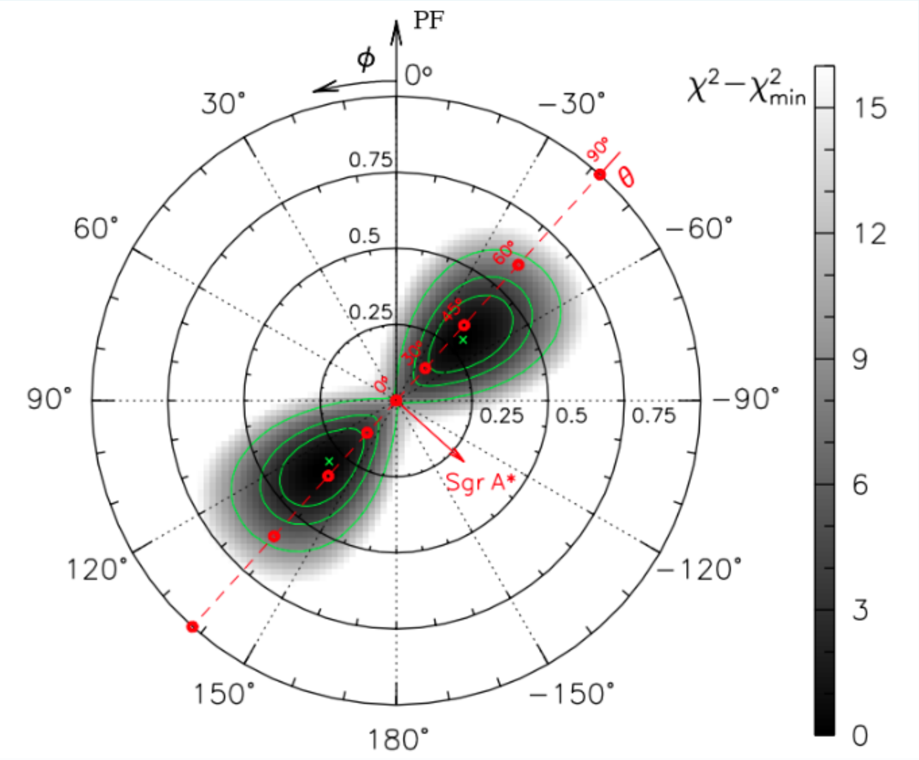








WAS THE GC ACTIVE A FEW CENTURIES AGO?



2.7σ result. Polarization angle consistent with Sgr A* as the origin of the illuminating radiation *(Marin et al. 2023)*

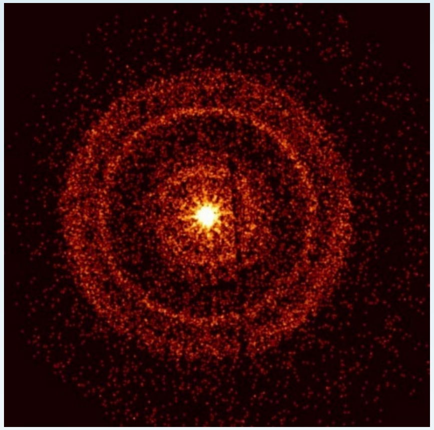
.

From the polarization degree, two solutions for the age of the burst: ~30 or ~200 years ago. Second solution much more probable.

GRB 221009A

IXPE did not plan to follow-up on GRBs, because of the relatively slow reaction time (2-3 days).

However, GRB 221009A (the 'BOAT' GRB – Brightest Of All Times) was so exceptional in terms of brightness, that it has been decided to observe it.

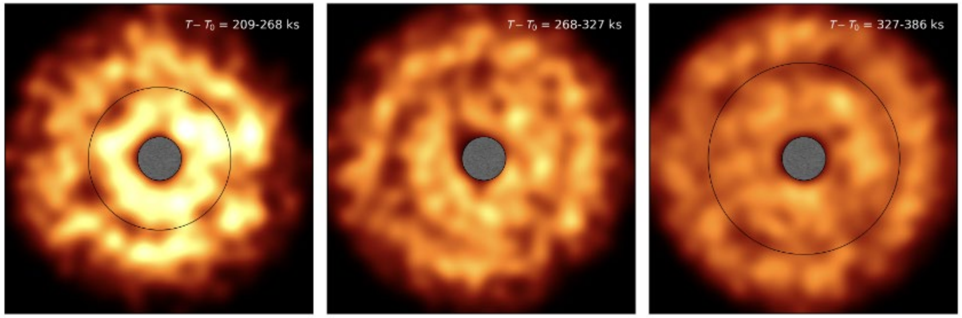


Swift/XRT image

P<13.8% (99% c.l.)

(Negro et al. 2023)

Dust rings also observed → polarization of the prompt emission (<55%)



Time evolution of dust rings as seen by IXPE

SOME IXPE RESULTS:

TWG 1: (Pulsar Wind Nebulae): The magnetic field is very ordered even at a large distance from the pulsar.

TWG 2: (Supernova Remnants): The magnetic field is radially directed even in vicinity of the shock.

TWG 3: (Accreting Black Holes): The corona in hard X-ray sandwiches the accretion disk and the lamp-post is excluded.

