Joint NICER/IXPE Workshop 2024

IXPE Highly Significant Detection of Polarization in Scorpius X-1

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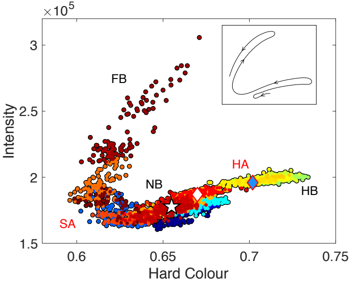
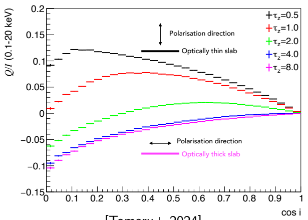


[Motta & Fender, MNRAS, 483:3686 (2019)]

- First extra-solar X-ray source discovered and the brightest in the X-ray sky
- NS-LMXB with peak luminosity near the Eddington-limit for a $1.4\,M_\odot$
- First X-ray binary where radio emission was detected:
  - VLBI observations spatially resolved **radio jet** at a position angle of $\sim 54^\circ$ (from north to east), deriving the inclination of the system: $44^\circ \pm 6^\circ$ (Fomalont et al., 2001)
- This is a prototype for Z-sources: usually divided in Sco-like and Cyg-like
- An ideal candidate to **attempt to measure X-ray polarization**: OSO-8 satellite (Long et al., 1979) and PolarLight (Long et al., 2022)

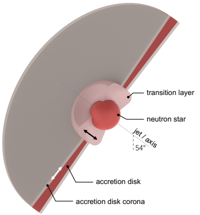
X-ray polarization of Sco X-1 before IXPE

- **Polarization can help to study "corona" geometry**
  - ➥ Accretion disk PA expected parallel to the disk and perpendicular to the radio-jet
  - ➥ SL/BL PA expected parallel or perpendicular to the disk depending on τ (Sunyaev & Titarchuk, 1985; Tomaru+ 2024)



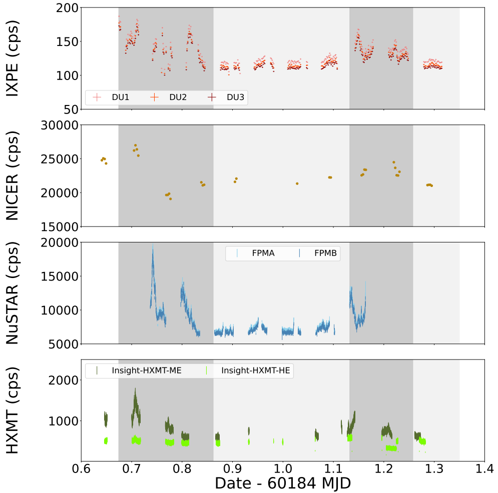
[Tomaru+ 2024]

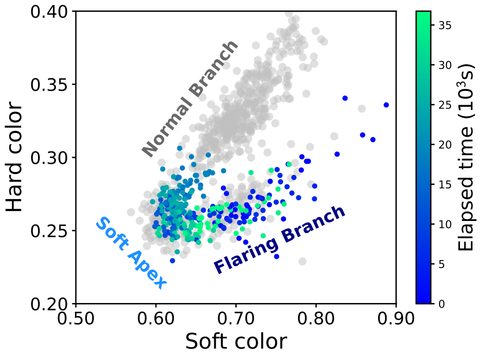
- In 1977, OSO-8 (Long et al. 1979) obtained a low-significance detection at 2.6 keV and at 5.2 keV (PD $= 1.3\% \pm 0.4\%$ and PA $= 57° \pm 6°$ at $\sim 3\sigma$ CL)
- In 2022, PolarLight (Long et al., 2022) obtained hints of variations of polarization with the energy and the source flux:
  - ➥ a 5σ detection (PD $\sim 4\%$) **only in the 4–8 keV energy band and when the flux was high** with a **PA aligned with the radio jet**



[Long+ 2022]

