

Probing the emission geometry of the X-ray pulsar 2S 1417–624 during a weak outburst with NICER, IXPE, and NuSTAR

M. Zhou¹, P.-J. Wang^{2,3,*}, H.-H. Liu^{1,*}, L. Ducci¹, S. S. Tsygankov^{4,1,5}, Q.-C. Zhao^{5,6}, J. Poutanen⁴,
L. Ji⁷, V. F. Suleimanov¹, A. A. Mushtukov⁸, Q. Liu⁹, C. M. Diez¹⁰, L. Abalo¹¹,
V. Grinberg¹², and A. Santangelo¹

¹ Institut für Astronomie und Astrophysik, Universität Tübingen, Sand 1, D-72076 Tübingen, Germany

² Research Center of Astronomy, QingHai University, Xining 810016, China

³ Department of Physics and Astronomy, QingHai University, Xining 810016, China

⁴ Department of Physics and Astronomy, University of Turku, 20014 Turku, Finland

⁵ Key Laboratory of Particle Astrophysics, Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China

⁶ University of Chinese Academy of Sciences, Chinese Academy of Sciences, Beijing 100049, China

⁷ School of Physics and Astronomy, Sun Yat-Sen University, Zhuhai 519082, China

⁸ Astrophysics, Department of Physics, University of Oxford, Denys Wilkinson Building, Keble Road, Oxford OX1 3RH, UK

⁹ School of Physics, Hebei Normal University, Shijiazhuang 050024, China

¹⁰ European Space Agency (ESA), European Space Astronomy Centre (ESAC), Camino Bajo del Castillo s/n, 28692 Villanueva de la Cañada, Madrid, Spain

¹¹ Huygens-Kamerlingh Onnes Laboratory, Leiden University, Postbus 9504, 2300 RA Leiden, The Netherlands

¹² European Space Agency (ESA), European Space Research and Technology Centre (ESTEC), Keplerlaan 1, 2201 AZ Noordwijk, The Netherlands

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ABSTRACT

We report results from a multi-mission observational campaign of the transient X-ray pulsar 2S 1417–624 during its 2025 outburst, using data from NICER, IXPE, and NuSTAR. Phase-averaged and phase-resolved spectroscopy with NICER and NuSTAR reveal that a typical broken power-law model with a high-energy cutoff describes the broadband spectra well. Several spectral parameters, however, show clear and systematic modulations with pulse phase, indicating variations in the physical conditions of the emitting plasma over the neutron star’s rotation. IXPE provides the first polarimetric measurements of this source, yielding a phase-averaged polarization degree (PD) of $4.8 \pm 1.2\%$ and a polarization angle (PA) of $17^\circ \pm 7^\circ$, both quoted at the 1σ confidence level. Fitting the phase-resolved PA with the rotating vector model (RVM) gives a magnetic obliquity of $\theta = 69^{+13}_{-29}$ deg, indicating a significantly inclined magnetic geometry that may approach a quasi-orthogonal configuration. In addition, using the unbinned photon-by-photon method, we obtain a PD of $5.9 \pm 1.2\%$ across the pulse phase, together with a pulsar geometry consistent with that inferred from the binned analysis, assuming the variable PA predicted by the RVM. A simultaneous RVM fit across the three energy bands, 2–5 keV, 5–6 keV, and 6–8 keV, provides the strongest constraints on the geometrical parameters, yielding $\theta = 84^{+4}_{-6}$ deg. Together, these findings demonstrate pronounced phase-dependent spectral and polarization variability, offering valuable constraints on the geometry and emission processes within the accretion region of this transient X-ray pulsar.

Key words. accretion, accretion disks – magnetic fields – polarization – stars: neutron – pulsars: individual: 2S 1417-624 – X-rays: binaries

1. Introduction

Accreting X-ray pulsars (XRP) are binary systems consisting of a strongly magnetized neutron star ($B \sim 10^{12}$ G) and a companion star. The neutron star accretes material from its companion, releasing gravitational energy and forming highly concentrated emission regions near its magnetic poles (for a review, see, e.g., Mushtukov & Tsygankov 2024). Constrained by the magnetic field, the infalling matter is channeled along field lines toward the poles, where it forms a hot plasma in the polar cap. The neutron star’s rotation modulates this emission, producing periodic X-ray pulses. The beam pattern depends on the geometry of the emitting regions and the luminosity.

In the subcritical regime, radiation is predominantly emitted along the magnetic axis (“pencil beam”), whereas in the supercritical regime, radiation escapes laterally below the radiation-dominated shock, forming a “fan beam” (Basko & Sunyaev 1975; Becker et al. 2012; Mushtukov et al. 2015). Transitions between these patterns manifest through changes in the pulse profile, pulsed fraction, and spectral properties, highlighting the importance of broadband, long-term monitoring for constraining accretion geometry and emission physics (Reig & Nespola 2013; Kong et al. 2021; Wang et al. 2022).

Recent advances in X-ray polarimetry have opened a new avenue for probing accreting XRP. Measurements of the energy and phase dependence of the polarization degree (PD) and polarization angle (PA) can tightly constrain the emission geometry. While PD values in the X-ray band are generally modest (from a few to $\sim 10\%$), PA values often exhibit systematic variations

* Corresponding authors: wangpj@qhu.edu.cn,
honghui.liu@uni-tuebingen.de

with pulse phase. Modeling such variations with the rotating vector model (RVM) can yield the relative orientations of the magnetic axis, spin axis, and observer's line of sight (Poutanen 2020; Poutanen et al. 2024). Combined with spectral and pulse profile analyses, polarization measurements can provide direct observations of radiation from the accretion column and probe the neutron star's magnetic field structure (Krawczynski et al. 2019; Doroshenko et al. 2022).

2S 1417–624 is a prototypical transient Be/X-ray binary, discovered by SAS-3 in 1978 (Apparao et al. 1980). It has an orbital period of ~ 42.12 d and an eccentricity e of ~ 0.446 and exhibits coherent X-ray pulsations with a period of ~ 17.64 s (Kelley et al. 1981; Finger et al. 1996). Its optical companion is a B1 Ve star (Grindlay et al. 1984). *Gaia* measurements place the system at a distance of $9.9^{+3.1}_{-2.4}$ kpc using the data release 2 (Bailer-Jones et al. 2018) and $7.4^{+3.1}_{-1.8}$ kpc using the data release 3 (Bailer-Jones et al. 2021), whereas torque modeling suggests a significantly greater distance of ~ 20 kpc (Ji et al. 2020). The surface magnetic field strength of the neutron star is estimated to be $\sim 9 \times 10^{12}$ G, inferred from the cyclotron resonant scattering feature (CRSF) detected at ~ 100 keV (Liu et al. 2024). The source has undergone several bright type-II outbursts in 1994, 1999, 2009, 2018, and 2021, during which the pulse profile, pulsed fraction, and their luminosity dependence show pronounced evolution. For example, the profile can evolve from double- to triple- or quadruple-peaked, and in some cases, the pulsed fraction anticorrelates with luminosity (Inam et al. 2004; Gupta et al. 2018, 2019; Ji et al. 2020; Liu et al. 2024, 2025). In addition to these bright events, the source exhibits lower-luminosity type-I outbursts near periastron, which are shorter in duration and significantly fainter (Finger et al. 1996). Systematic studies of type-I outbursts are scarce, with only a few studies (e.g., Inam et al. 2004) analyzing their pulse and spectral properties using 1999–2000 RXTE data.

In this work, we present an analysis of the timing and spectral characteristics of 2S 1417–624 during a new outburst observed in 2025 and report the first X-ray polarization measurement for this source. The remainder of this paper is organized as follows. Section 2 describes the long-term behavior of the source and provides an overview of the datasets analyzed. The main results are presented in Sect. 3, followed by a discussion in Sect. 4. Finally, Sect. 5 summarizes our findings and offers an outlook for future work.

2. Observations and data reduction

2S 1417–624 underwent a new type-II outburst in April 2025 that was significantly weaker than previous giant outbursts from the source, as revealed by continuous monitoring with all-sky X-ray instruments. Figure 1 shows the long-term light curves from MAXI¹ (Matsuoka et al. 2009) in the 2–20 keV band and from Swift/BAT² (Barthelmy et al. 2005) in the 15–50 keV band. The maximum brightness reached ~ 70 mCrab in the BAT band around MJD 60825, indicating a significant enhancement in the hard X-ray flux compared to the quiescent level. Around the outburst peak, the source also became harder, as indicated by an increase in the MAXI hardness ratio between the 4–10 and 2–4 keV bands. Following the peak, the source entered a slow decay and eventually returned to its pre-outburst flux level. The entire event lasted for roughly two months.

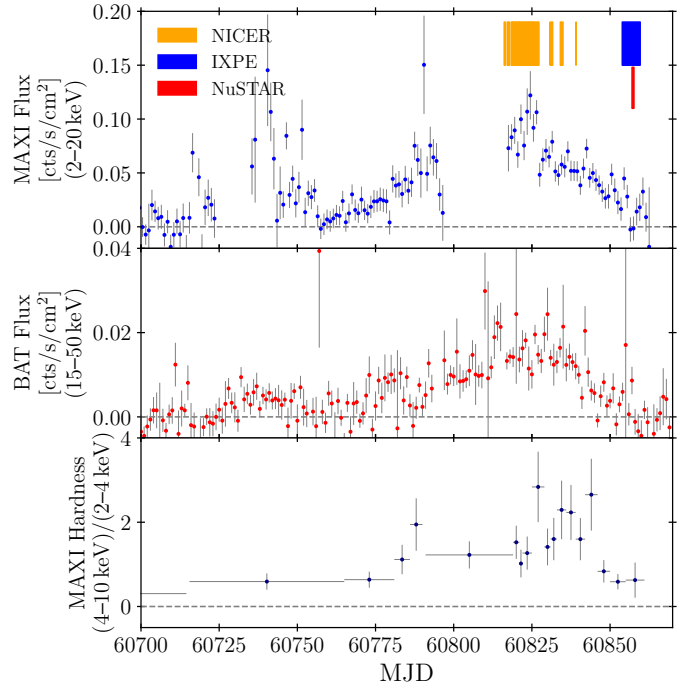


Fig. 1. Light curves of 2S 1417–624 during its 2025 outburst observed with MAXI and Swift/BAT. Bottom: Source hardness, defined as the ratio of the MAXI photon flux in the 4–10 keV band to that in the 2–4 keV band, rebinned to achieve a significance of at least 3σ . The NICER, IXPE, and NuSTAR observation periods are indicated by orange, blue, and red bars, respectively.