TWG 4: (Accreting Neutron Stars): The rotating vector model works in X-rays. The degree of polarization is 5-6 times smaller with respect to models predictions.

TWG 5: (Magnetars): Different magnetars showed unexpectedly very different behavior on the polarization degree and angle.

TWG 6: (Radio-Quiet AGN & SgrA clouds): Corona is sandwiching the disk. Lamp-post is excluded. Reflection confirms obscuring torus in Compton-thick AGNs. Molecular clouds points to Sgr A* as origin of their reflected emission.

TWG 7: (Blazars and Radio Galaxies): Energy stratified shock acceleration is confirmed. In X-ray fast rotation of the polarization vector with time is present in Synchrotron dominated blazars.

Conclusions

IXPE is really opening a new observing window!

As expected, significant polarization is rather common in X-ray sources

Not surprisingly, most of the detections are related to strong Magnetic Fields (PWN, SNR, Magnetars, X-ray Pulsars, Blazars)

But scattering polarization is also often detected! (e.g. coronal emission in X-ray binaries, reflection in obscured AGN, Sgr A*, …)

In many cases, results (even upper limits) are discriminating between competing models, or challenging popular ones

Results and proposed interpretations are published in so called ``discovery papers`` but in the next years we expect a ``flood`` of theoretical work and alternative interpretations: IXPE data are paradigm-shifting in many cases!

Where we are now:

Guest Observers Program

The IXPE baseline program endend at the end of January 2024.

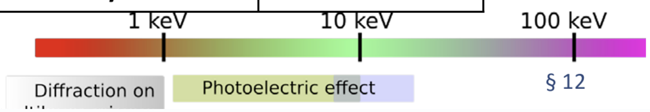
The next NASA senior review for mission extension is foreseen in 2025.

NASA asked us to submit a Mission Extension Request to extend the mission till September 2025 (a "bridge" extension). This request was approved in June 2023.

A General Observer Program has been then issued (deadline for Cycle 1 proposal was October 18, 2023; start of the GO Program: February 1, 2024).
Now we are awaiting for Cycle 2 (expected deadline Aug 2024, start of the programme Feb 2025)

WHY POLARIMETRY IN THE CLASSICAL X-RAY ENERGY BAND

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



In black potential studies not yet performed with IXPE data

OTHER MISSIONS :XPoSat

भारतीय अंतरिक्ष अनुसंधान संगठन, अंतरिक्ष विभाग
Indian Space Research Organisation, Department of Space
भारत सरकार / Government of India

Home | About | Activities | Services | Programmes | Resources | Engagements | search

Launch service
Satellite: system, bus, sub-system, testing
Mission support
Ground systems support
Space based Earth observation: Bhuvan & Bhoonidhi
Meteorological & Oceanographic Satellite Data
Disaster Management: National & International
North-East India region specific applications Services

X-ray Polarimeter Satellite (XPoSat)

Home /Activities/Science/X-ray Polarimeter Satellite (XPoSat)

XPoSat (X-ray Polarimeter Satellite) is India's first dedicated polarimetry mission to study various dynamics of bright astronomical X-ray sources in extreme conditions. The spacecraft will carry two scientific payloads in a low earth orbit. The primary payload POLIX (Polarimeter Instrument in X-rays) will measure the polarimetry parameters (degree and angle of polarization) in medium X-ray energy range of 8-30 keV photons of astronomical origin. The XSPECT (X-ray Spectroscopy and Timing) payload will give spectroscopic information in the energy range of 0.8-15 keV.

The emission mechanism from various astronomical sources such as blackhole, neutron stars, active galactic nuclei, pulsar wind nebulae etc. originates from complex physical processes and are challenging to understand. While the spectroscopic and timing information by various space based observatories provide a wealth of information, the exact nature of the emission from such sources still poses deeper challenges to astror
our understanding, the degree of
diagnostic tool to understand the
observations along with spectros
various theoretical models of astr
research from XPoSat by Indian sc

More Details
- PSLV-C58 / XPoSat Mission
- XPoSat
- Launch Streaming
- Brochure PDF - 12.3 MB
- Gallery
- Teaser Video

Launch 1 Jan 2024

First light from CAS A (SNR), 11 Jan 2024

POLIX validation with CRAB observations , 13 Feb 2024

XPoSat payloads:

1. POLIX

POLIX is an X-ray Polarimeter for astronomical observations in the energy band of 8-30 keV. The payload is being developed by Ramam Research Institute (RRI), Bangalore in collaboration with U R Rao Satellite Centre (URSC). The instrument is made of a collimator, a scatterer and four X-ray proportional counter detectors that surrounds the scatterer. The scatterer is made of low atomic mass material which causes anisotropic Thomson scattering of incoming polarised X-rays. The collimator restricts the field of view to 3 degree x 3 degree so as to have only one bright source in the field of view for most observations. POLIX is expected to observer about 40 bright astronomical sources of different categories during the planned lifetime of XPoSat mission of about 5 years. This is the first payload in the medium X-ray energy band dedicated for polarimetry measurements.

