X-ray Polarisation: What We Can Learn

Ruth Kelly, MSSL, UCL, UK

Feeling the Pull and the Pulse of Relativistic Magnetospheres

Les Houches, France

6-11 April 2025

Contents:

Magnetars

Isolated neutron stars

Powered by huge magnetic fields
(B ~10^{14} - 10^{15} G, $B_Q \approx 4.4 \times 10^{13}$ G)

active magnetosphere (non dipolar)

Soft X-ray spectrum (0.5-10keV) well represented by two components

- BB+PL
- BB+BB

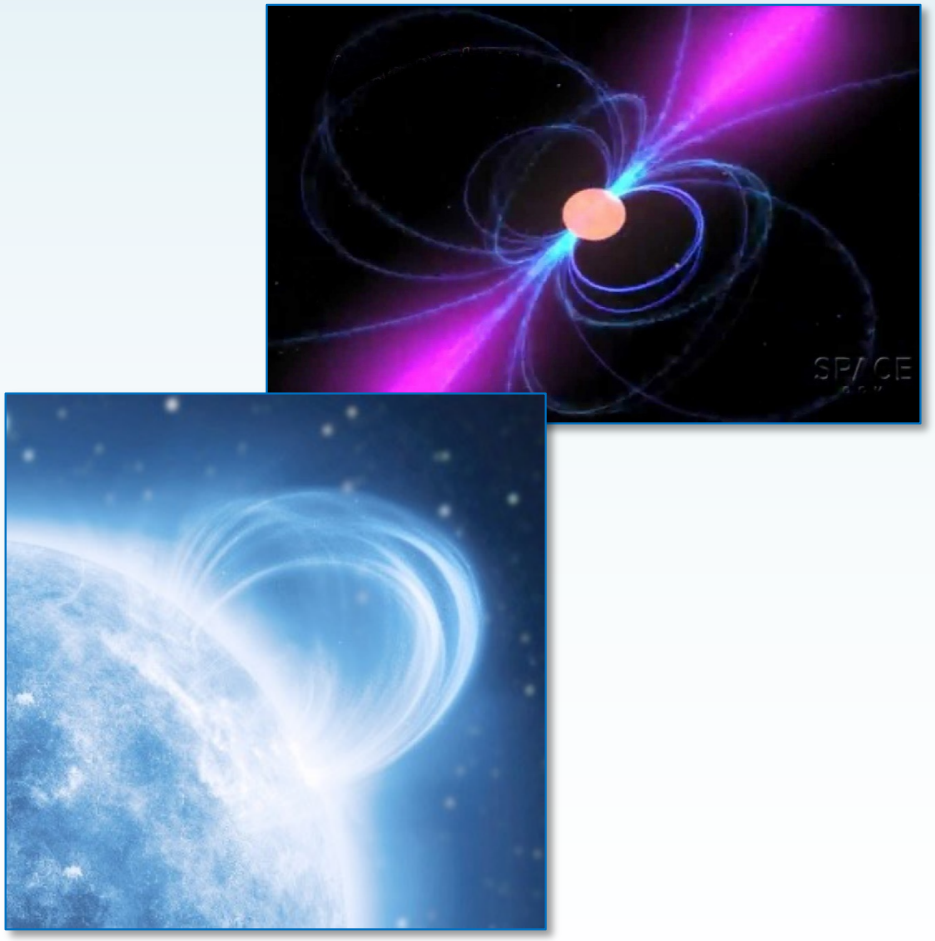
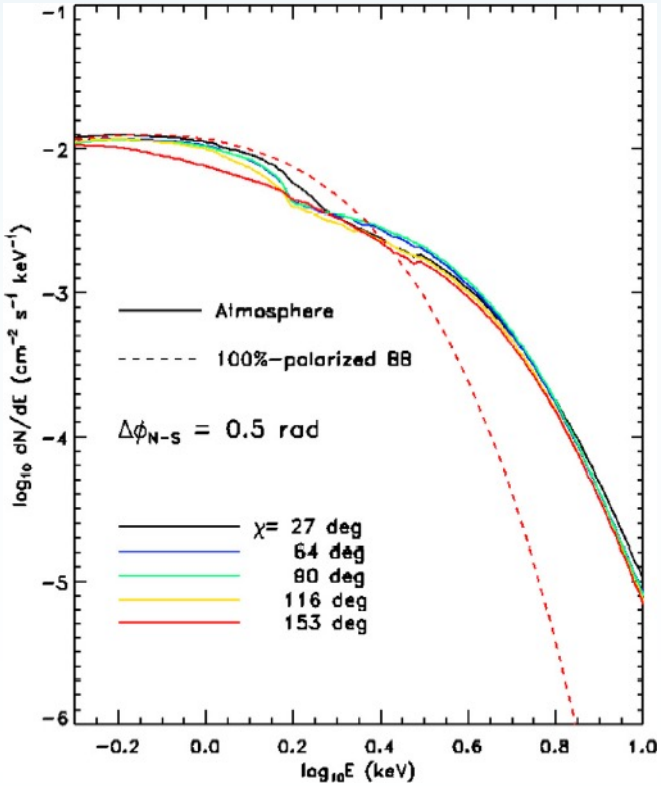


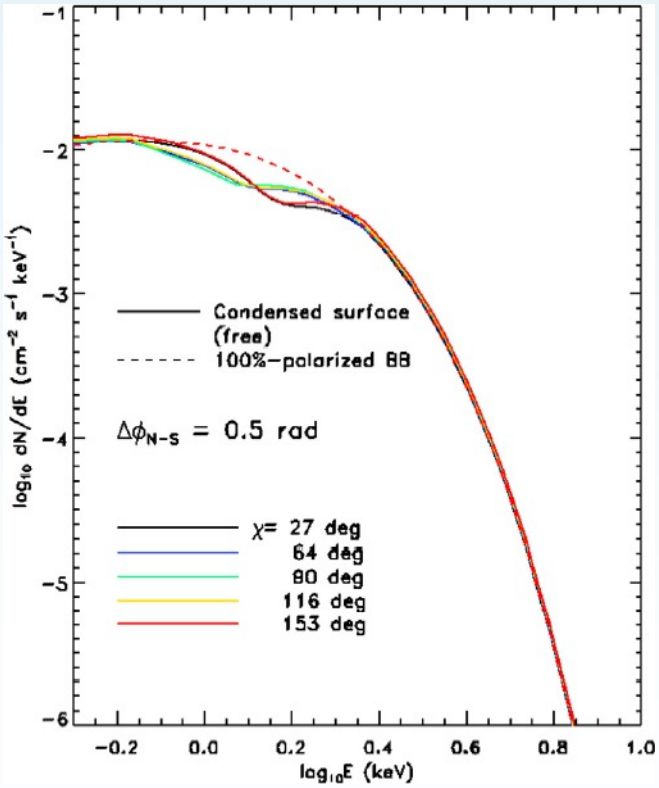
Image Credit:
NASA/Goddard Space Flight Center
X-ray: NASA/CXC/Huntingdon Inst. for X-ray Astronomy/G.Garmire, Optical: ESO/VLT

Thermal emission

- Atmospheric
- Condensed
  - Atoms elongated along B
  - Molecular chains
  - Deposit on crust
  - “Magnetic condensation”