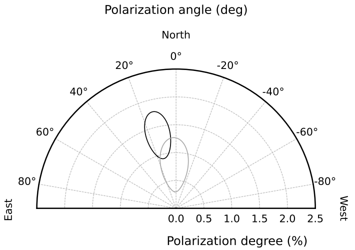
- Both these observations were **performed with long exposure ($\sim$15 d for OSO-8 and $\sim$322 d for PolarLight), and none of them could clearly distinguish the source state**

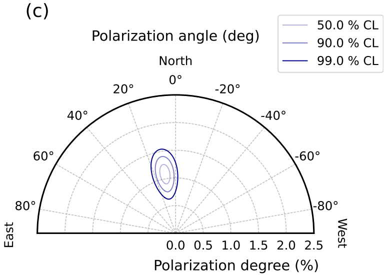




- **Flaring activity** highlighted in dark gray
- NuSTAR Color–Color diagram: **observation mainly in SA with short periods in FB**
- NICER timing analysis: observed transient QPO at ∼6 Hz **compatible with SA**

Sco X–1: polarization I

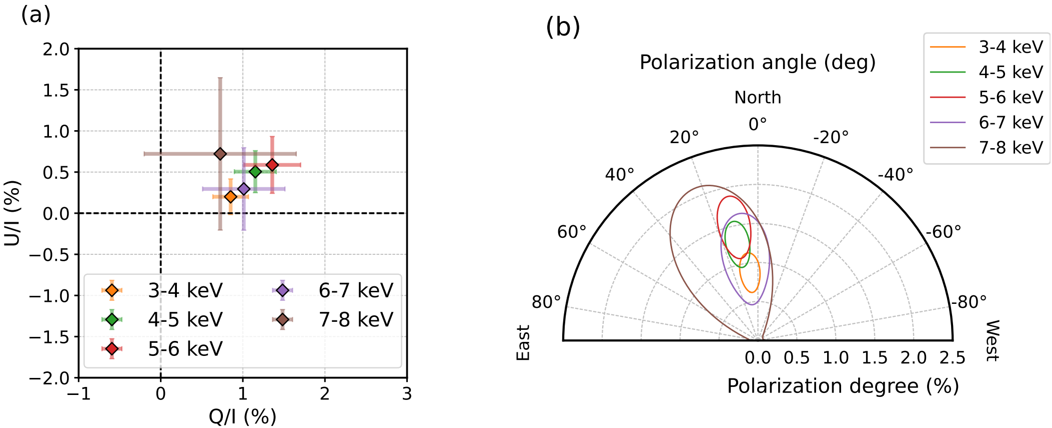




- Polarization for the flaring branch and non-flaring are **compatible within 90% CL**; thus, the analysis can be carried out on the entire observation

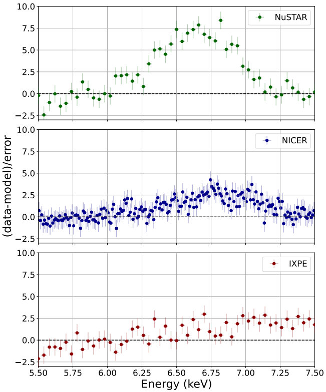
- **Secure detection** of polarization in 3-8 keV
  - ➥ probability of obtaining such polarization in the case of an unpolarized source is 6×10^{-12}, corresponding to **a detection significance of $\sim$7σ CL.**

Sco X–1: polarization II



- **No evidence of PD or PA variation with energy**
- All contours in the different 1 keV energy bins are compatible at 68% CL

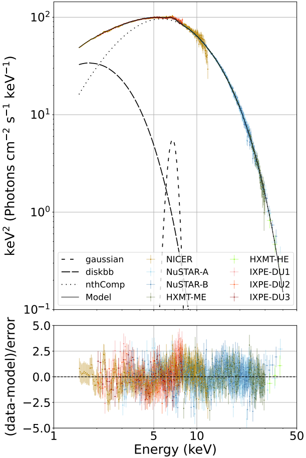
Sco X-1: spectral model



Presence of a clear broad Fe line at ∼6.7 keV observed in the data as a reflection feature