2. XSPECT

XSPECT is an X-ray SPECtroscopy and Timing payload onboard XPoSat, which can provide fast timing and good spectroscopic resolution in soft X-rays. Taking advantage of the long duration observations required by POLIX to measure X-ray polarization, XSPECT can provide long-term monitoring of spectral state changes in continuum emission, changes in their line flux and profile, simultaneous long term temporal monitoring of soft X-ray emission in the X-ray energy range 0.8-15 keV. An array of Swept Charge Devices (SCDs) provide an effective area >30 cm2 at 6 keV with energy resolution better than 200 eV at 6 keV. Passive collimators are used to reduce the background by narrowing the field of view of XSPECT. XSPECT would observe several types of sources viz X-ray pulsars, blackhole binaries, low-magnetic field neutron star (NS) in LMXBs, AGNs and Magnetars.

eXTP

An X-ray polarimeter similar to IXPE on-board the Chinese-led mission eXTP

eXTP (enhanced X-ray Timing and Polarimetry Mission). Proposed to CAS; selected in 2011 as one of 8 "background missions". P.I: Shuang-Nan Zhang (Tsinghua Univ.). An international consortium (China + many european countries). Launch: 2028+

Simultaneous spectroscopic, timing and polarimetric observations

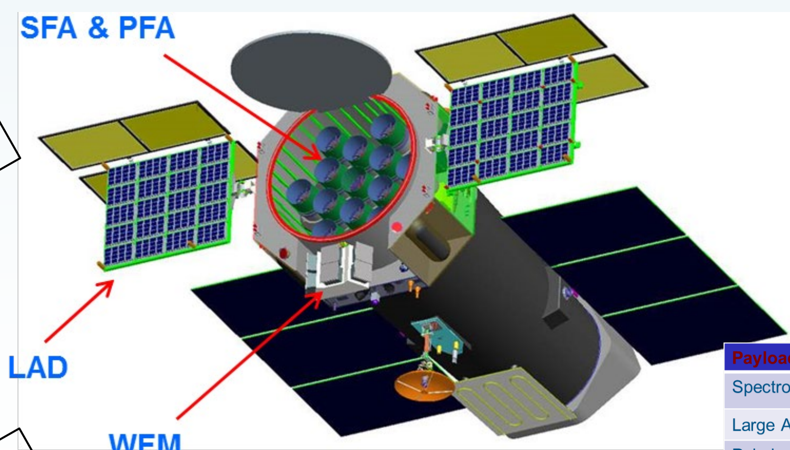
A **flagship astronomy mission** to explore **fundamental physics problems,** and to serve as a **powerful high energy observatory**

Soft Response

Polarization

Large area timing

Monitoring

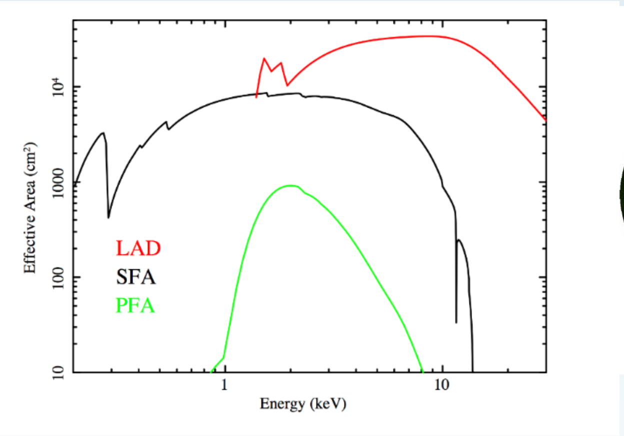


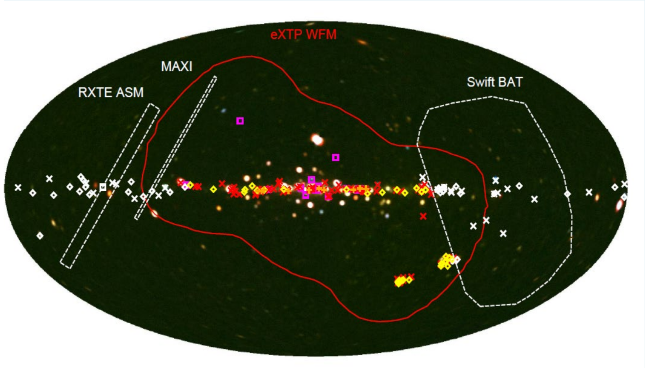
Wide energy range: 0.5-30 keV
Large eff. Area : ~4 m²@6keV
High spectr. res. <180eV@6keV
High throughput: max Flux 15 Crab

Payload	Configuration	Eff. area (m²)	Timing res. (μs)
Spectroscopic Focusing Array (SFA)	9 telescopes	~ 0.8 m²@1keV	10
Large Area Detector (LAD)	40 modules	~3.4 m²@2-10keV	10
Polarimetry Focusing Array (PFA)	4 telescopes	~900 cm²@2keV	500
Wide Field Monitor (WFM)	6 cameras	3.2 Sr （FOV）	10
Gamma Ray Burst Monitor (GRM) **(optional)!!!**	3 units		