Blackbody emission



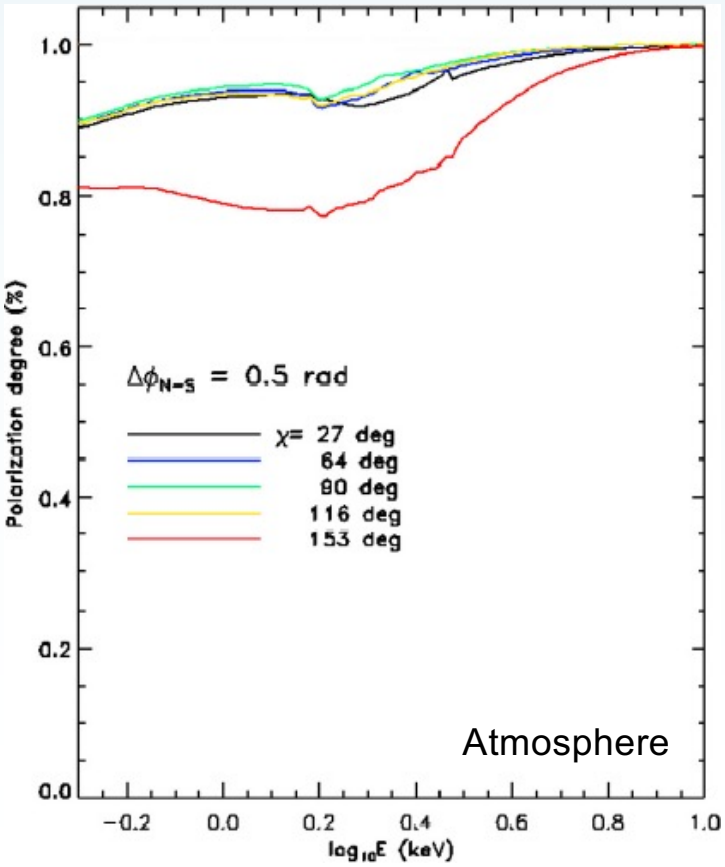


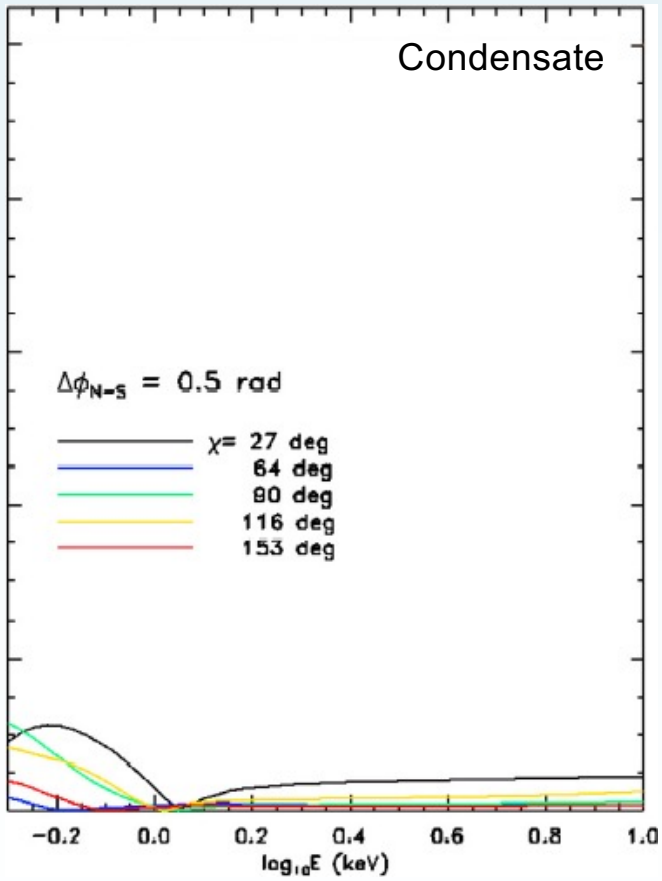
Taverna et al. (2020)

Thermal emission

- Atmospheric
- Condensed
  - Atoms elongated along B
  - Molecular chains
  - Deposit on crust
  - “Magnetic condensation”

Blackbody emission





Taverna et al. (2020)

X-ray polarized in two normal modes

X-mode

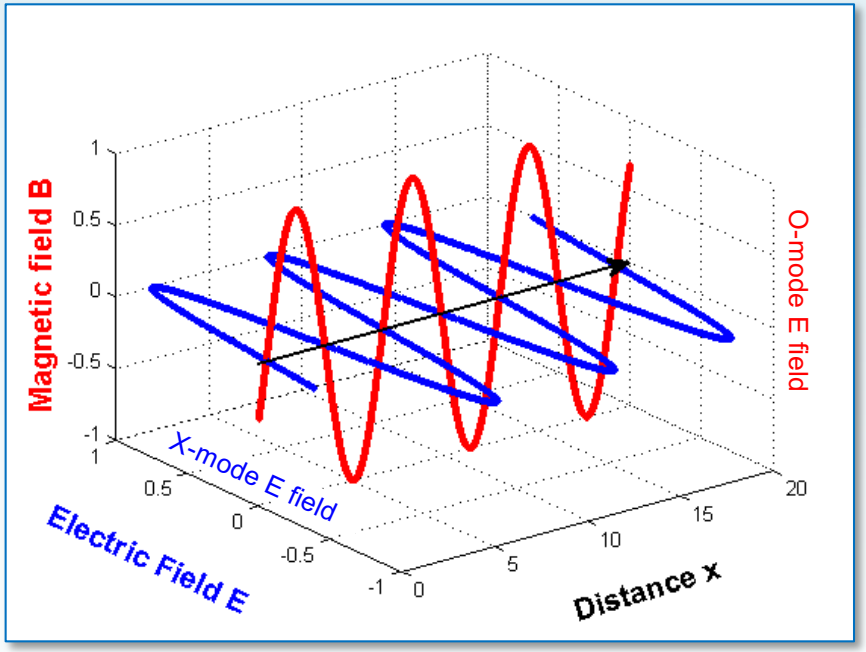
O-mode

Opacity in highly magnetized plasma (atmosphere)

→ $k_{\perp} \neq k_{\parallel}$

Atmospheric emission (plasma) – highly polarised in X-mode

Condensed surface – low polarization in either mode



O-mode:	**E**-field oscillates in the **k-B** plane
X-mode:	**E**-field oscillates perp. to the **k-B** plane

X-ray polarized in two normal modes

X-mode

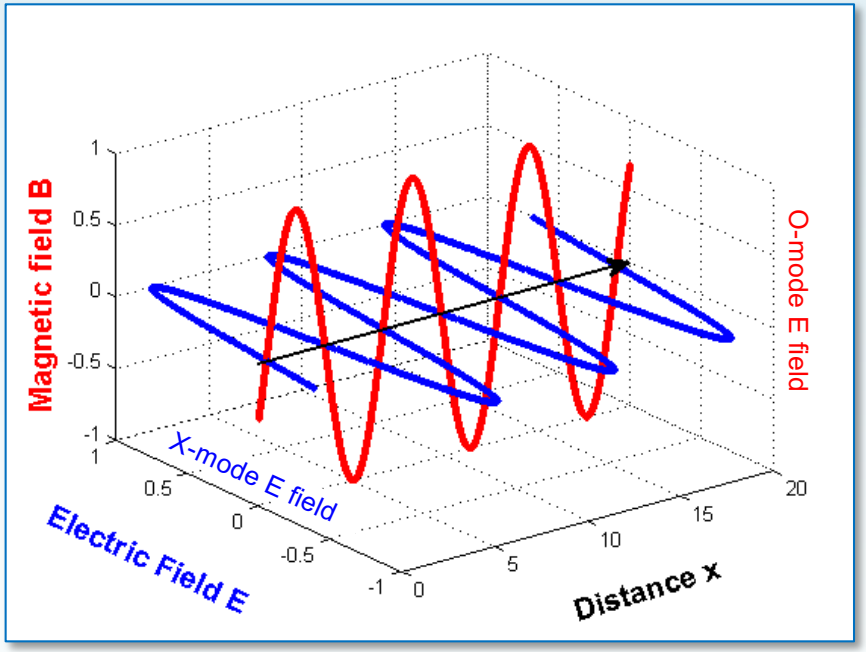
O-mode

Opacity in highly magnetized plasma (atmosphere)

→ $k_{\perp} \neq k_{\parallel}$

Vacuum birefringence (QED)

"Vacuum Resonance"



O-mode:	**E**-field oscillates in the **k-B** plane
X-mode:	**E**-field oscillates perp. to the **k-B** plane

Vacuum birefringence (QED)

"Vacuum Resonance"

- No mode conversion (—)
- Complete mode conversion (…)
- Partial mode conversion (- - -)
  - Adiabatic mode conversion

$$Prob\colon 1 - exp\left[-\frac{\pi}{2}\left(\frac{E}{E_{ad}}\right)^3\right],$$