The outburst was observed with the Neutron Star Interior Composition Explorer (NICER; Gendreau et al. 2016), the Imaging X-ray Polarimetry Explorer (IXPE; Weisskopf et al. 2022), and the Nuclear Spectroscopic Telescope Array (NuSTAR; Harrison et al. 2013). An overview of the observations from each X-ray mission, along with the corresponding data reduction procedures, is provided below.

2.1. NICER

2S 1417–624 was observed with NICER between May 21 and June 13, 2025 (MJD 60816–60839), near the peak of the outburst, with a total effective exposure time of 27.5 ks. Data reduction was performed using HEASoft v6.36 and the xti20240206 calibration database. The cleaned event lists were generated by the standard `nicer12` task, which includes calibration and filtering steps. To minimize background effects, we applied a custom set of selection criteria to identify good time intervals (GTIs) based on standard NICER screening criteria: an overshoot rate lower than 10 cts per FPM (`FPM_OVERONLY_COUNT < 10`), an undershoot rate lower than 200 cts per FPM (`FPM_UNDERONLY_COUNT < 200`), and a geomagnetic cutoff rigidity greater than 1.5 GV (`COR_SAX > 1.5`). Spectra were extracted from the resulting GTIs using the `nicer13-spect` tool. The background spectrum was estimated with the `SCORPEON` model. The energy band for the spectral analyses is 0.7–10 keV.

2.2. IXPE

IXPE is a collaborative project between NASA and the Italian Space Agency, launched aboard a Falcon 9 rocket on

¹ <http://maxi.riken.jp/>

² <https://swift.gsfc.nasa.gov/results/transients/>

December 9, 2021, intending to conduct imaging polarimetry in the 2–8 keV energy range (Weisskopf et al. 2022). The observatory is composed of three identical grazing-incidence X-ray telescopes, each consisting of a mirror module and a polarization-sensitive detector unit (DU) that employs a gas pixel detector (Soffitta et al. 2021; Baldini et al. 2021). For every detected photon, IXPE records its sky position, arrival time, and energy, as well as the emission direction of the associated photoelectron, which is essential for deriving polarization information.

IXPE observed 2S 1417–624 from June 27 to July 3, 2025 (MJD 60853–60859), during which the source was in the final phase of its outburst, with a total effective exposure of 320 ks. We used data from all three DUs, including the reprocessed DU2 data provided by the IXPE team, which corrects for the pixel failures that occurred in April 2025, around MJD 60779.

The data were processed using the HEASoft package together with calibration files from the calibration database released on April 27, 2026. Before analysis, position offset corrections and energy calibration were applied. Source photons were extracted from a circular region of radius $R_{\text{src}} = 70''$ centered on the target, while the background was estimated from an annular region around the source, defined by inner and outer radii of $R_{\text{in}} = 120''$ and $R_{\text{out}} = 240''$, respectively. In the 2–8 keV energy range, the total source count rate from all the three DUs is approximately 0.3 cps, whereas the average background rate in the same band is about $0.001 \text{ cps arcmin}^{-2}$ per DU. Given the relatively low count rate, we performed both background rejection using version 3.2 of the rejection script and background subtraction in the polarimetric analysis, following the recommendations of Di Marco et al. (2023) and Di Marco (2026).

The Stokes I , Q , and U spectra for the three DUs were produced using the xselect tool, adopting the weighted method NEFF to improve the statistical significance (Di Marco et al. 2022). The corresponding ancillary response files were generated with ixpecalcarf, using the proper data files in the calibration database. The I spectra were then rebinned to ensure a minimum of 30 counts per energy channel, and the Q and U spectra were rebinned using a constant energy bin width of 120 eV, as suggested by Di Marco (2026). The resulting spectra were fitted simultaneously with the XSPEC package (version 12.15.1; Arnaud 1996). Fits were performed using χ^2 statistics, and uncertainties are quoted at the 68.3% confidence level (1σ), unless stated otherwise.

We also applied the tool ixpepolarization from the HEASoft package to carry out a model-independent polarimetric analysis. This approach bypasses the use of the full energy response matrix but incorporates energy dependence by assigning weights to individual photon contributions. All photons within the chosen time interval and energy range were included, and the Stokes parameters were derived via “unweighted” summation, as suggested by the IXPE team. We also performed background subtraction by conducting model-independent polarimetric analysis on both the source and background regions, obtaining the unnormalized Stokes parameters, and by applying a scaled subtraction to estimate the Stokes parameters and their associated uncertainties.

2.3. NuSTAR

NuSTAR observed 2S 1417–624 on July 1, 2025 (MJD 60857) with observation ID 91101319002 and an exposure time of approximately 32.5 ks, overlapping with the IXPE observation. We processed the data using nupipeline to produce the cleaned event files and employed nuproducts to extract the source and

Table 1. Orbital parameters for 2S 1417–624 (ephemeris adopted from the Fermi Gamma-ray Burst Monitor³).

Parameter	Value	Unit
Orbital period	42.175	d
$T_{\text{periastron}}$	51612.17000	MJD
$a_X \sin i$	188	light-sec
Longitude of periastron	300.30	deg
Eccentricity	0.4460	

background spectra and light curves. The source region was defined as a circular aperture with a radius of $120''$ centered on the source position, while the background region was chosen as a circular aperture of the same radius located as far from the source as possible.

3. Results

3.1. Pulsar timing studies and the pulse profiles

Before determining the precise pulse period, we first removed the effects of both the Earth’s motion and the binary’s orbital motion. Event arrival times were corrected to the Solar System barycenter using the barycorr tool from the FTOOLS package. To compensate for orbital motion, we applied additional corrections using the orbital ephemerides provided by the Fermi Gamma-ray Burst Monitor³ (Malacaria et al. 2020), which are based on the solutions of Finger et al. (1996) and İnam et al. (2004) but include an adjustment of the orbital period by $-1.25/84$ days, extrapolated to the epoch of the IXPE observation (see Table 1).

The pulse period (P) and its first derivative ($\dot{P}$) for the NICER and IXPE data were independently determined using Z^2 statistics with two harmonics (Bucccheri et al. 1983) by maximizing the Z^2 values from all photon events in the 0.7–10 keV band for NICER and the 2–8 keV band for IXPE. The resulting spin parameters and pulse epochs are listed in Table 2. The zero phase of the pulse profile is defined at the phase corresponding to the minimum count rate. Figure 2 shows the NICER and IXPE pulse profiles in their respective energy bands, together with phaseograms tracing the pulse profile evolution over 23 days for NICER and 6 days for IXPE. This method naturally maintains phase alignment over extended time spans, as illustrated in Fig. 2. For the NuSTAR data, since the observation lasted less than one day, only the pulse period was determined by maximizing the Z^2 values in the 3–79 keV band, as listed in the last column of Table 2.

The pulse profiles from NICER and IXPE are similar, each showing a prominent dip at phase zero and a shallower dip near phase ~ 0.45 . Both also display two broad peaks, each containing subtle sub-peaks. No significant changes in pulse shape are observed during either observational period. At higher energies, the pulse profile exhibits a sharper double-peaked structure than at lower energies, as indicated by the pulse profile analysis over the broad NuSTAR energy range shown in Fig. 3.

³ <https://gammaray.nsstc.nasa.gov/gbm/science/pulsars/lightcurves/2s1417.html>

Table 2. Pulsar ephemerides of 2S 1417–624 with NICER, IXPE, and NuSTAR.

Parameter	NICER	IXPE	NuSTAR
Start [MJD]	60816.2	60853.9	60857.0
End [MJD]	60839.1	60859.6	60857.6
Exposure [ks]	27.5	320.2	32.5
t_0 [MJD] ^a	60831.000178	60857.000098	60857.000098
Pulse period [s]	17.31294(1)	17.307216(6)	17.3072(2)
Pulse period derivative [10^{-9} s s^{-1}]	-4.36(1)	-1.38(8)	$ \dot{P} \leq 7.5$

Notes. The uncertainties are reported at a 1σ confidence level. ^aThe reported reference time, t_0 , defines the zero phases of the pulse profiles (see Fig. 2).

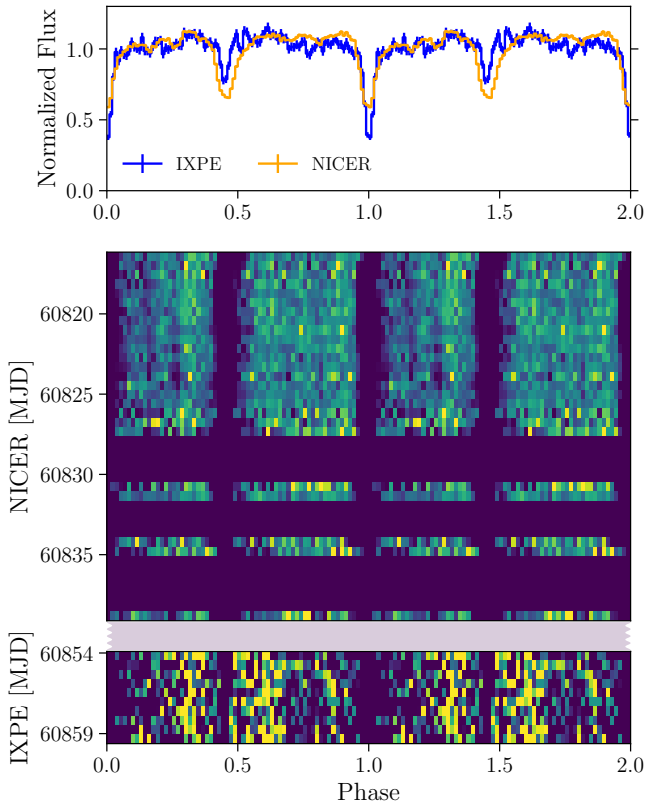


Fig. 2. Pulse profiles of 2S 1417–624, observed by NICER and IXPE, and their phaseograms as a function of time (MJD). The fluxes are normalized to a unit mean. The profiles use 100 phase bins, and the phaseograms use 64 phase bins. The phaseograms are divided into 40 time bins for NICER and 10 for IXPE.