	Payload	Parameter	Specification
Soft Response	SFA	Energy range	0.5-10 keV
		Effective area	>7000 cm^2 @1 keV, >5000 cm^2 @6 keV
		Energy resolution	<180 eV FWHM @6 keV
		FoV/HPD	12 arcmin / 1 arcmin
		Focal plane detector	Pixelated SDD (19 pixels)
Large area	LAD	Energy range	2-30 keV (extended: 30-80 keV for out-FoV)
		Effective area	34000 cm^2
		Energy resolution	<240 eV FWHM @6 keV
		FoV	1° (FWHM)
		Detector	Large area SDD (640 units, 40 Modules)
Polarization	PFA	Energy range	2-10 keV
		Effective area	>900 cm^2 @2 keV (including QE)
		Energy resolution	1.2 keV FWHM @6 keV
		FoV/HPD	12 arcmin / 20 arcsec
		Focal plane detector	GPD (4 units)
Monitoring	WFM	Energy range	2-50 keV
		Energy resolution	300 eV FWHM @6keV
		FoV	>4 sr (at 20% of peak response)
		Angular resolution	<5 arcmin
		Localization accuracy	<1 arcmin
		Detector	Large area SDD

eXTP Scientific Payload   Performance in context

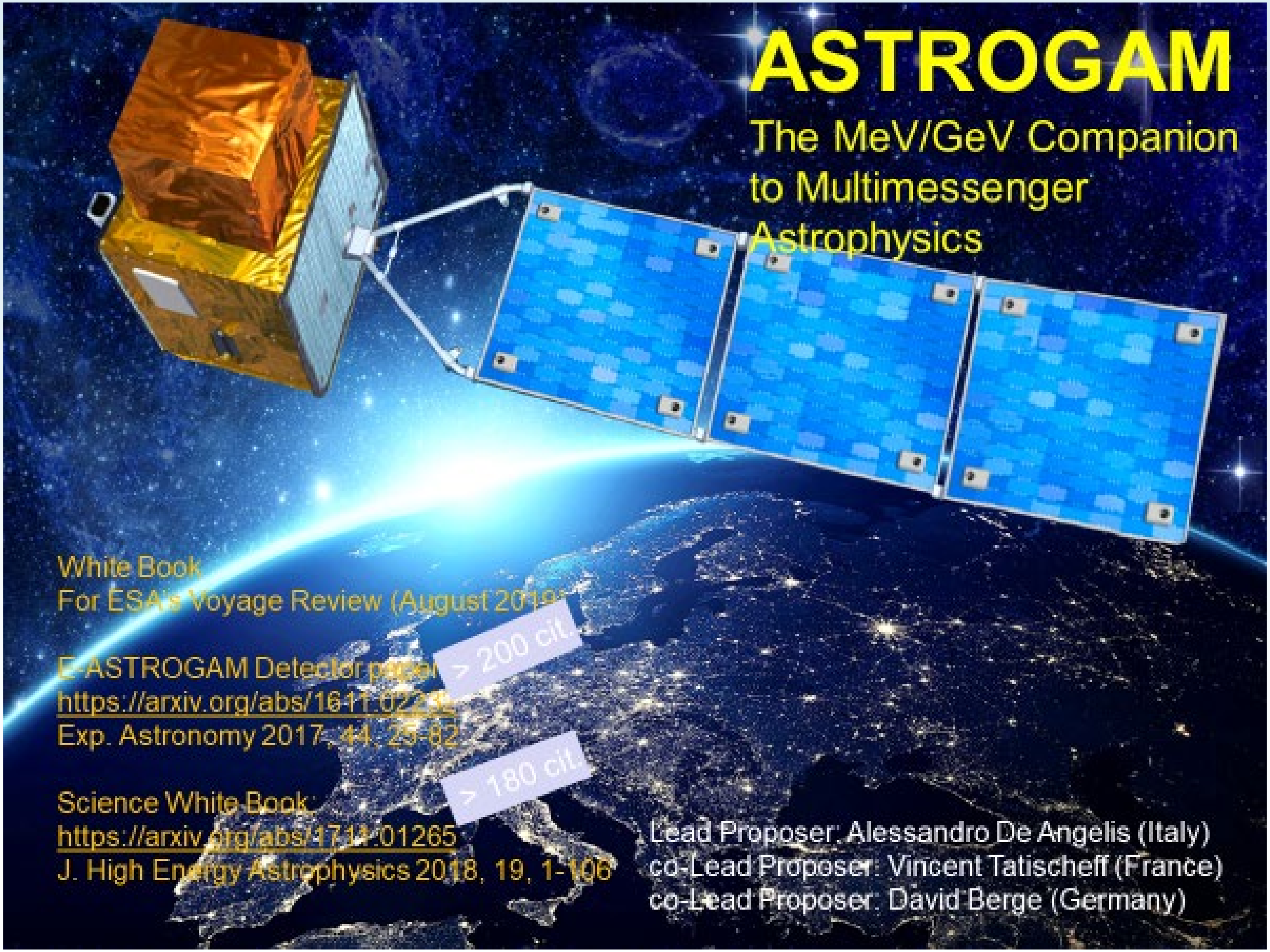




- **LAD: 6x RXTE/PCA, 35x XMM-Newton + hard-X response**
- **SFA: 8x XMM-Newton and 0.3-2x Athena/WFI .**