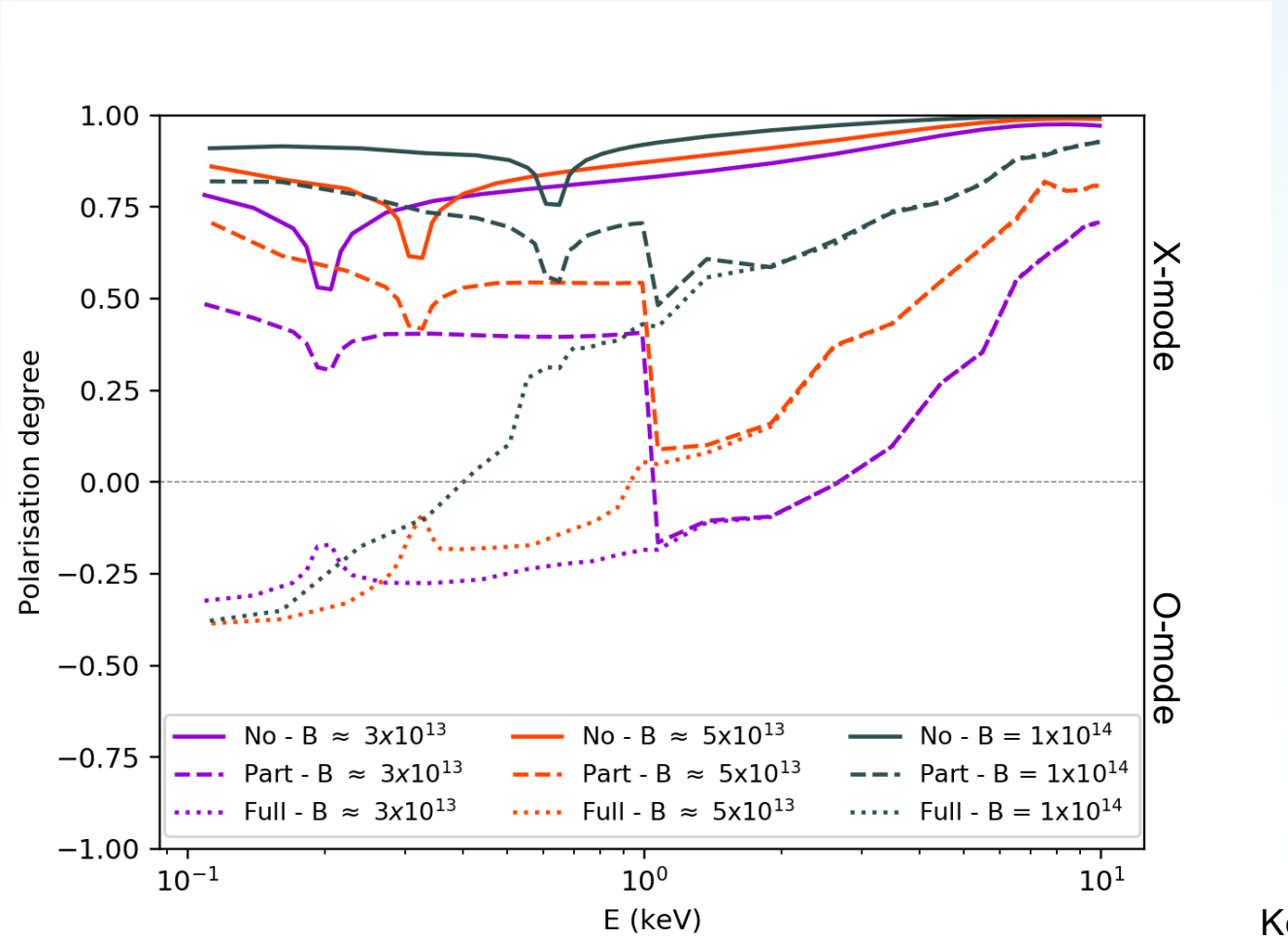
$$E_{ad} = 2.52(f\ tan\theta_B)^{\frac{2}{3}}\left(\frac{1cm}{H_p}\right)^{\frac{1}{3}}\text{keV}$$

Lai 2023, Lai and Ho 2002

Vacuum birefringence (QED)

"Vacuum Resonance"

- No mode conversion (—)
- Complete mode conversion (…)
- Partial mode conversion (- - -)
  - Adiabatic mode conversion

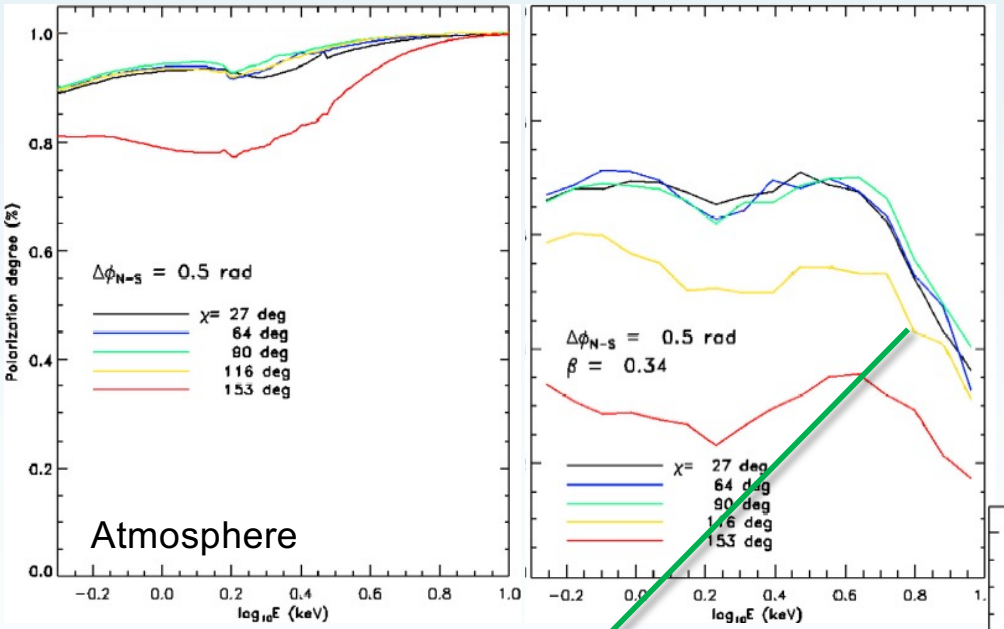


Kelly et al 2024(a)

Magnetosphere?

- Complex (non-dipolar)
- Twists
- Populated by charged particles
  - Optically thick for Resonant Compton Scattering (RCS)

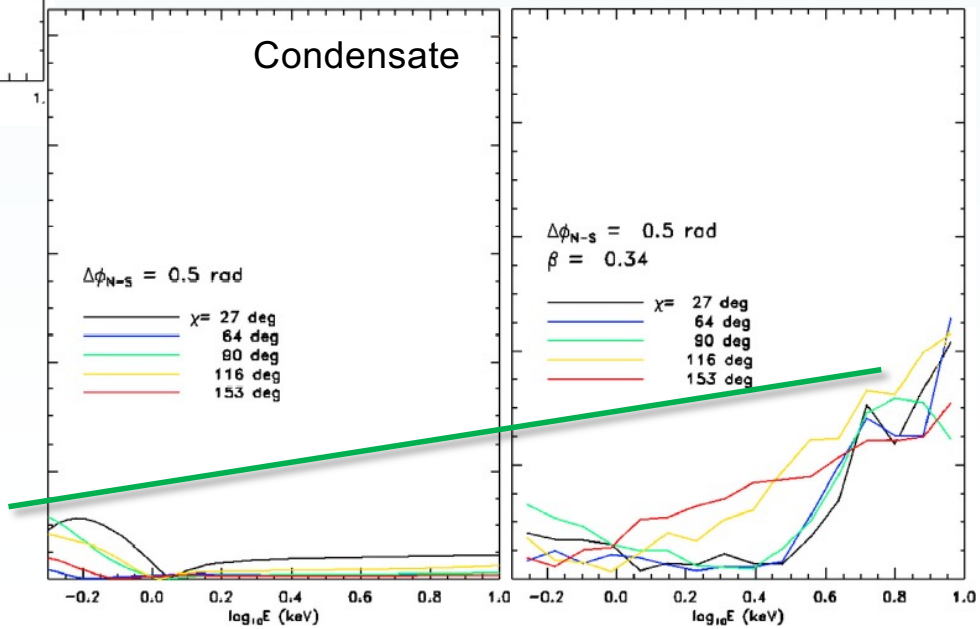
Magnetosphere



- PL at high energy
- X-mode dominated
- Scattering PD saturates at ~33%

Taverna, … SZ et al, 2020

PL tail is expected



PL tail is expected

Magnetosphere

- Complex (non-dipolar)
- Twists
- Populated by charged particles
  - Optically thick for Resonant Compton Scattering (RCS)

Atmospheric Particle Bombardment

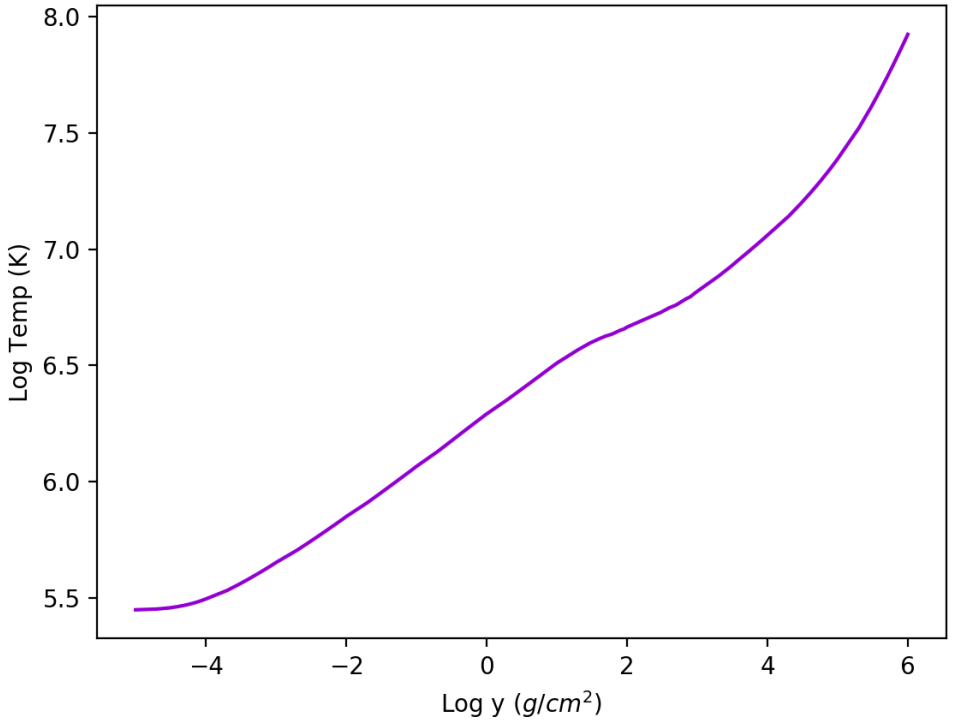
- Inverted temperature profile

Magnetosphere

- Complex (non-dipolar)
- Twists
- Populated by charged particles
  - Optically thick for Resonant Compton Scattering (RCS)