3.2. Spectral analysis

3.2.1. Phase-averaged spectral analysis

NICER’s large effective area in the soft X-ray band ($\sim 1900 \text{ cm}^2$ at $\sim 1.5 \text{ keV}$) makes it particularly effective for probing soft X-ray emission, whereas NuSTAR’s broader energy coverage, extending up to $\sim 79 \text{ keV}$, provides strong constraints on the continuum slope at high energies.

We adopted a systematic error of $\sim 1.5\%$ for all NICER/XTI spectra, as set by default in the `nicer13-spect` tool. All NICER spectra were grouped using the optimal binning method described by [Kaastra & Bleeker \(2016\)](#), ensuring a minimum of 30 counts per bin.

The spectra of 2S 1417–624 in the soft energy band (0.7–10 keV) can be well described by an absorbed broken power

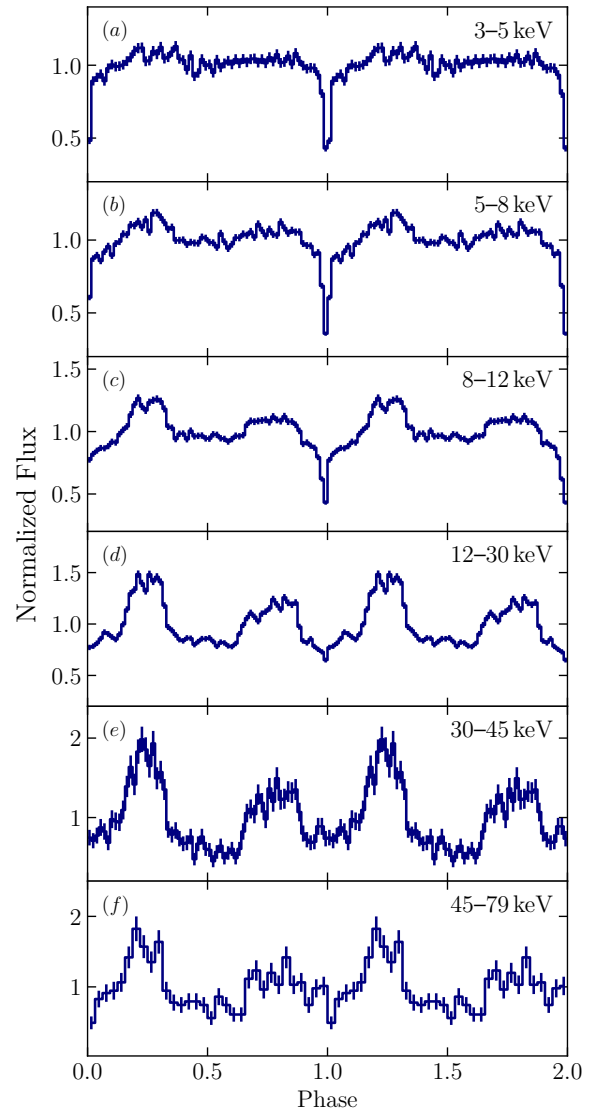


Fig. 3. Pulse profiles at different energies observed by NuSTAR. The fluxes are normalized such that their mean values equal unity.

law, plus a Gaussian emission line at $\sim 6.4 \text{ keV}$ corresponding to the iron fluorescent line. However, the break energy of the broken power law (E_{break} , typically around 4–6 keV) is poorly constrained in the NICER spectral fits, which also prevents the high-energy photon index Γ_2 from being well determined. To obtain smoother spectra and reduce the number of free parameters, we therefore replaced the broken power law with a cutoff

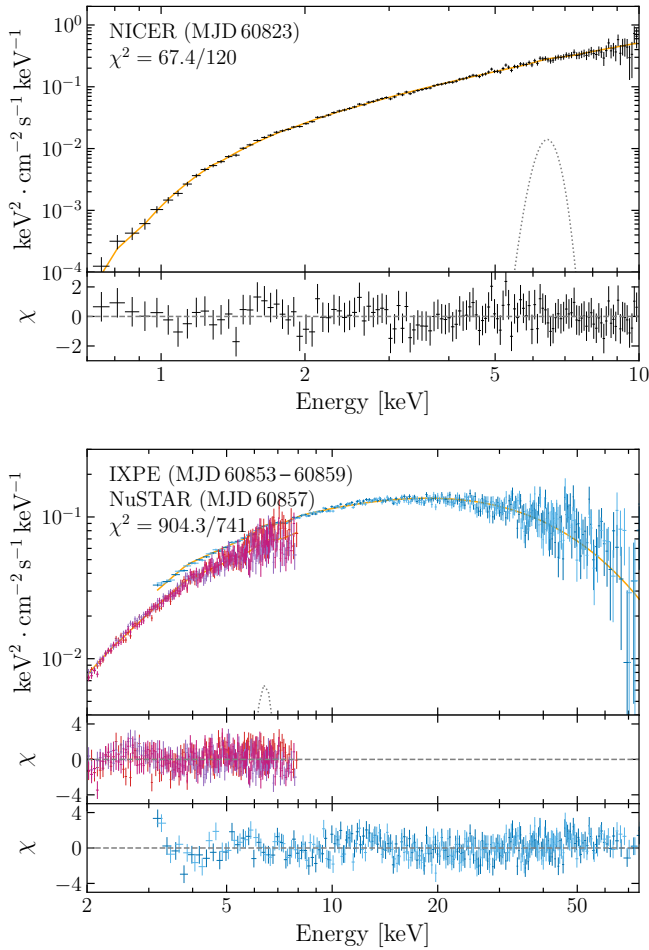


Fig. 4. Spectral composition of a representative phase-averaged NICER spectrum and the IXPE-NuSTAR spectra. Upper panel: NICER data fitted with the model $\text{TBabs} \times (\text{cutoffpl} + \text{gaussian})$. The solid orange line represents the best-fitting model, while the dotted gray line indicates the Gaussian component at 6.4 keV. Lower panel: IXPE and NuSTAR data jointly fitted with the model $\text{TBabs} \times (\text{bknpower} \times \text{highcut} + \text{gaussian})$. The blue and cyan crosses correspond to the FPMA and FPMB data, respectively, while the red, purple, and magenta crosses correspond to the DU1, DU2, and DU3 data. The solid orange line shows the best-fitting model, and the dotted gray line represents the Gaussian component at 6.4 keV.

power-law model. In XSPEC, the model can be written as

$$\text{TBabs} \times (\text{cutoffpl} + \text{Gaussian}),$$

where TBabs accounts for photoelectric absorption by the interstellar medium, with cross sections from [Verner et al. \(1996\)](#) and elemental abundances from [Wilms et al. \(2000\)](#). The centroid energy of the Gaussian component is fixed at 6.4 keV, while the width parameter, σ , is constrained to an upper limit of 0.3 keV, corresponding to a narrow iron line.

We first carried out spectral analysis of the phase-averaged data, which provides a more reliable representation of the spectral shape over an extended timescale. A representative spectrum is shown in the upper panel of Fig. 4, and the best-fit parameters resulting from the spectral analysis are presented in Fig. 5 as a function of time. No significant variations are found in the key spectral parameters during the NICER observations, except for the source luminosity, which initially increases and subsequently stabilizes. The equivalent hydrogen column density (N_H) toward 2S 1417–624 is consistently measured to be $\sim 1.2 \times 10^{22} \text{ cm}^{-2}$.

Table 3. Best-fit spectral parameters from the phase-averaged NuSTAR and IXPE spectra with the model $\text{constant} \times \text{TBabs} \times (\text{bknpower} \times \text{highcut} \times \text{polconst}_1 + \text{Gaussian} \times \text{polconst}_2)$.

Component	Parameter	Value
TBabs	$N_H [10^{22} \text{ cm}^{-2}]$	1.2 (fixed)
bknpower	Γ_1	0.09 ± 0.03
	$E_{\text{break}} [\text{keV}]$	$3.86^{+0.06}_{-0.07}$
	Γ_2	1.00 ± 0.02
highcut	$E_{\text{cut}} [\text{keV}]$	8.2 ± 0.2
	$E_{\text{fold}} [\text{keV}]$	18.6 ± 0.3
polconst ₁	PD [%]	4.8 ± 1.2
	PA [deg]	17 ± 7
Gaussian	$E_{\text{line}} [\text{keV}]$	6.4 (fixed)
	$\text{EW}_{\text{Fe}} [\text{eV}]$	62 ± 12
	$\sigma_{\text{Fe}} [\text{keV}]$	$0.30^{p}_{-0.01}$
polconst ₂	PD [%]	0 (fixed)
constant	const _{NuSTAR/FPMA}	1 (fixed)
	const _{NuSTAR/FPMB}	0.994 ± 0.004
	const _{IXPE/DU1}	0.779 ± 0.006
	const _{IXPE/DU2}	0.786 ± 0.006
	const _{IXPE/DU3}	0.769 ± 0.006
	Flux _{2–79 keV} ^a	$(4.91 \pm 0.02) \times 10^{-10}$
	$\chi^2/\text{d.o.f.}$	1184.2/1033

Notes. The uncertainties are given at the 68.3% (1σ) confidence level and were obtained using the `error` command in XSPEC with $\Delta\chi^2 = 1$ for one parameter of interest. ^(a)Unabsorbed flux in units of $\text{erg s}^{-1} \text{ cm}^{-2}$ in the 2–79 keV range. ^(p)The symbol *p* denotes that the parameter hits its upper boundary.

The NuSTAR spectra were grouped following the same procedure as adopted for the NICER data, and spectral fitting was performed over the 3–79 keV energy range. Since the absorbing column density is well constrained by the NICER observations, we fixed this value at $1.2 \times 10^{22} \text{ cm}^{-2}$ for the IXPE-NuSTAR simultaneous observation. A multiplicative constant was included to account for the slight normalization differences between FPMA and FPMB.