  Limiting sensitivity ~10^{-14}-10^{-15} erg cm^{-2} s^{-1}
- **PFA: 5xIXPE. Sensitivity: 1% MDP in 50ks for a 100 mCrab source**
- **WFM: largest FoV ever, first time with 300 eV resolution. 3 mCrab in 50ks**

ASTROGAM



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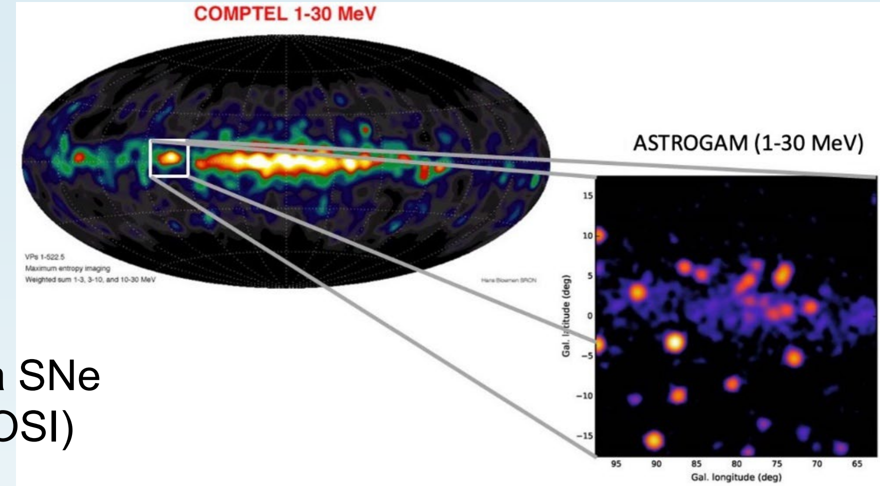
ASTROGAM

- Broad energy coverage (100 keV to 3 GeV), with one to two orders of magnitude improvement in continuum sensitivity in the range 0.1–100 MeV compared to previous instruments;

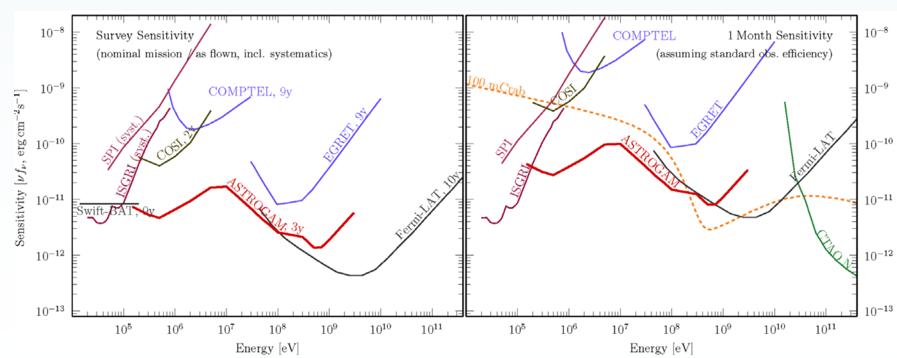


- Unprecedented performance for γ-ray lines, e.g. a sensitivity for the 847 keV line from Type Ia SNe 70 times better than INTEGRAL/SPI (5 times COSI) probing a 10 times larger volume;

- Large field of view (>2.5 sr), ideal to detect transient sources, i.e. about 300 GRBs per year,including about 70 short GRBs per year

- **Pioneering polarimetric capability for both steady and transient sources;**

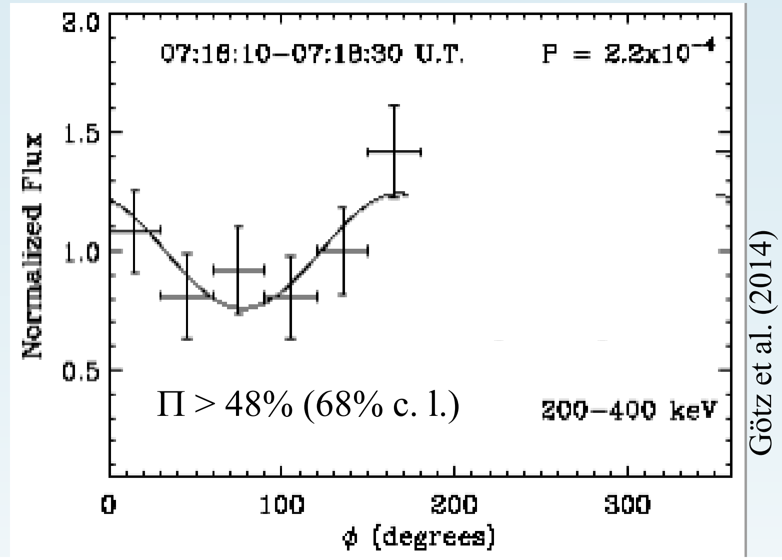
- Improved angular resolution
- Sub minute alert capability for GRBs and other transients.