- Spectral joint fit:
  - ➥ NICER (1.5–12 keV) with SCORPEON background
  - ➥ NuSTAR (3–40 keV)
  - ➥ Insight-HXMT Medium Energy (ME) (8–20 and 23–30 keV) and High Energy (HE) telescopes (30–40 keV);
    Insight-HXMT Low Energy (LE) excluded from the analysis due to a reported calibration issue
  - ➥ IXPE (2–8 keV)
- **Fit the continuum** with:
  - ➥ `tbabs*(diskbb+nthcomp)`
- $N_H = 0.15 \times 10^{22}$ cm^{-2}
- `nthcomp` has `inp_type`=0 corresponding to hot electrons Compton upscattering seed photons distributed as a blackbody, e.g., from the neutron star SL/BL

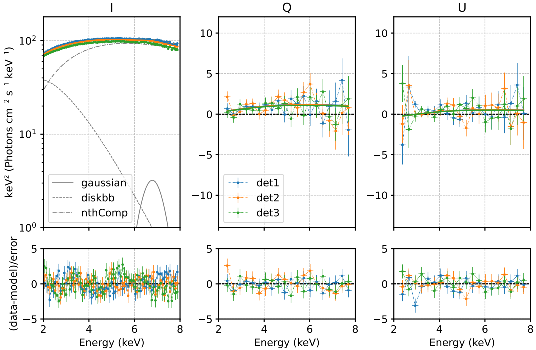
Sco X-1: spectro-polarimetry for a model with Gaussian line



Component	Parameter	Continuum	Model A
tbabs	$N_{\rm H}$ ($\times 10^{22}$ cm^{-2})	0.15	0.15
diskbb	$kT_{\rm in}$ (keV)	0.692 ± 0.004	0.683 ± 0.011
	norm ($[R_{\rm in}/D_{10}]^2 \cos\theta$)	25500 ± 700	25500 ± 1400
	$R_{\rm in}$ (km)	40.1 ± 1.1	40.1 ± 2
nthcomp	Γ	2.78 ± 0.02	2.58 ± 0.02
	τ	5.95 ± 0.04	6.70 ± 0.05
	$kT_{\rm e}$ (keV)	3.41 ± 0.03	3.21 ± 0.03
	$kT_{\rm bb}$ (keV)	1.148 ± 0.008	1.08 ± 0.01
	norm	6.34 ± 0.05	6.94 ± 0.16
gauss	$E_{\rm line}$ (keV)	–	6.72 ± 0.02
	σ (keV)	–	0.45 ± 0.03
	norm (photon cm^{-2} s^{-1})	–	0.139 ± 0.009
	Equivalent width (eV)	–	66.836 ± 0.014
	χ^2/dof	$5365/2890 = 1.9$	$3033/2887 = 1.05$
	Photon flux ratios in 2–8 keV		
	$F_{\rm diskbb}/F_{\rm tot}$	0.23	0.21
	$F_{\rm nthcomp}/F_{\rm tot}$	0.77	0.78
	$F_{\rm gauss}/F_{\rm tot}$	–	0.01

- Flux dominated by the Comptonization component

- `tbabs*(gaussian+(diskbb+nthcomp)*`**polconst**`)`:
  - ➥ PD $= 1.0\% \pm 0.2\%$ and PA $= 8^\circ \pm 6^\circ$
  - ➥ χ^2/dof $= 1371/1341 = 1.02$
- `tbabs*(gaussian+(diskbb+nthcomp)*`**pollin**`)`:
  - ➥ **no polarization varying linearly with energy**: PD and PA slopes compatible with zero



- The iron line is assumed to be unpolarized

Table 4. Best-fit parameters for the spectro-polarimetric analysis with the model `polconst*diskbb+polconst*nthcomp+gauss`.

Component		Value
`diskbb`	PD (%)	< 3.2
	PA (deg)	—
`nthcomp`	PD (%)	1.3 ± 0.4
	PA (deg)	14 ± 8
	χ^2/dof	$1329/1337 = 0.99$

NOTE—Errors are at 90% CL.