Owing to the broadband coverage of NuSTAR, the high-energy photon index, Γ_2 , can be well constrained, together with the break energy (E_{break}) of the power-law component at lower energies. To describe the full continuum, we adopted the combination $\text{bknpower} \times \text{highcut}$. A narrow iron line was also included in our model. The Stokes *I* spectra from the simultaneous IXPE observation were incorporated in the fit to perform a joint spectral analysis. We therefore adopted the model

$$\text{constant} \times \text{TBabs} \times (\text{bknpower} \times \text{highcut} + \text{Gaussian}),$$

which yields a fit with $\chi^2/\text{d.o.f.} = 904.3/741$, as shown in the lower panel of Fig. 4. This model is commonly used in spectral analyses of accreting XRP (see, e.g., [Hemphill et al. 2019](#); [Serim et al. 2022](#); [Mandal & Pal 2022](#)). The best-fit parameters are summarized in Table 3.

3.2.2. Phase-resolved spectral analysis

To investigate spectral variability as a function of rotational phase, we performed phase-resolved spectroscopy of the NICER and IXPE-NuSTAR data. This method enables the examination of changes in the continuum shape and line features across the pulse profile, offering insights into the geometry and emission

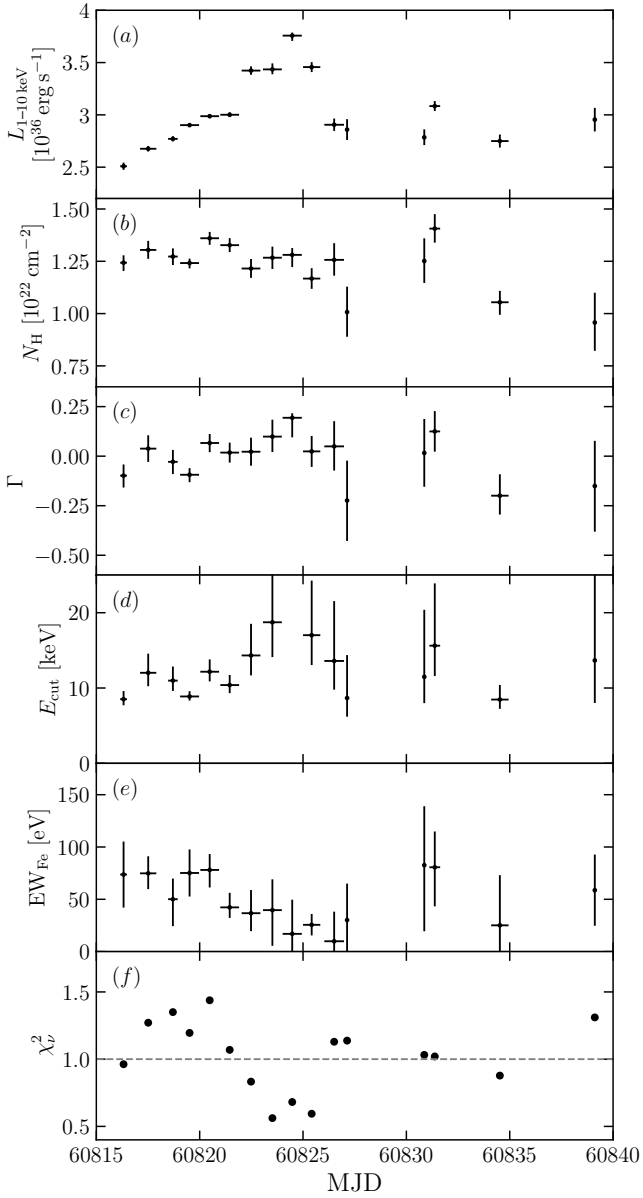


Fig. 5. Evolution of the key parameters of 2S 1417–624 obtained from NICER phase-averaged spectral analysis as a function of time. From (a) to (f): 1–10 keV luminosity assuming a distance of 7.4 kpc; equivalent hydrogen column density, N_{H} , of the interstellar medium; photon index, Γ , and cutoff energy, E_{cut} , of the continuum; equivalent width of the iron $K\alpha$ line at 6.4 keV; and reduced chi-square, χ^2_{ν} , of the best fits.

mechanisms of the system. The pulse phase was computed using the ephemerides listed in Table 2 according to

$$\phi = \frac{1}{P}(t - t_0) - \frac{1}{2} \frac{\dot{P}}{P^2}(t - t_0)^2, \quad (1)$$

where P is the pulse period and $\dot{P}$ is its time derivative at the reference epoch t_0 , with t_0 also defining the zero phase. The data were divided into ten equally spaced phase bins, with source spectra and background spectra extracted using the corresponding GTIs. Each spectrum was fitted with the same model used in the phase-averaged analysis to trace the evolution of the emission components over the pulsation cycle.

In Fig. 6, we show the key parameters of the phase-resolved spectra, together with their average values in each phase bin, to

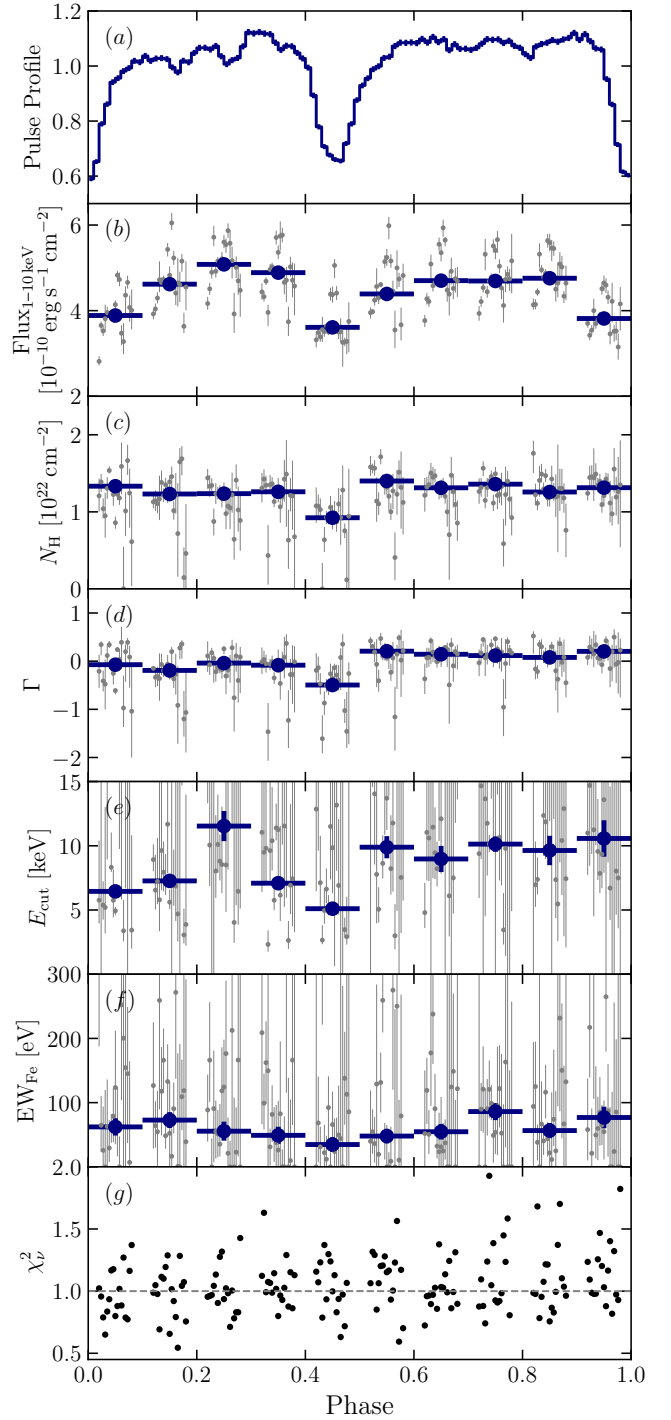


Fig. 6. Phase-dependent parameters of 2S 1417–624 obtained from NICER phase-resolved spectral analysis. From (a) to (g): Normalized pulse profile measured by NICER; unabsorbed flux in 1–10 keV; equivalent hydrogen column density, N_{H} , of the interstellar medium; photon index, Γ , and cutoff energy, E_{cut} , of the continuum; equivalent width of the iron $K\alpha$ line at 6.4 keV; and reduced chi-square, χ^2_{ν} , of the best fits of each spectrum. The gray dots indicate measurements from the phase-resolved spectral analysis of individual observations (slightly offset for clarity), while the navy dots represent the average parameter values in each phase bin.

examine their modulation with pulse phase. The decrease in the unabsorbed flux likely produces the dips observed at phases 0.0 and 0.45. The iron line is relatively weak during the NICER

observation period, while the other parameters exhibit systematic modulations with pulse phase.

For the NuSTAR observation, we primarily used the data to constrain the slope of the continuum and the strength of the narrow iron fluorescent line in the phase-resolved polarimetric analysis together with the IXPE Stokes I , Q , and U spectra. The results are presented in Sect. 3.3.2.

3.3. Polarimetric analysis

The exploratory polarimetric analysis of 2S 1417–624 was carried out in XSPEC, fully accounting for both energy dispersion and the source’s spectral shape. Stokes I , Q , and U spectra were first extracted from all three DUs, following the methods in Sect. 2.2. All nine spectra were then fitted simultaneously with XSPEC.

The source continuum is well described by an absorbed broken power law with a high-energy cutoff. Given the relatively soft X-ray band of IXPE, we performed a joint spectral fit with the phase-resolved NuSTAR spectra and adopted a phenomenological model that includes polarimetric information:

$$\text{constant} \times \text{TBabs} \times (\text{bknpower} \times \text{highcut} \times \text{polconst}_1 + \text{Gaussian} \times \text{polcosnt}_2),$$

where `constant` accounts for cross-calibration between the five detectors, with the NuSTAR/FPMA factor fixed at unity. The `polconst1` component was used to model polarization, assuming an energy-independent PD and PA, while the PD of `polconst2` was fixed at 0, consistent with the assumption that the emission line is unpolarized. This setup was applied to both phase-averaged and phase-resolved analyses.

Additionally, the model-independent `ixpepolarization` method was employed as a reference to the XSPEC results, since the two approaches are expected to produce consistent outcomes. We calculated the normalized Stokes parameters $q = Q/I$ and $u = U/I$, the PD as $\text{PD} = \sqrt{q^2 + u^2}$, and the PA as $\text{PA} = \frac{1}{2} \arctan(u/q)$, measured counterclockwise from north to east on the sky (Kislat et al. 2015).