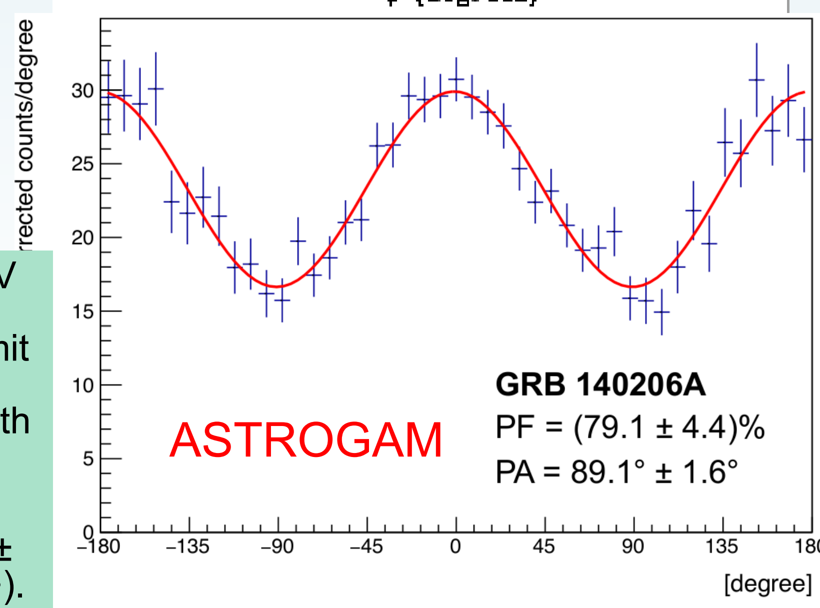


ASTROGAM : Power of Polarization

- Study **objects emitting jets** (GRBs, blazars, X-ray binaries) or with **strong B-field** (pulsars, magnetars)
  - Physics of **ultra-relativistic jets** and emission mechanism (determine the radiation process, constrain the magnetic geometry in the jet and the width … competing models predict different levels of linear polarisation at energies above 1 MeV)
  - Shed new light on the process of **pair cascades** in **pulsar magnetospheres**

INTEGRAL/IBIS – GRB 140206A ($z = 2.74$)





Example: the simulated signal modulation in the 100–500 keV range for a GRB similar to GRB 140206A (at redshift z = 2.739) detected with INTEGRAL (Gotz et al). Only a lower limit to the polarisation fraction of 48% (at the 68% confidence level) could be derived from the INTEGRAL data, together with a polarisation angle of 80◦ ± 15◦

For such a burst ASTROGAM will be able to very accurately measure the polarisation fraction (reconstructed PF= 79.1% ± 4.4%) and polarisation angle (reconstructed PA= 89.1◦ ± 1.6◦).

PHEMTO

Experimental Astronomy (2021) 51:1143–1173
https://doi.org/10.1007/s10686-021-09723-x

ORIGINAL ARTICLE

PHEMTO: the polarimetric high energy modular telescope observatory

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Abstract
Based upon dual focusing techniques, the Polarimetric High-Energy Modular Telescope Observatory (PHEMTO) is designed to have performance several orders of magnitude better than the present hard X-ray instruments, in the 1–600 keV energy range. This, together with its angular resolution of around one arcsecond, and its sensitive polarimetry measurement capability, will give PHEMTO the improvements in scientific performance needed for a mission in the 2050 era in order to study AGN, galactic black holes, neutrons stars, and supernovae. In addition, its high performance will enable the study of the non-thermal processes in galaxy clusters with an unprecedented accuracy.

Keywords X–/γ–ray focussing telescopes · Space mission concept · ESA voyage 2050 · Active Galactic Nuclei · Supernovae and supernovae remnants · Non-thermal emission · Clusters of galaxies · Magnetic field · Accretion/ejection phenomena · Galaxy clusters

1 Introduction

With the opening of the X and gamma–ray windows in the sixties, thanks to sounding rockets and satellite-borne instruments, extremely energetic and violent phenomena

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Springer

PHEMTO
Polarimetric High Energy Modular Telescope Observatory

Laurent P. et al.

August 2019

White Paper submitted to ESA Voyage 2050 Call

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DESIDERATA FOR A FOLLOW-UP MISSION

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ORIGINAL ARTICLE

A polarized view of the hot and violent universe

Paolo Soffitta, et al. *[full author details at the end of the article]*

Received: 27 July 2020 / Accepted: 2 March 2021 / Published online: 10 May 2021

Abstract
X-ray polarimetry has long been considered the 'holy grail' of X-ray astronomy. Fortunately, after a silence of more than 40 years, the field is now rejuvenating. In fact, an X-ray polarimeter onboard a Cube-sat nano-satellite has been recently successfully operated. IXPE, the Imaging X-ray Polarimetry Explorer, will be launched in 2021 while eXTP, containing a larger version of IXPE, is expected to be launched in 2027. Although at present it is difficult to predict the discoveries that, given their exploratory nature, IXPE and eXTP will obtain, the path for a follow-up mission can already be envisaged. In this paper we describe the scientific goals of such a follow-up mission, and present a medium-size mission profile that can accomplish this task.