Atmospheric Particle Bombardment

- Inverted temperature profile

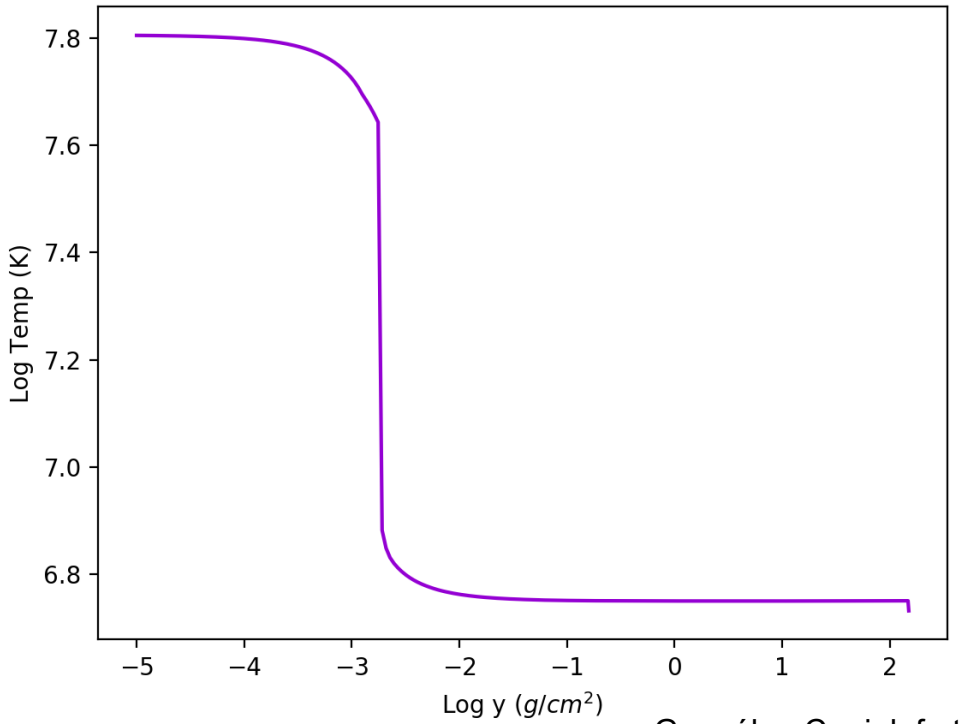


Magnetosphere

- Complex (non-dipolar)
- Twists
- Populated by charged particles
  - Optically thick for Resonant Compton Scattering (RCS)

Atmospheric Particle Bombardment

- Inverted temperature profile



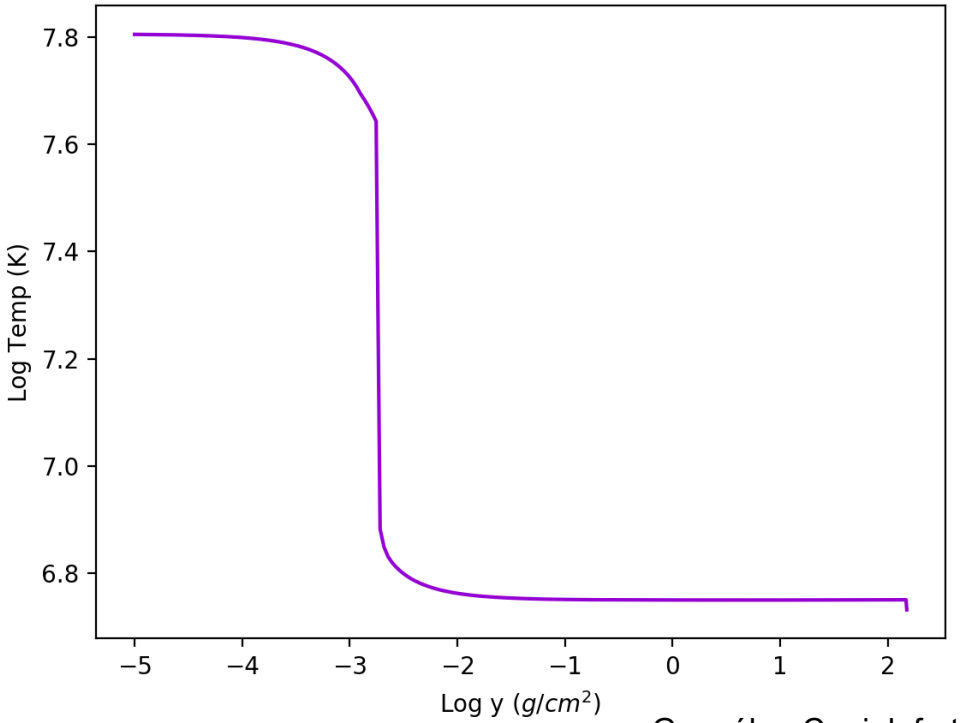
González-Caniulef et al (2019)

Magnetosphere

- Complex (non-dipolar)
- Twists
- Populated by charged particles
  - Optically thick for Resonant Compton Scattering (RCS)

Atmospheric Particle Bombardment

- Inverted temperature profile
- Low polarisation?
- O-mode dominated?



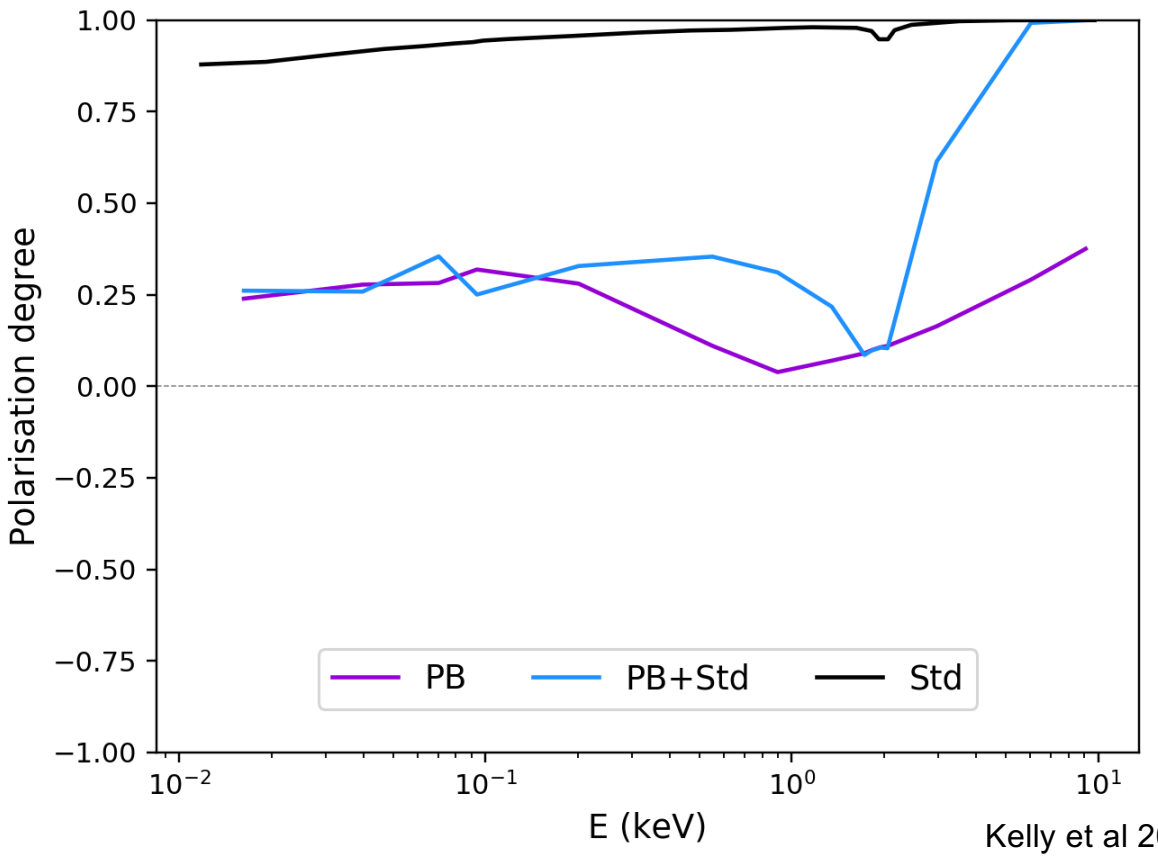
González-Caniulef et al (2019)

Magnetosphere

- Complex (non-dipolar)
- Twists
- Populated by charged particles
  - Optically thick for Resonant Compton Scattering (RCS)

Atmospheric Particle Bombardment

- Inverted temperature profile
- Low polarisation?
- O-mode dominated?