3.3.1. Phase-averaged polarimetric analysis

A joint phase-averaged polarimetric analysis of the IXPE–NuSTAR observation over the full 2–79 keV band was conducted, with the results summarized in Table 3. We measure a PD of $4.8 \pm 1.2\%$ and a PA of $17^\circ \pm 7^\circ$. Assuming a source distance of $d \approx 7.4$ kpc (Bailer-Jones et al. 2021), the corresponding luminosity of 2S 1417–624 at the end of the outburst is estimated as $L \approx 3.2 \times 10^{36} \text{ erg s}^{-1}$ in the 2–79 keV band.

To investigate possible spectral trends, we performed an energy-resolved polarimetric analysis by dividing the data into five intervals (2–3, 3–4, 4–5, 5–6, and 6–8 keV). Fitting was carried out in XSPEC, using the full 2–8 keV range for the IXPE Stokes I spectra and excluding bins outside the energy range of interest for the Stokes Q and U spectra. The results are presented in Table 4. For comparison, we also applied the unweighted model-independent `ixpepolarization` algorithm, which yielded broadly consistent values.

Most energy bins show no significant polarization, with the exception of the 5–6 keV interval, where a relatively high PD is detected. This excess is intriguing given that no additional spectral component is observed in this band, suggesting that the polarization signal may instead reflect phase-dependent variations in the PA. Although the overall phase-averaged PD is mod-

Table 4. Polarimetric parameters in different energy bins for the IXPE observations using the XSPEC and `ixpepolarization` methods.

Energy [keV]	PD _{XSPEC} [%]	PA _{XSPEC} [deg]	PD _{ixpepol} [%]	PA _{ixpepol} [deg]
2–3	5 ± 3	14 ± 15	6 ± 3	13 ± 15
3–4	2 ± 2	17 ± 34	3 ± 2	20 ± 20
4–5	$<8^\dagger$	...	$<6^\dagger$	...
5–6	14 ± 4	15 ± 7	14 ± 4	26 ± 8
6–8	8 ± 4	1 ± 16	7 ± 4	-10 ± 20
2–8	4.8 ± 1.2	17 ± 7	4.5 ± 1.4	17 ± 9

Notes. The uncertainties computed using the `error` command are given at the 68.3% (1σ) confidence level ($\Delta\chi^2 = 1$ for one parameter of interest). ^(†)The PD is not significantly detected at the 1σ confidence level; therefore, we report the corresponding 90% confidence upper limit on the PD ($\Delta\chi^2 = 2.71$ for the XSPEC method, and by solving the cumulative distribution function of PD for `ixpepolarization` method).

est, the localized enhancement around 5–6 keV points to underlying geometric or emission-related effects that warrant further investigation.

3.3.2. Phase-resolved polarimetric analysis

Investigating the phase-dependent properties of pulsars is essential, as their geometry evolves with rotation. Using the ephemerides listed in Table 2, the phase of each photon event was calculated by Eq. (1). The photons were divided into ten evenly spaced phase bins, consistent with the phase-resolved analyses of NICER and NuSTAR. For each phase bin, Stokes I , Q , and U spectra were generated following the procedure described in Sect. 2.2.

We first applied the XSPEC method to each phase bin, restricting the analysis to the 2–8 keV energy range for IXPE data and 3–79 keV for NuSTAR. The results for the combined dataset are summarized in Table 5 and illustrated in Figs. 7–9. Polarization is marginally detected at a significance level exceeding 1σ in eight of the ten phase bins, providing tentative evidence for phase-dependent polarization associated with the emission geometry of the accretion column.

The model-independent `ixpepolarization` algorithm was then applied to the phase-resolved data, and the results are presented in the last two columns of Table 5. In general, the polarimetric parameters derived from `ixpepolarization` are consistent with those obtained with XSPEC, even though a weighted method was adopted in XSPEC, whereas an unweighted method was used in `ixpepolarization`.

4. Discussion

4.1. The rotating vector model and the geometry of the pulsar

In Sect. 3.3.2, we demonstrated that the PA varies with phase. Utilizing the polarimetric measurements in the eight detectable bins, we aim to explore whether some geometrical parameters can be derived using the RVM (Radhakrishnan & Cooke 1969; Meszaros et al. 1988; Poutanen 2020), which has been successfully applied to several XRP observed by IXPE (see, e.g., Doroshenko et al. 2022; Tsygankov et al. 2022; Mushtukov et al. 2023; Doroshenko et al. 2023; Tsygankov et al. 2023; Forsblom et al. 2024). In brief, when the

Table 5. Spectro-polarimetric measurement for different pulse-phase bins of 2S 1417–624 from the IXPE observations in the 2–8 keV band, derived using XSPEC and ixpepolarization.

No.	Phase	PD _{XSPEC} [%]	PA _{XSPEC} [deg]	$\chi^2/\text{d.o.f.}$	PD _{ixpepol} [%]	PA _{ixpepol} [deg]
1	0.00–0.10	5 ± 4	−30 ± 30	641.6/681	<11 [†]	...
2	0.10–0.20	8 ± 4	13 ± 14	613.5/681	8 ± 4	13 ± 16
3	0.20–0.30	7 ± 4	28 ± 17	682.6/704	11 ± 4	8 ± 12
4	0.30–0.40	5 ± 4	20 ± 30	672.0/709	7 ± 4	0 ± 20
5	0.40–0.50	10 ± 4	61 ± 12	646.6/685	9 ± 4	68 ± 15
6	0.50–0.60	6 ± 4	−60 ± 20	644.9/661	6 ± 4	−40 ± 20
7	0.60–0.70	<8 [†]	...	663.1/696	<9 [†]	...
8	0.70–0.80	20 ± 4	−2 ± 6	673.8/698	16 ± 4	−1 ± 8
9	0.80–0.90	13 ± 4	35 ± 9	700.3/722	13 ± 4	43 ± 10
10	0.90–1.00	<11 [†]	...	620.4/690	10 ± 5	48 ± 15

Notes. The uncertainties in the spectro-polarimetric parameters, computed using the `error` command in XSPEC, are provided at the 68.3% (1σ) confidence level ($\Delta\chi^2 = 1$ for one parameter of interest). The right two columns give PD and PA estimated with the `ixpepolarization` algorithm and the uncertainties given at the 1σ confidence level. ^(†)The PD is not significantly detected at the 1σ confidence level; therefore, we report the corresponding 90% confidence upper limit on the PD ($\Delta\chi^2 = 2.71$ for XSPEC method, and by solving the cumulative distribution function of PD for `ixpepolarization` method).

emission is dominated by ordinary-mode (O-mode) photons, the RVM predicts that the PA follows Eq. (30) from Poutanen (2020):

$$\tan(\text{PA} - \chi_p) = \frac{-\sin\theta \sin(\phi - \phi_0)}{\sin i_p \cos\theta - \cos i_p \sin\theta \cos(\phi - \phi_0)}, \quad (2)$$

where χ_p is the position angle of the pulsar angular momentum measured from north to east, i_p is the inclination of the neutron star angular momentum to the line of sight, θ is the angle between the spin axis and the magnetic dipole, and ϕ_0 indicates the phase when the northern magnetic pole passes in front of the observer.

If the observed radiation is dominated by the extraordinary mode (X-mode), the position angle of the pulsar’s angular momentum is given by $\chi_p \pm 90^\circ$. In the nonrelativistic case, the PA is independent of the PD of the radiation emerging from the neutron star surface.

The distribution of PA deviates from a normal distribution, particularly when the PD is low. Therefore, we adopted the probability density function of the PA, ψ , as derived by Naghizadeh-Khouei & Clarke (1993):

$$G(\psi) = \frac{1}{\sqrt{\pi}} \left\{ \frac{1}{\sqrt{\pi}} + \eta e^{\eta^2} [1 + \text{erf}(\eta)] \right\} e^{-p_0^2/2}, \quad (3)$$

where $p_0 = \text{PD}/\text{PD}_{\text{err}}$ is the measured PD in units of its error, $\eta = p_0 \cos[2(\psi - \psi_0)] / \sqrt{2}$, and ψ_0 is the expectation value of PA. Here, `erf` denotes the error function.

The best-fit RVM parameters were obtained by maximizing the likelihood function $\log L = \sum \log G(\psi)$. To explore the parameter space, we employed the Markov chain Monte Carlo (MCMC) ensemble sampler implemented in the UltraNest package (Buchner 2021) to compute the posterior distributions of the four free RVM parameters. The resulting best-fit values from PAs derived by both the XSPEC and `ixpepolarization` methods are summarized in Table 6. We show the corresponding covariance plots using the XSPEC method in Fig. 10 and the best-fit RVM curve to the measured PAs in Fig. 9. The parameter distributions obtained from the two methods are consistent within their respective uncertainties.

Table 6. Best-fit RVM parameters for 2S 1417–624, derived from PAs measured with IXPE using the XSPEC, `ixpepolarization`, and the unbinned photon-by-photon methods.

Parameter	XSPEC	ixpepol	unbinned method
χ_p [deg]	−90 ⁺²⁰ _{−30}	−70 ⁺⁷⁰ _{−30}	−100 ⁺⁴⁰ _{−20}
θ [deg]	69 ⁺¹³ _{−29}	77 ⁺¹⁰ _{−42}	50 ± 20
i_p [deg]	30 ⁺³⁰ _{−20}	40 ± 40	20 ⁺¹⁷ _{−12}
$\phi_0/2\pi$	−0.03 ^{+0.07} _{−0.09}	0.0 ^{+0.3} _{−0.2}	−0.09 ^{+0.10} _{−0.06}

We also applied the unbinned photon-by-photon method to fit the RVM (González-Caniulef et al. 2023) (see also Malacaria et al. 2023 and Suleimanov et al. 2023 for examples). In this approach, we assumed a constant PD while allowing the PA to vary across the pulse phase. The results, presented in the last column of Table 6 and in Fig. 11, are consistent within uncertainties with those obtained from the binned PA fittings using XSPEC and `ixpepolarization`. Notably, we obtain a more significant PD of $5.9 \pm 1.2\%$ across the phase, corresponding to a detection significance of 5.1σ . This outcome is expected: variable PA naturally reduces the phase-averaged PD (with the extreme case of X Persei; see Mushtukov et al. 2023), but when the variation of PA is accounted for, the unbinned method provides a more appropriate assessment of the overall detection significance than the phase-averaged PD reported in Sect. 3.3.1. We caution, however, that the instrument’s effective area was not considered in this approach. Since the effective area of IXPE peaks at ~ 2 keV, most of the detected photons are concentrated in this energy range, which may introduce bias into the fit.