Keywords Astrophysics · X-rays · Polarimetry

1 Introduction

Since the birth of X-ray astronomy, spectacular advances have been seen in the imaging, spectroscopic, and timing studies of the hot and violent X-ray Universe, and further leaps forward are expected in the future with the launch in the early 2030s of ESA's L2 mission, Athena. One technique, however, is still lagging behind: polarimetry. In fact, after the measurement, at 2.6 and 5.2 keV, of the 19% average polarization of the Crab Nebula and a tight upper limit of about 1% to the accreting neutron star Scorpius X-1 (not surprisingly, the two brightest X-ray sources in the sky), obtained by OSO-8 in the 70s, no more observations have been performed in the classical X-ray band, even if some interesting results have been obtained in hard X-rays by balloon flights like POGO+ [1–4] and X-Calibur [5, 6], and in soft gamma-rays by INTEGRAL [7–9], Hitomi [10], and AstroSAT [11]. The lack of polarimetric measurements implies that we are missing vital physical and geometrical information on many sources which can be provided by the two additional quantities polarimetry can provide: the polarization degree, which is related to the level of asymmetry in the systems (not only in the distribution of the emitting matter, but also in the magnetic or gravitational field), and the polarization angle, which indicates the main orientation of the system.

Fortunately, in 2021 the NASA/ASI mission IXPE (Imaging X-ray Polarimetry Explorer mission, [12]) will re-open the X-ray polarimetry window. IXPE will provide for the first time imaging X-ray polarimetry in the 2–8 keV band thanks to its

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A Polarized View of the Hot and Violent Universe

A White Paper for the Voyage 2050 long-term plan in the ESA Science Programme

Contact Scientist: **Paolo Soffitta**

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ESA VOYAGE 2050

The Rocket Experiment Demonstration of a Soft X-ray Polarimeter — REDSoX*

Herman L. Marshall, Sarah Heine, Alan Garner, Rebecca Masterson, Moritz Günther, Ralf Heilmann (MIT), Steve Bongiorno (MSFC), Eric Gullikson (LBNL)

*Used with permission of the Red Sox and Major League Baseball.

Rocket Experiment Demonstration of a Soft X-ray Polarimeter

REDSoX*, A Sounding Rocket Payload in Development

- **PI**: Herman L. Marshall (MIT Kavli Institute)
- **Co-Is**
  - MIT: Sarah Heine (DPI), Sean MacNeil (PE), Alan Garner (PM), Moritz Günther
  - MSFC: Steve Bongiorno
  - LBNL: Eric Gullikson
- **Goals**:
  - 1- Prototype a soft X-ray polarimeter for an orbital mission (GOSoX)
  - 2- Train early career researchers

Key Facts of the REDSoX* Polarimeter:

- **Science**: 0.18-0.40 keV polarimetry of a BL Lac object, isolated neutron star or pulsar, to determine magnetic fields where X-rays are produced, and observe the effects of vacuum birefringence
- **Status**:
  - Developed a rotatable, polarized X-ray source (0.15-0.7 keV)
  - Demonstrated workable components
  - **Funded for launch in 2027**
  - Design work in progress, PDR in Feb. 2024

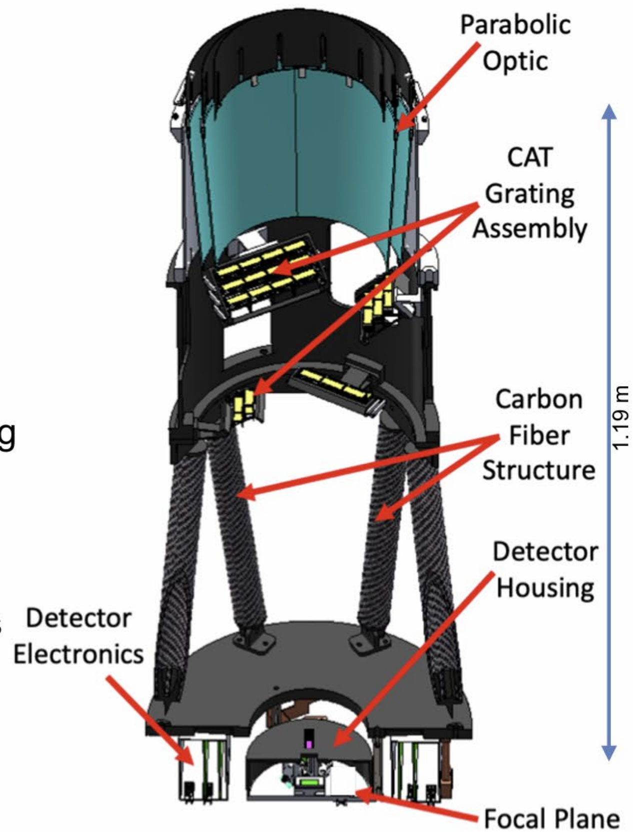
3 m

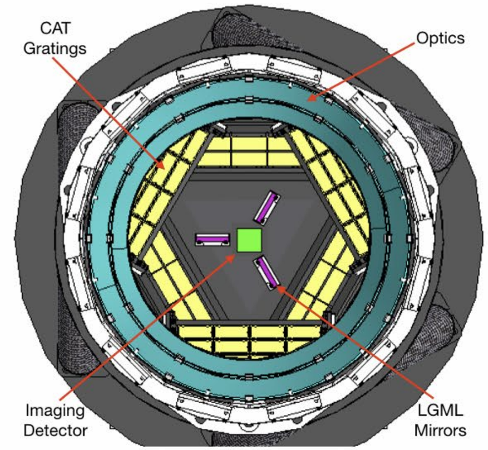
(Marshall et al. 2018, JATIS, 4,011005)