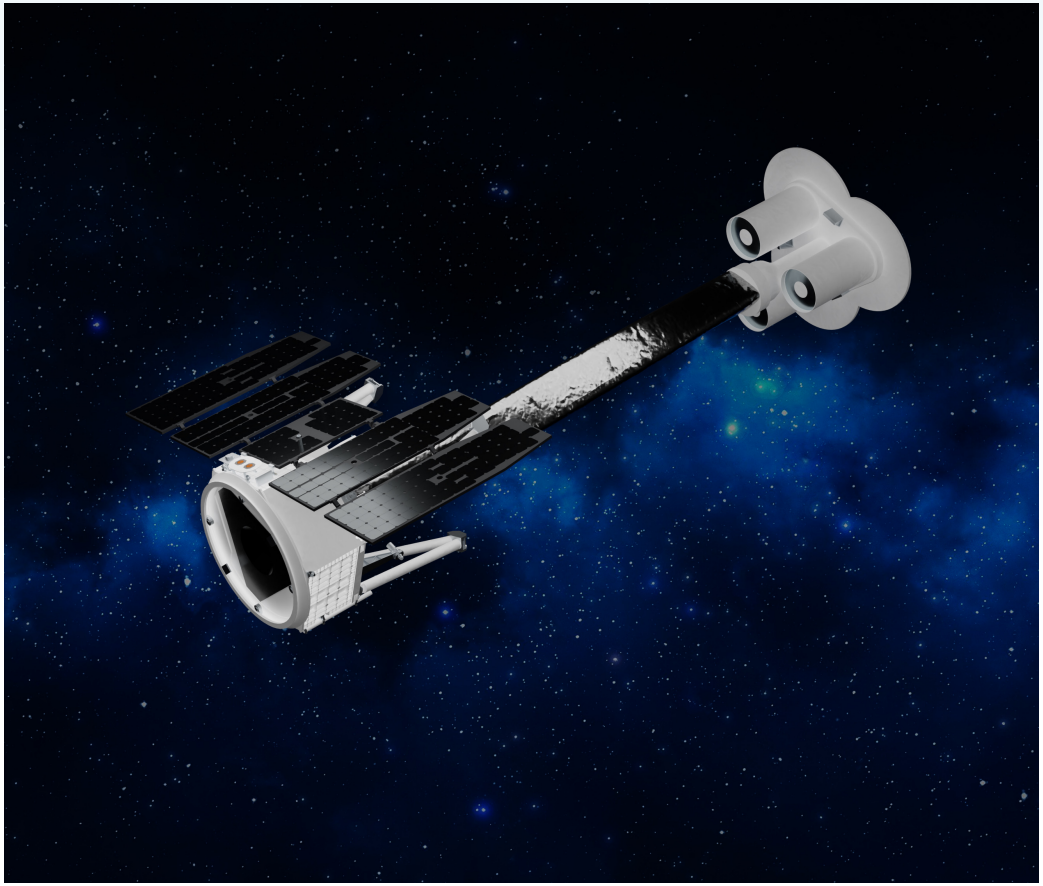
Kelly et al 2024(b)

Imaging X-ray Polarimetry Explorer (IXPE)

NASA-ASI mission
2 - 8 keV

Five magnetars to date:

- 4U 0142+61
- IRXS J1708
- SGR 1806
- IE 2259+586
- IE 1841-045

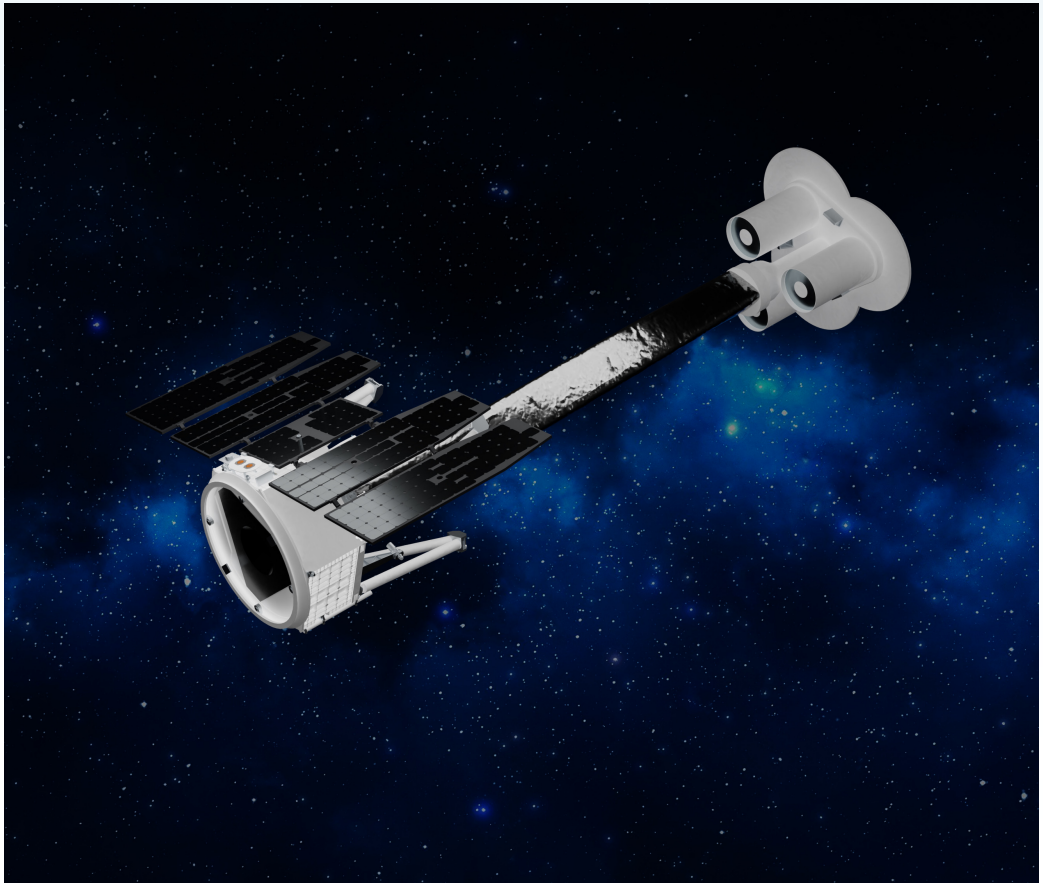


Imaging X-ray Polarimetry Explorer (IXPE)

NASA-ASI mission
2 - 8 keV

Five magnetars to date:

- 4U 0142+61
- IRXS J1708
- SGR 1806
- IE 2259+586
- IE 1841-045



IXPE observation of 4U 0142

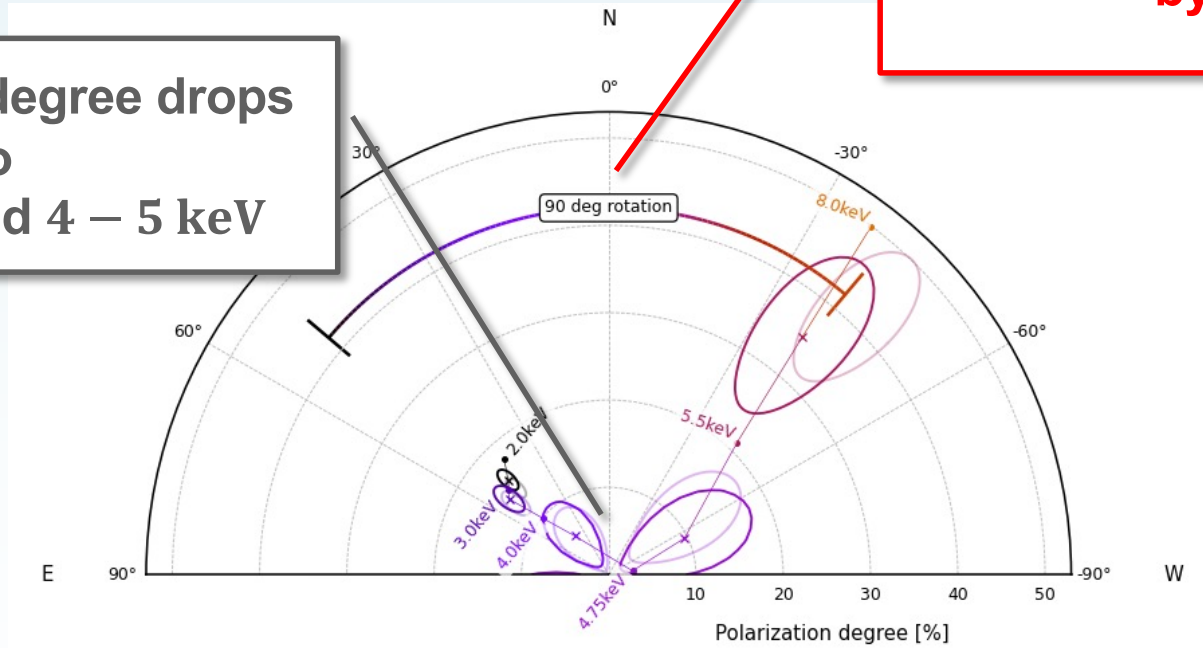
$B \approx 1.3 \times 10^{14}$G

Polarimetric analysis

- Phase-integrated/energy-dependent

Polarization angle swings by 90°

Polarization degree drops to ~ 0 at around $4 - 5$ keV



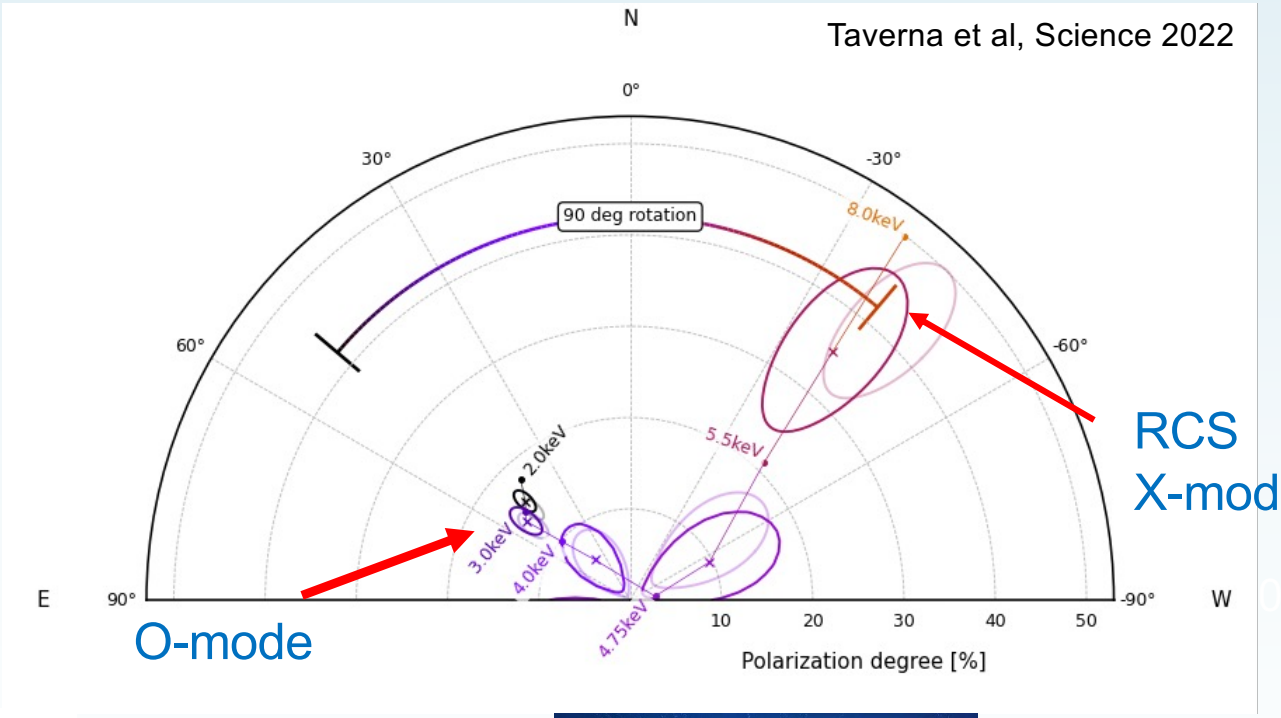
	2-3 keV	3-4 keV	4-4.75 keV	4.75-5.5 keV	5.5-8 keV
PD (%)	16^{+2}_{-2}	14^{+2}_{-2}	6^{+5}_{-5}	10^{+8}_{-8}	35^{+11}_{-11}
PA (deg)	47^{+3}_{-3}	53^{+4}_{-4}	41^{+26}_{-26}	-64^{+29}_{-64}	-39^{+9}_{-9}

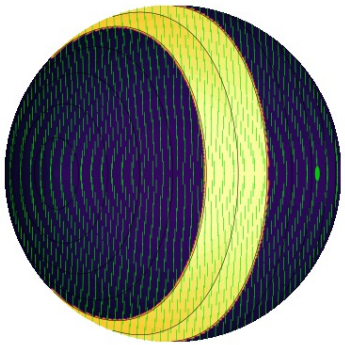
XSPEC	2-3 keV	3-4 keV	4-4.75 keV	4.75-5.5 keV	5.5-8 keV
PD (%)	16^{+2}_{-2}	14^{+2}_{-2}	6^{+5}_{-5}	10^{+8}_{-8}	35^{+11}_{-11}
PA (deg)	47^{+3}_{-3}	53^{+4}_{-4}	41^{+26}_{-26}	-64^{+29}_{-64}	-39^{+9}_{-9}

Taverna et al, Science 2022

IXPE observation of 4U 0142

Well reproduced by
BB+PL model





Hotter equatorial belt
in a NS condensate surface

De Grandis et al, 2021; Taverna et al 2022

Image courtesy of NASA GSFC

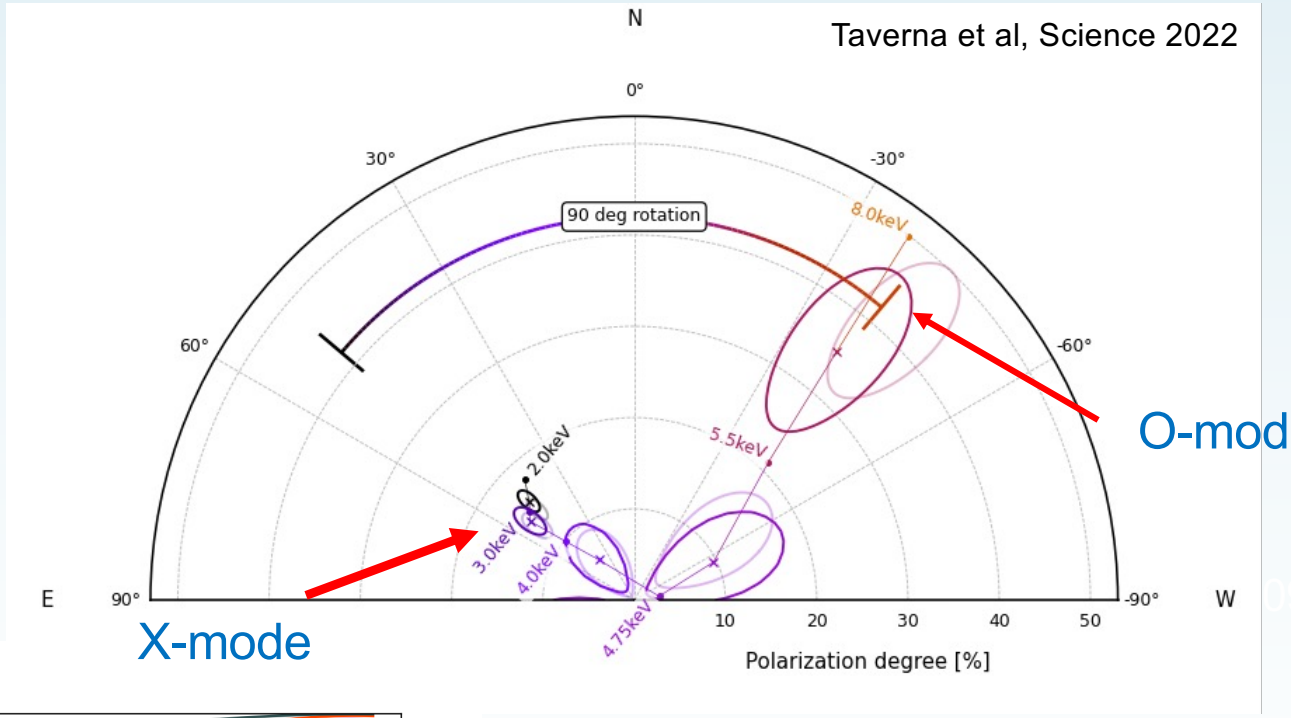
Gaseous atmosphere heated from
above : particle bombardment