Sco X-1: spectro-polarimety for a model with reflection

- Model C: `tbabs*(diskbb+nthcomp+`**relxillNS**`)`
  - inclination frozen at 44° (Fomalont et al., 2001)
  - frozen Fe abundance and log N frozen to the maximum; similar effect seen for other bright sources, e.g. Cyg X-1 (Tomsick et al. ApJ, 855, 3, 2018)
  - relative flux for the reflection component at level of 10%

- Different constant polarization to each spectral component:

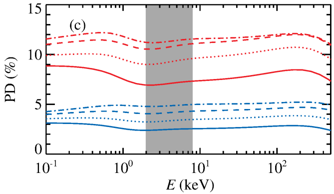
	Disk		Comptonization		Reflection	
Case A	$< 1.9\%$	–	$< 8.2\%$	–	$< 66\%$	–
Case B	1.1%	-40°	0%	–	$14\% \pm 5\%$	$15° \pm 7°$

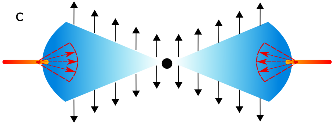
  - upper limits and errors at 90% CL

- **A clear polarimetric disentanglement of the three spectral components is not possible with the present data**

Sco X-1: IXPE polarization results

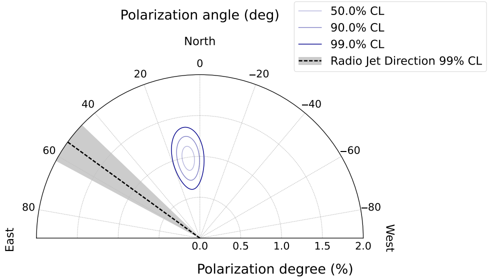
- **Highly significant polarization** in 2–8 keV energy band (PD=1.0%±0.2% and PA=8°±6°)
- **No evidence of PD or PA variation with the energy**: the **constant PD**, even if smaller than expectations, can be compatible with a **sandwich corona geometry** (Poutanen et al., ApJL 949:L10, 2023)
- PD of the disk **compatible with expectations from an electron-scattering dominated optically thick accretion disk** (Chandrasekhar, 1960) that is $\sim$1% for an inclination $\sim$44°
- PD of the Comptonized component of 1.3% $\pm$ 0.4%, **compatible with the scenario of a coplanar corona having Thomson optical depth $\tau_T \sim$7 and $kT_e \sim$3 keV** as in Sunyaev & Titarchuk, 1985
- PD of the reflection component **compatible with the predicted polarization values for a Compton-reflected spectrum from cold matter** (Matt et al.,1993 and Poutanen et al., 1996).





Sco X-1: polarization angle VS radio-jet direction

- **The present Sco X-1 measurement shows a PA rotated of $\sim 46^\circ$ with respect to the radio-jet position angle.** In contrast with:
  - ➡ previous OSO-8 and PolarLight **attempts performed with long exposure times without branch selection/identification limiting their usefulness in the comparison**
  - ➡ IXPE results for Cyg X-2 (Farinelli+ 2023), Cyg X-1 (Krawczynski+ 2022)



- **The IXPE measured PA may be due to relativistic precession or HR variations**:
  - ➡ **relativistic precession**: radio-jet observed in few sources to change up to 36°on short timescales (Miller-Jones+ 2019) likely related to the relativistic Lense-Thirring precession of the accretion disk; Observed also for NS: **evidence of precession of the radio-jet in Cir X-1** (F. Cowie, in preparation); this effect can produce a rotation of the PA if aligned with radio-jet with respect to previous measurements
  - ➡ **variation of the corona geometry** in the different states of the source with PA variations up to $\sim 50^\circ$: see e.g., Cir X-1 (Rankin+ 2023) and GX 13+1 (Bobrikova+ 2024)
  - ➡ **new Sco X-1 observations by IXPE** could try to answer this open question
- **More details: La Monaca F., Di Marco A., Poutanen, J. et al. (ApJL 960, L11, 2024)**