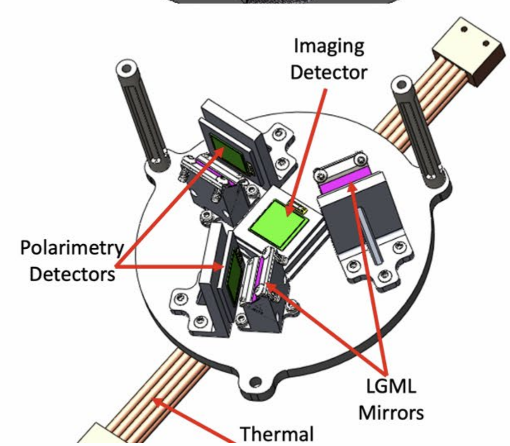
*Used with permission of the Red Sox and Major League Baseball.

Astrophysics Pioneer (GOSoX Polarimeter)

- Same principles as REDSoX
- Differences:
  - 4 year development, $20M
  - Shorter, less area
  - 2 paraboloidal shells — 15 kg
  - 4 sCMOS, not CCDs, thermoelectrically cooled
  - Orbital: exposures of 0.1-3 Ms (3-100 d)

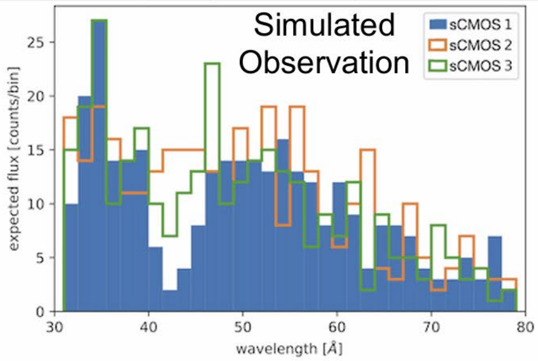


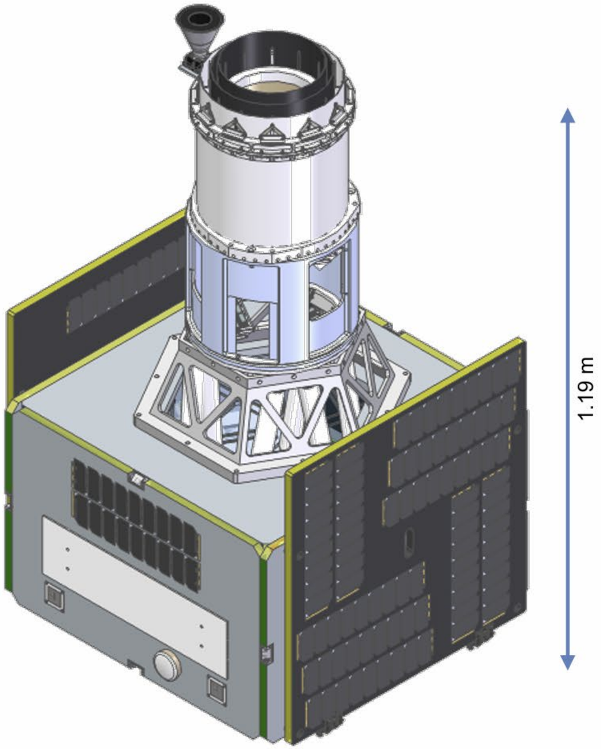




Globe Orbiting Soft X-ray Polarimeter (GOSoX)

Category	Name	T_{min} (Ms)	1 Yr Plan Time (Ms)	1 Yr Plan MDP (%)	Notes
NSs	RX J1856.5−3754		1.0	4.4	Brightest isolated neutron star
	RX J0720.4−3125[T]	0.40	1.3	4.9	Absorption line at 293 eV [15, 14]
	RX J1605.3+3249		1.5	4.8	Abs'n line at 403 eV [14]
	RX J1308.6+2127		1.0	5.8	Abs'n varies: 107-256 eV [14, 17]
	Her X-1[T]	0.10	0.4	3.2[b]	Magnetosphere-disk interaction
	PSR B0656+14[T]	0.15	1.0	3.8	Magnetospheric emission
AGN	Mk 421[T]	0.10	0.2	1.9[b]	High spectral peak (HSP) blazar
	PKS 2155−304		0.2	5.0[b]	HSP blazar
	3C 273[T]	0.75	3.0	4.8	Low spectral peak blazar
	RE J1034+396[T]	0.25	1.0	4.8	Narrow Line Sy 1 (NLS1)
	Ark 564		1.0	5.0	NLS1
Null	Capella	0.25	1.0	2.5	Null polarization target





GREAT TIMES AHEAD !

STAY TUNED AND JOIN THE TEAMS

THANKS!!