Although subject to considerable uncertainties, the RVM fit suggests that 2S 1417–624 possesses a large magnetic obliquity, compatible with a quasi-orthogonal geometry, though smaller obliquities cannot be entirely ruled out. The ϕ_0 angle, which denotes the phase at which the northern magnetic pole comes closest to the observer, is well constrained to be near phase zero, coinciding with the main dip in the pulse profile. Such a geometry approaches that of an orthogonal rotator, an extreme case of pulsar configuration that gives rise to the most pronounced

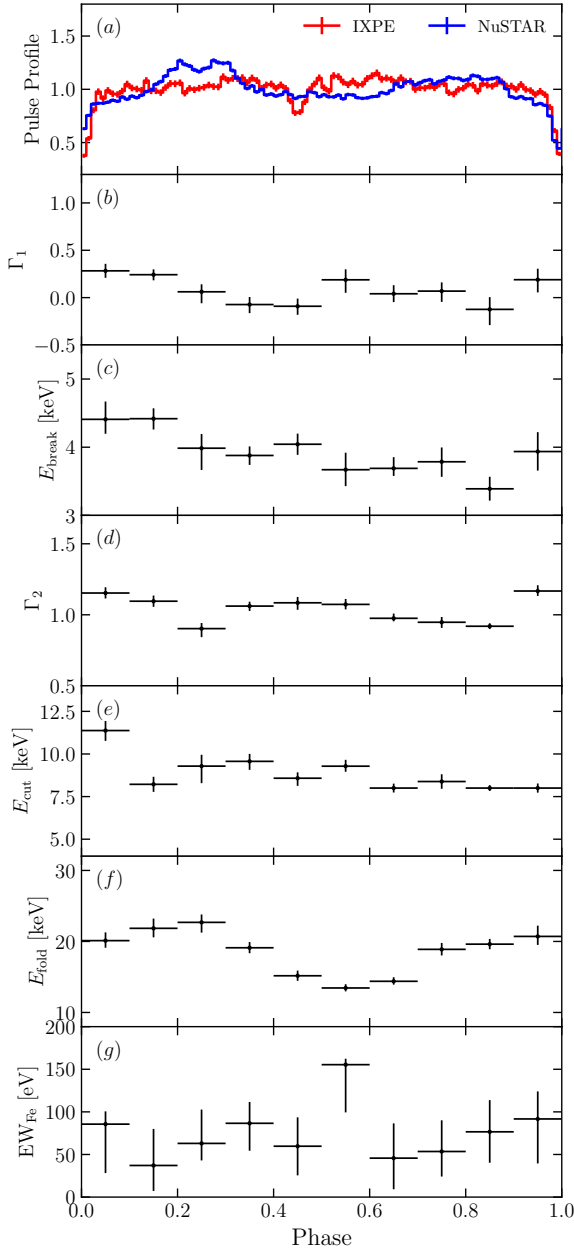


Fig. 7. Phase-dependent spectral parameters of 2S 1417–624 derived from the joint IXPE and NuSTAR spectral-polarimetric analysis. From (a) to (g): Normalized pulse profile, soft photon index Γ_1 , break energy E_{break} , hard photon index Γ_2 , cutoff energy E_{cut} and folding energy E_{fold} of the highecut component, and equivalent width of the iron $K\alpha$ line at 6.4 keV.

emission and polarization signatures, and is therefore of fundamental importance for probing the magnetic field structure, radiation mechanisms, and geometrical evolution of neutron stars.

4.2. A more detailed polarimetric investigation in the 5–6 keV band

As shown in Sect. 3.3.1, the 5–6 keV band exhibits a notably stronger polarization than the other energy bands. This may indicate either that photons in this band have an intrinsically higher PD while following a PA modulation similar to that at other energies or that the PA modulation itself becomes weaker or changes with energy in the 5–6 keV band. To investigate this possibil-

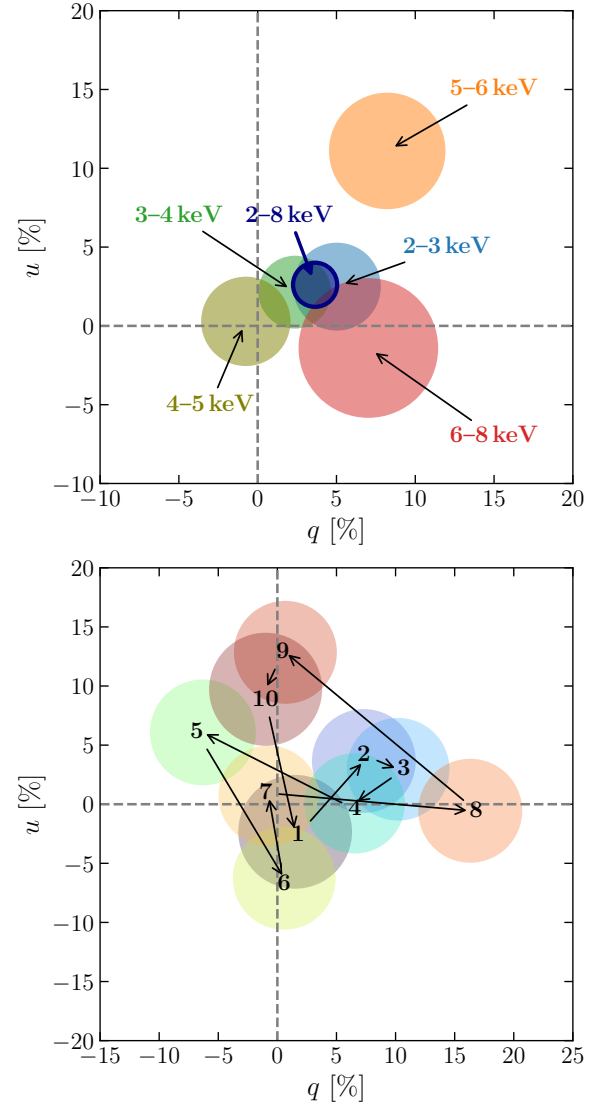


Fig. 8. Energy and phase dependence of the normalized Stokes parameters q and u during the IXPE observation, obtained using the ixpepolarization algorithm. For the phase-dependent analysis, the Stokes parameters were calculated in the 2–8 keV band. The 1σ confidence contours are shown as colored circles around each best-fit estimate.

ity, we followed the approach of Zhao et al. (2026) and divided the IXPE energy range into three bands: 2–5 keV, 5–6 keV, and 6–8 keV.

We then used the XSPEC method to measure the phase-resolved PAs and PDs in each energy band. The results are shown in Table 7 and Fig. 12. We find some PA discrepancies between different energy bands in individual phase bins. The largest difference occurs in the phase interval 0.90–1.00, where the PAs in the 5–6 keV and 6–8 keV bands differ by $\Delta\text{PA} \approx 68^\circ$, corresponding to a significance of 3.8σ . The second largest discrepancy is found in the phase interval 0.20–0.30, between the 2–5 keV and 6–8 keV bands, with $\Delta\text{PA} \approx 90^\circ$, corresponding to 2.2σ .

We fitted the RVM independently in the three energy bands but found that the resulting parameter constraints are rather weak (see Table 8). We also attempted a simultaneous fit to the Stokes parameters Q/U across the three energy bands (see Table A.1 in the Appendix), without including an additional

Table 7. Phase-resolved spectro-polarimetric measurements of 2S 1417–624 in different energy bands, derived using the XSPEC method.

No.	Phase	2–5 keV		5–6 keV		6–8 keV	
		PD [%]	PA [deg]	PD [%]	PA [deg]	PD [%]	PA [deg]
1	0.00–0.10	6 ± 5	-40 ± 30	20 ± 13	20 ± 20	$<37^{\dagger}$	...
2	0.10–0.20	$<10^{\dagger}$	...	18 ± 11	10 ± 20	39 ± 14	13 ± 11
3	0.20–0.30	7 ± 5	20 ± 20	22 ± 12	31 ± 16	16 ± 14	-80 ± 30
4	0.30–0.40	$<11^{\dagger}$	...	27 ± 11	32 ± 12	17 ± 13	60 ± 30
5	0.40–0.50	12 ± 5	54 ± 11	$<29^{\dagger}$	...	17 ± 14	70 ± 30
6	0.50–0.60	8 ± 5	-73 ± 17	17 ± 12	-20 ± 20	$<25^{\dagger}$	...
7	0.60–0.70	$<11^{\dagger}$	...	20^{+12}_{-11}	-6 ± 17	$<32^{\dagger}$	...
8	0.70–0.80	20 ± 5	2 ± 7	13 ± 12	-30 ± 40	32 ± 12	-8 ± 11
9	0.80–0.90	11 ± 5	34 ± 12	33 ± 12	21 ± 11	21 ± 14	50 ± 20
10	0.90–1.00	6 ± 5	70 ± 30	31 ± 13	21 ± 12	35 ± 15	-47 ± 13

Notes. The uncertainties in the spectro-polarimetric parameters, computed using the `error` command in XSPEC, are provided at the 68.3% (1σ) confidence level ($\Delta\chi^2 = 1$ for one parameter of interest). ^(†)The PD is not significantly detected at the 1σ confidence level; therefore, we report the corresponding 90% confidence upper limit on the PD ($\Delta\chi^2 = 2.71$ for XSPEC method).