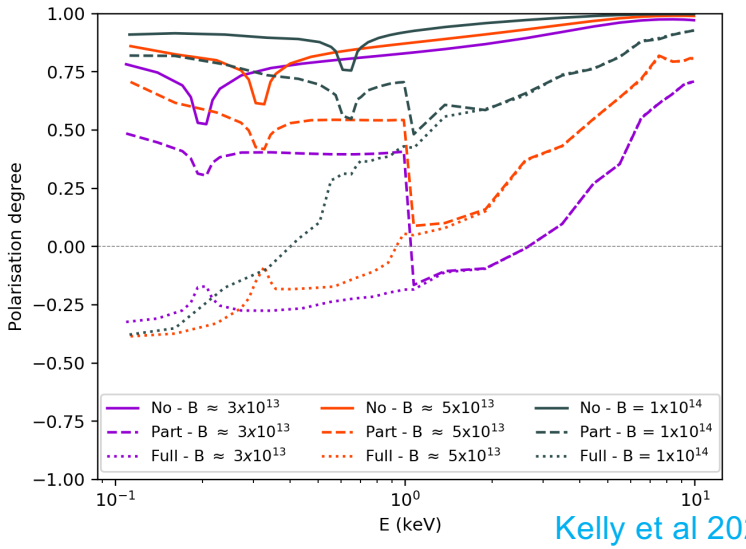
Taverna et al 2022; Gonzalez et al 2019; Kelly et al 2024(b)

Partial mode
conversion?

Lai 2023

IXPE observation of 4U 0142





Kelly et al 2024 (a)

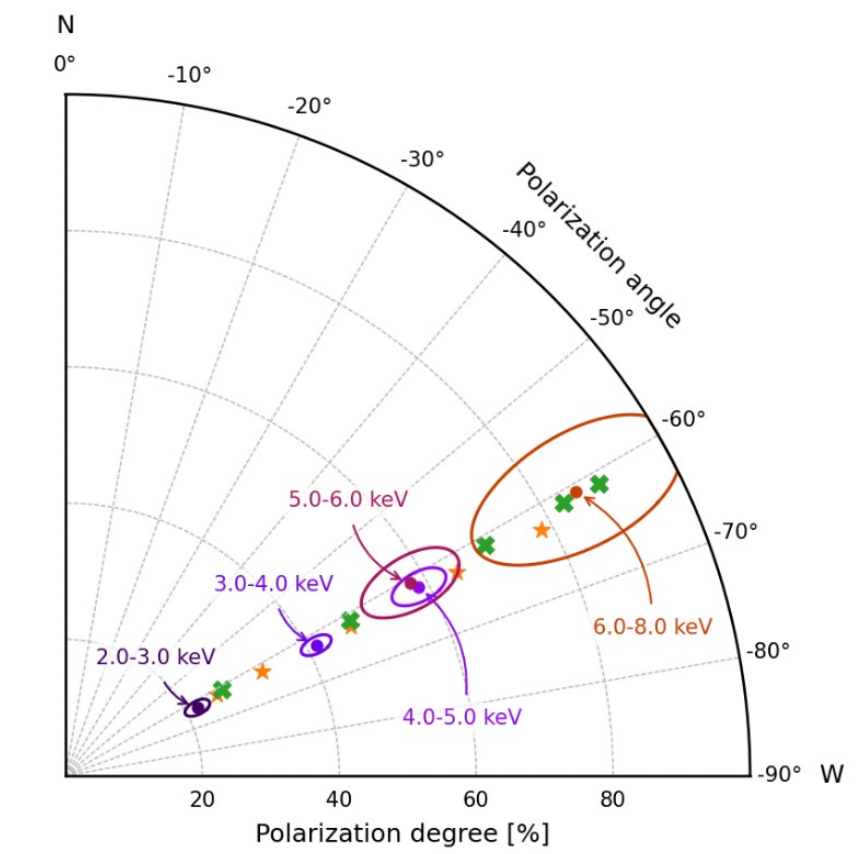
Partial mode conversion?

Lai 2023

IXPE observation of 1RXS J1708

Phase-integrated/energy-dependent analysis

$B \approx 4 - 5 \times 10^{14}$G



PD increases from ~ 20% to ~ 80%

PA constant

- one dominant mode

Spectrum compatible with BB+BB decomposition (IXPE, SWIFT, NICER joint fit)

	2–3 keV	3–4 keV	4–5 keV	5–6 keV	6–8 keV	2–8 keV
PD - sum [%]	$21.7^{+1.7}_{-1.7}$	$41.3^{+2.0}_{-2.0}$	$58.6^{+3.7}_{-3.7}$	$57.7^{+6.8}_{-6.8}$	85^{+15}_{-15}	$35.1^{+1.6}_{-1.6}$
PD S/N	12.9 σ	20.2 σ	15.8 σ	8.5 σ	5.8 σ	22.5 σ
PA - sum [deg]	$-62.6^{+2.2}_{-2.2}$	$-62.4^{+1.4}_{-1.4}$	$-61.8^{+1.8}_{-1.8}$	$-60.7^{+3.3}_{-3.3}$	$-60.8^{+4.7}_{-4.7}$	$-62.1^{+1.3}_{-1.3}$

Table 1. Values of the measured polarization degree and angle, obtained with the IXPEOBSSIM software suite. Reported values correspond to the sum of the three DUs (the measures of the single DUs are consistent with each other within errors). Uncertainties are obtained at 68.3% confidence level, assuming that the polarization degree and angle are independent. Signal-to-noise is calculated by dividing the polarization degree obtained by combining the results of the three telescopes on-board *IXPE* by its uncertainty.

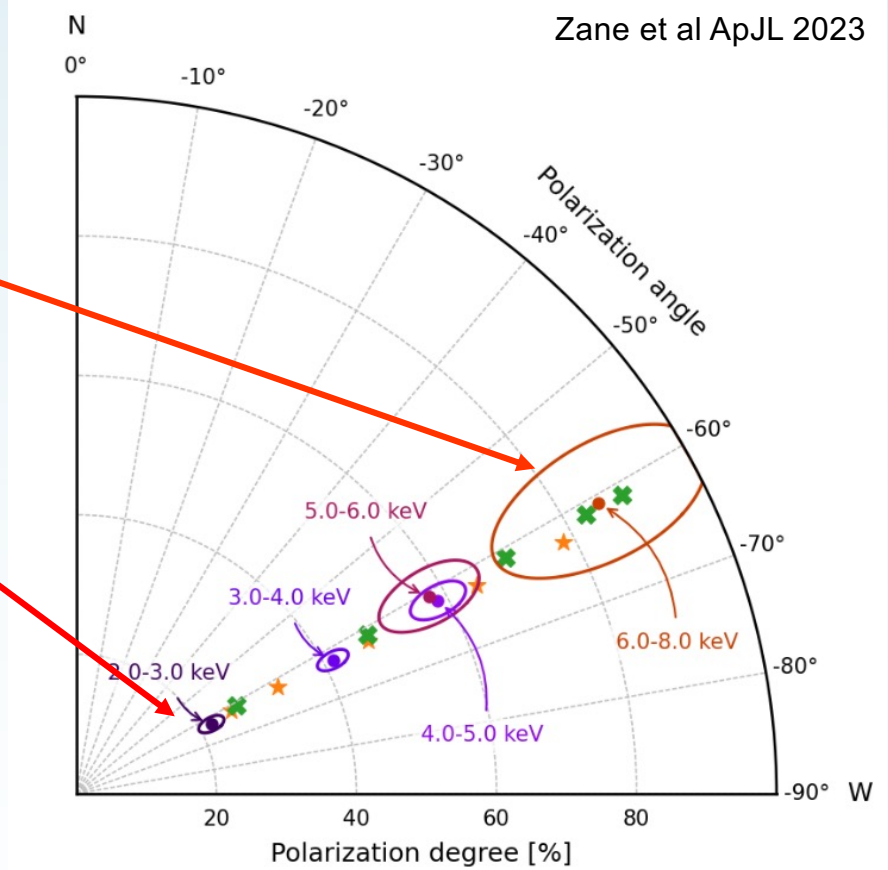
Zane et al ApJL 2023

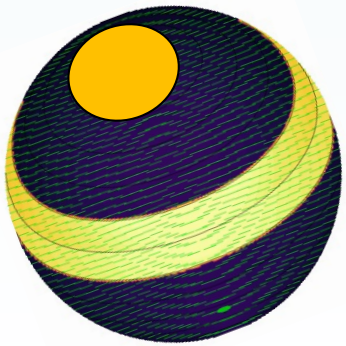
IXPE observation of 1RXS J1708

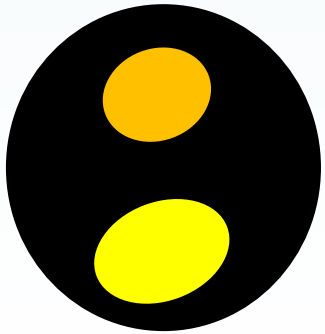
⇒ RCS is not present

⇒ Atmospheric emission

⇒ Condensed surface?
⇒ Particle bombardment?