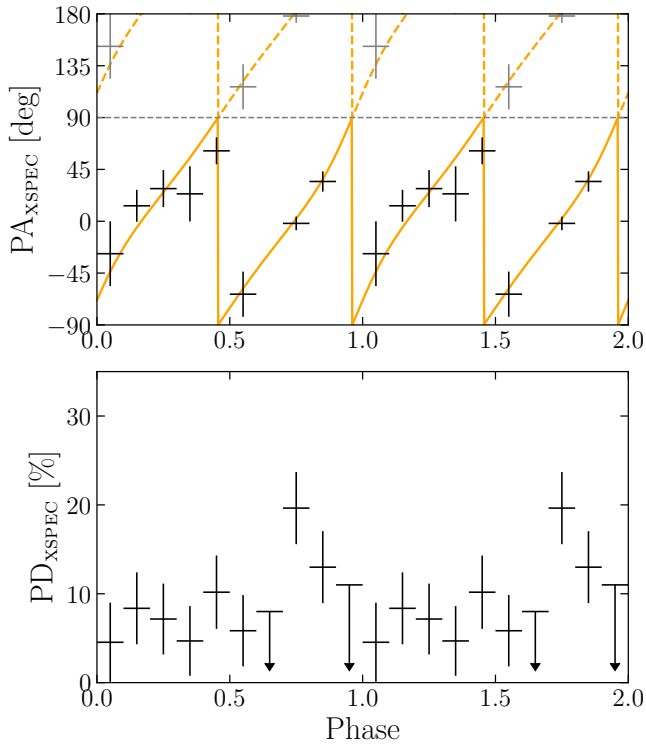


Fig. 9. Pulse-phase dependence of PA and PD in the 2–8 keV band derived using the XSPEC method. For the phase bins in which the PD is not significantly detected at the 1σ confidence level, we do not report PA values. Instead, we quote the 90% upper limits on the PD. Some PAs are shown twice with an added offset of 180° to illustrate phase continuity. The solid orange curve denotes the best-fit RVM to the original PA measurements.

constant polarized component, and obtained $\chi^2/\text{d.o.f.} = 26.8/56$. This fit yields the strongest constraints on the RVM parameters, as shown in the last column of Table 8 and in Fig. 13. The magnetic obliquity θ is tightly constrained to be close to a right angle, while the inclination of the neutron-star spin axis is approximately 60° . However, the very low reduced χ^2 suggests that the fit is likely overfitting the data. For this reason, we did not include an additional constant polarized component in our model. In addition, Fig. 12 shows that the PAs measured in

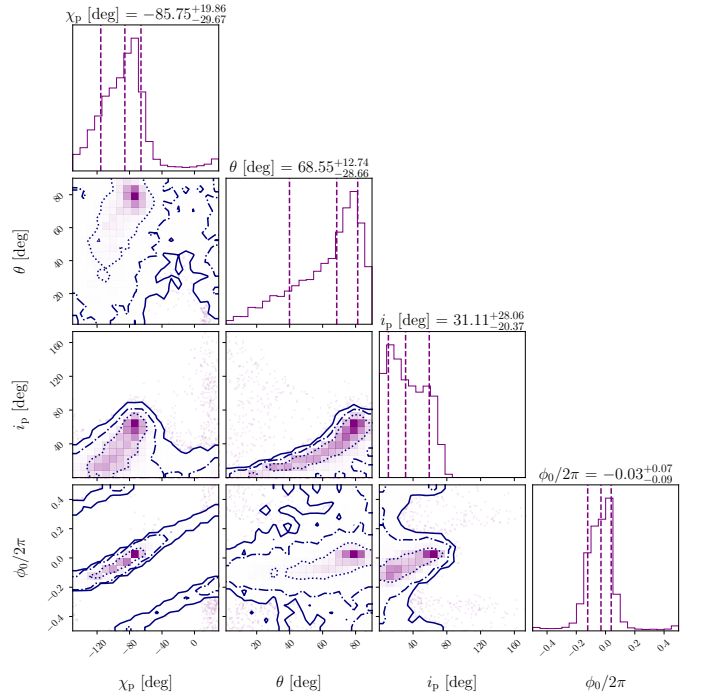


Fig. 10. Corner plot showing the posterior distributions of the RVM parameters describing the pulsar geometry, obtained from the PA values in the phase-resolved spectro-polarimetric analysis of the IXPE observation. The 2D contours represent the 68.27%, 95.45%, and 99.73% confidence levels, while the histograms display the normalized 1D distributions for each parameter derived from the posterior samples. The mean values and corresponding 1σ confidence intervals are indicated above each histogram, with the dashed lines marking these intervals.

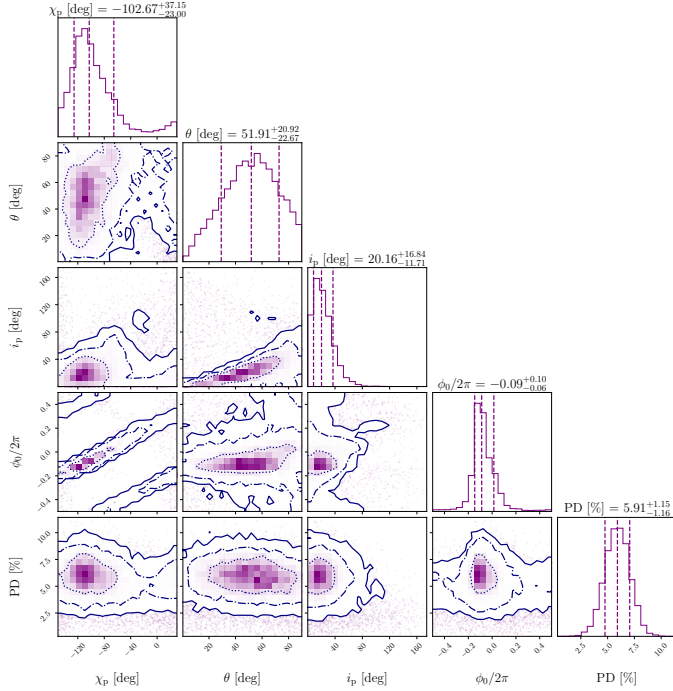
the individual energy bands remain compatible with a common RVM model across all three bands, although the resulting PA modulation may differ from the best-fit RVM curves obtained for the individual bands.

The PD values in the 5–6 keV band are higher than those in the 2–5 keV band in most phase bins. However, due to the large statistical uncertainties, these differences are not significant in individual phase bins. The enhanced polarization in the 5–6 keV band may be related to this interval sampling a relatively clean continuum window, whereas the broader bands

Table 8. Best-fit RVM parameters for 2S 1417–624 in different energy bands, derived from the PAs measured with IXPE using the XSPEC method.

Parameter	2–5 keV	5–6 keV	6–8 keV	Cross-fitting
χ_p [deg]	-60^{+60}_{-40}	13^{+7}_{-9}	-113^{+19}_{-15}	-80^{+9}_{-11}
θ [deg]	73^{+15}_{-29}	13^{+15}_{-8}	43 ± 19	84^{+4}_{-6}
i_p [deg]	14^{+23}_{-11}	80^{+40}_{-30}	28^{+21}_{-15}	64^{+8}_{-12}
$\phi_0/2\pi$	-0.2 ± 0.3	0.39 ± 0.13	-0.14 ± 0.04	-0.02 ± 0.04

Notes. The last column also reports the simultaneous best-fit RVM to the Stokes parameters Q/U across the three energy bands.


Fig. 11. Similar to Fig. 10 but showing the values derived from the unbinned photon-by-photon method.

may be more strongly diluted by additional weakly polarized or unpolarized components, such as reprocessed emission and fluorescent lines. At the same time, the PA differences seen in some phase bins suggest that simple dilution alone may not fully explain the broadband polarization behavior. Instead, the data may require the superposition of multiple components with distinct polarization properties.

The observed energy dependence is also likely coupled to the pulse phase. This implies that the relative contributions of the different emission and reprocessing components change as the neutron star rotates, naturally producing phase-dependent variations in both PD and PA. In this picture, the polarization measurements indicate that the observed radiation in the 2–8 keV band does not originate from a single homogeneous emission region, but instead reflects a combination of direct accretion-column emission and additional phase-dependent reprocessed components.

At present, few attempts have been made to explain the relatively smooth energy dependence of the PA in XRPs at photon energies well below the cyclotron resonance energy (e.g., Forsblom et al. 2025). Consequently, an abrupt PA change between two nearby energy bands in the soft X-ray regime is not straightforward to interpret within the current theoretical

framework. A comparable phenomenon has been reported in 4U 1907+09 (Zhou et al. 2025), where a PA swing of approximately 90° was marginally detected between two adjacent energy bands within a single phase bin. It is worth noting that both cases were observed under photon-starved conditions, where limited photon statistics reduce the robustness of the measurements. Recent theoretical and observational studies have also emphasized that complex mixtures of emission components and reprocessing regions may introduce additional energy-dependent polarization signatures in accreting XRPs (e.g., Zhao et al. 2026). Future observations with significantly improved photon statistics and broader energy coverage will therefore be crucial for confirming these features and for providing the empirical basis needed to develop a physical explanation.

4.3. Possible scenario for the 2025 outburst of 2S 1417–624

The observed flux from NuSTAR is $\sim 4.91 \times 10^{-10} \text{ erg s}^{-1} \text{ cm}^{-2}$ (in the 2–79 keV band), which corresponds to a luminosity of $3.2 \times 10^{36} \text{ erg s}^{-1}$, assuming a source distance of 7.4 kpc (Bailer-Jones et al. 2021). Liu et al. (2024) report a possible cyclotron line at 100 keV in this source, implying a magnetic field strength of $\sim 9 \times 10^{12} \text{ G}$. Given that accreting pulsars can operate in different radiative regimes depending on their luminosity, the critical luminosities of this source are estimated to be $\sim 1.55 \times 10^{37} \text{ erg s}^{-1}$ and $\sim 5 \times 10^{37} \text{ erg s}^{-1}$, as determined using the approaches of Becker et al. (2012) and Mushtukov et al. (2015), respectively. Since the NuSTAR observation occurred at the end of the outburst, the corresponding MAXI count rate was $\sim 0.025 \text{ cts/s}$, whereas the outburst peak reached a MAXI count rate of $\sim 0.1 \text{ cts/s}$, four times higher than during the NuSTAR observation. Therefore, the peak luminosity of the 2025 outburst can be roughly estimated as four times the NuSTAR luminosity: $L_{\text{peak}} \approx 4 \times L_{\text{NuSTAR}} = 1.3 \times 10^{37} \text{ erg s}^{-1}$. It is shown that even the peak luminosity did not exceed the critical luminosity; therefore, the radiation regime remained in the pencil-beam pattern throughout the entire outburst. The absence of significant luminosity-dependent changes in the pulse profile (as observed with NICER, IXPE, and NuSTAR) further supports this conclusion. We also note that the distance to this source may carry some uncertainty, which in turn affects the luminosity estimate. Liu et al. (2025) report two characteristic flux levels associated with changes in the pulse profile, at $\sim 4.1 \times 10^{-9}$ and $6.4 \times 10^{-9} \text{ erg cm}^{-2} \text{ s}^{-1}$ (2–140 keV). Below $4.1 \times 10^{-9} \text{ erg cm}^{-2} \text{ s}^{-1}$, the emission is thought to be dominated by a pencil-beam pattern. Therefore, even though the peak flux of the 2025 outburst is about $F_{\text{peak}} \approx 2.0 \times 10^{-9} \text{ erg cm}^{-2} \text{ s}^{-1}$ (3–79 keV, equivalent to $4 \times F_{\text{NuSTAR}}$), it still lies below the threshold at which a transition in the radiation pattern is expected. (The difference in flux integration energy bands does not significantly affect this conclusion, as the broader energy band is not expected to further increase the measured flux