Belt + cap model (Taverna et al), model A	Cap + cap model (Caiazzo et al), model B

IXPE observation of IE 1841-045

UCL

+ NuSTAR

Phase-integrated/energy-dependent analysis

$B \approx 7 \times 10^{14}$G

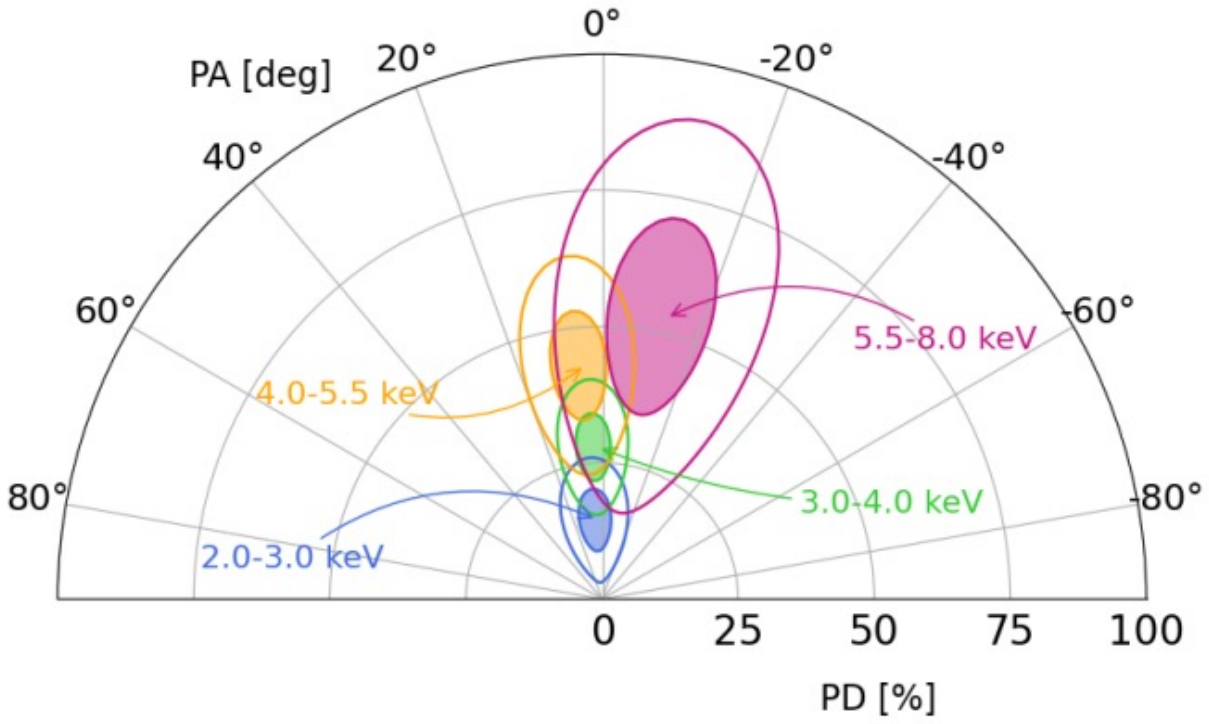


Table 3. Energy-resolved polarization degree and angle

	2.0–3.0 keV	3.0–4.0 keV	4.0–5.5 keV	5.5–8.0 keV	2.0–8.0 keV
pcube PD (%)	16.1 ± 3.5	28.0 ± 4.0	37.9 ± 6.1	54.2 ± 15.2	25.8 ± 3.1
pcube PA (deg)	4.6 ± 6.3	2.1 ± 4.1	2.0 ± 4.6	-6.7 ± 8.0	1.1 ± 3.5
pcube PD S/N	4.6σ	7.0σ	6.2σ	3.6σ	8.3σ
pcube MDP_{99} (%)	10.7	12.1	18.5	45.9	9.5
XSPEC PD (%)	14.5 ± 3.8	27.9 ± 4.1	43.1 ± 6.6	52.9 ± 12.1	25.3 ± 2.4
XSPEC PA (deg)	3.3 ± 7.5	1.7 ± 4.2	4.1 ± 4.4	-12.9 ± 6.7	2.3 ± 2.7
XSPEC PD S/N	3.8σ	6.8σ	6.5σ	4.4σ	10.5σ

Rigoselli et al 2025 (accepted ApJL)

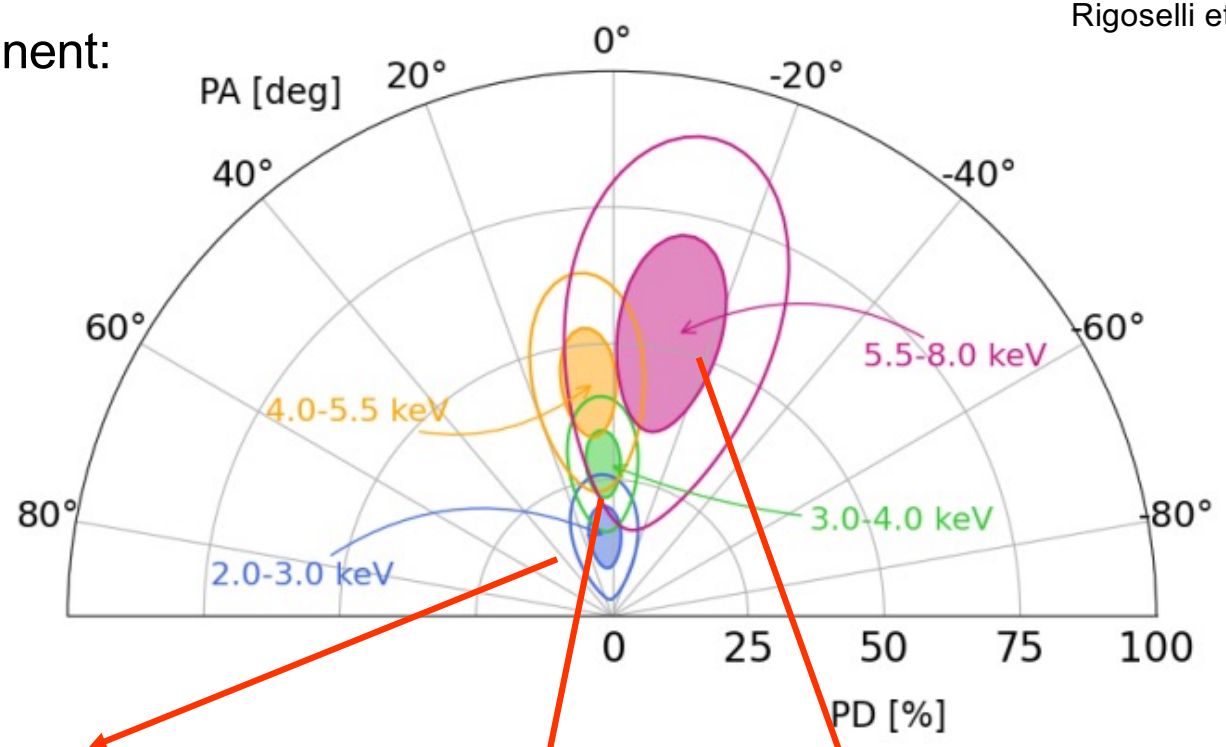
See also Stewart et al 2025 (accepted ApJL)

IXPE observation of IE 1841-045

Phase-integrated/energy-dependent analysis

Three component:
BB+BB+PL
BB+PL+PL

Rigoselli et al 2025



BB (PD 20%):
- Condensed surface
- Particle bombardment

Soft PL (PD: 30%):
- RCS

Hard PL (PD 75%):
- Synchrotron / curvature radiation
- RICS

Summary

- New window in compact objects science thanks to X-ray polarimetry
- Magnetars are the highest polarized IXPE sources
- Identification of two components: solid and magnetospheric in 4U0142, solid and gaseous for 1RXS J1708 at the NS surface
- IE 1841-045 three components, strong magnetospheric activity – RCS + synchrotron radiation
- Polarimetry - constrain magnetic field topology
- Hunt for QED vacuum birefringency test is still on

$\Rightarrow$ Great times ahead for NS physics, thanks to IXPE!

Thanks !