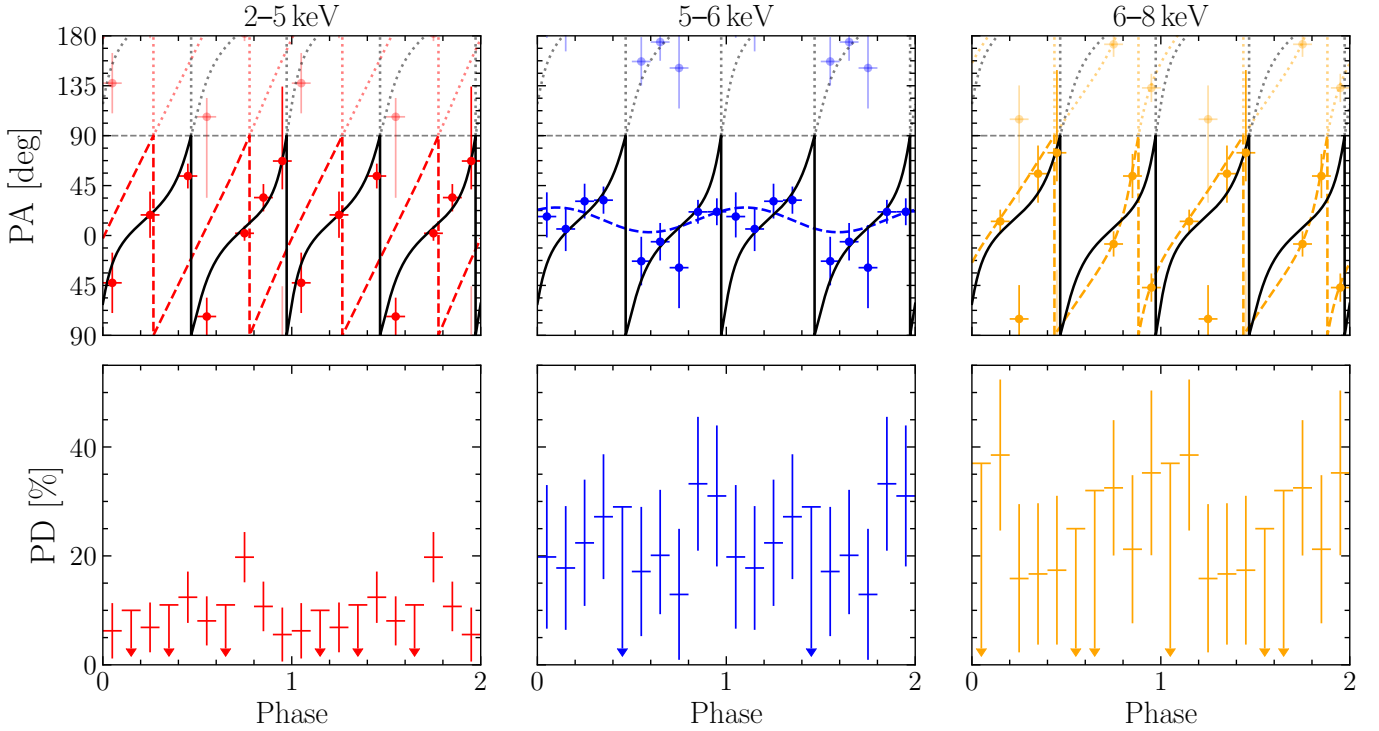


Fig. 12. Pulse-phase-resolved PAs and PDs in different energy bands obtained using the XSPEC method. For phase bins in which the PD is not significantly detected at the 1σ confidence level, we do not report PA values. Instead, we quote the 90% upper limits on the PD. Some PA values are shifted by 180° to better illustrate their phase continuity. The dashed colored curve in each panel represents the best-fit RVM to the PA measurements in the corresponding energy band, while the solid black curves show the simultaneous best-fit RVM to the Stokes parameters across the three energy bands.

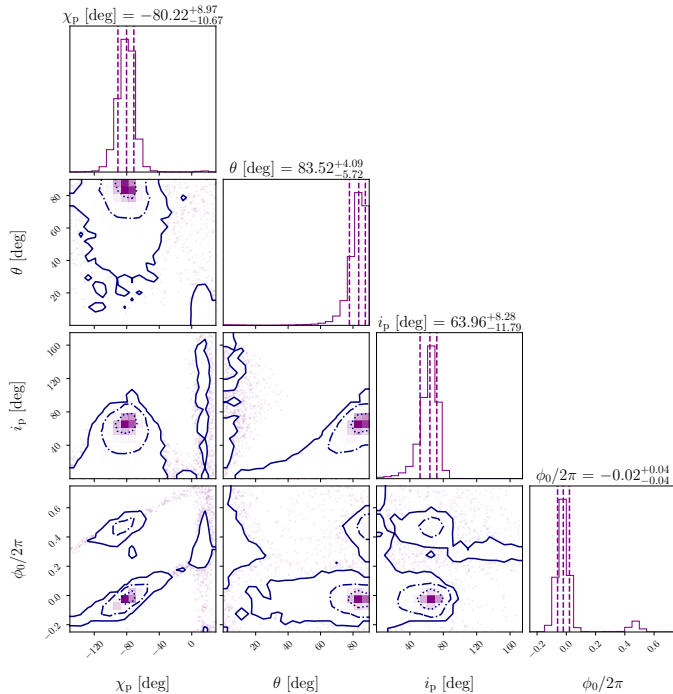


Fig. 13. Similar to Fig. 10 but showing the values derived from the cross-fitting of the Stokes Q/U parameters in the three energy bands (2–5 keV, 5–6 keV, and 6–8 keV).

substantially.) Polarization measurements, which constrain the geometry of accreting pulsars, greatly enhance our understanding of the pulse profile. With $\theta \approx 70^\circ$, as determined by fit-

ting PAs obtained by XSPEC and ixpepolarization, and also the unbinned method, the source is probably close to a quasi-orthogonal rotator configuration. Considering $i_p \approx 24^\circ$ from the same methods and the relatively wide beam angle of a pencil-beam emission pattern (Hu et al. 2023), it is plausible to observe two flux maxima within a single rotational cycle, consistent with the observed pulse profile.

5. Conclusions

The multi-mission campaign on 2S 1417–624 during its weak type-II outburst in 2025 has provided new insights into the source’s spectral and polarimetric properties. Phase-averaged and phase-resolved spectroscopy with NICER and NuSTAR shows that the spectra are well described by a broken power law with a high-energy cutoff, with several parameters exhibiting systematic pulse-phase modulations indicative of changes in emission geometry. With IXPE, we obtained the first polarimetric measurements of this source, yielding a phase-averaged PD of $4.8 \pm 1.2\%$ and a PA of $17 \pm 7^\circ$. By applying the unbinned photon-by-photon method and accounting for PA variation across the pulse phase, we obtain a PD of $5.9 \pm 1.2\%$, corresponding to a detection significance of 5.1σ , thereby reinforcing the robustness of our polarimetric results. Complementary phase-resolved polarimetric analysis suggests that 2S 1417–624 possesses a magnetic obliquity of $\theta = 69^{+13}_{-29}$ deg, indicating that the geometry is compatible with a quasi-orthogonal rotator within uncertainties. The tightest constraints on the geometrical parameters can be obtained from a simultaneous RVM fit to the Stokes Q/U parameters of the three energy bands, 2–5 keV, 5–6 keV, and 6–8 keV, which gives

$\theta = 84^{+4}_{-6}$ deg. Together, these results establish a consistent picture in which both the spectral and polarization properties vary significantly over the pulse cycle, offering important constraints on the geometry and emission processes in the accretion region of this transient XRP.

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Appendix A: The phase-resolved Stokes parameters of the 2–5 keV, 5–6 keV, and 6–8 keV band**Table A.1.** Phase-resolved Stokes parameters of 2S 1417–624 in different energy bands, derived with the ixpepolarization method using the NEFF weighting scheme.

No.	Phase	2–5 keV		5–6 keV		6–8 keV	
		Q	U	Q	U	Q	U
1	0.00–0.10	10 ± 70	-60 ± 70	20 ± 30	10 ± 30	-10 ± 20	10 ± 20
2	0.10–0.20	50 ± 80	30 ± 80	40 ± 30	10 ± 30	60 ± 30	20 ± 30
3	0.20–0.30	60 ± 80	60 ± 80	40 ± 30	30 ± 30	-20 ± 30	-40 ± 30
4	0.30–0.40	30 ± 80	-10 ± 80	30 ± 30	80 ± 30	0 ± 30	10 ± 30
5	0.40–0.50	-50 ± 80	90 ± 80	-20 ± 30	-20 ± 30	-10 ± 20	0 ± 20
6	0.50–0.60	-40 ± 80	-50 ± 80	30 ± 30	-30 ± 30	10 ± 20	0 ± 20
7	0.60–0.70	-10 ± 80	20 ± 80	50 ± 30	0 ± 30	20 ± 30	-10 ± 30
8	0.70–0.80	210 ± 80	0 ± 80	0 ± 30	-10 ± 30	70 ± 20	10 ± 20
9	0.80–0.90	30 ± 80	140 ± 80	30 ± 30	70 ± 30	0 ± 20	30 ± 20
10	0.90–1.00	-40 ± 70	60 ± 70	20 ± 30	30 ± 30	0 ± 20	-30 ± 20

Notes. The uncertainties of the Stokes parameters are provided at the 68.3% confidence level. This approach can lead to differences between the PAs and PDs derived from the Stokes parameters and those reported in Table 7.