X-ray polarimetry of X-ray pulsar X Persei: another orthogonal rotator?

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ABSTRACT

X Persei is a persistent low luminosity X-ray pulsar in Be binary system. The field strength at the neutron star surface is not known precisely, but indirect signs indicate a magnetic field above 10^{13} G, which makes the object one of the most magnetized known X-ray pulsars. Here we present the results of observations of 835-s X-ray pulsar X Persei performed with the *Imaging X-ray Polarimetry Explorer* (*IXPE*). The X-ray polarization signal was found to be strongly dependent on the spin phase of the pulsar. The polarization degree varied from several to ~ 15 per cent over the pulse with a positive correlation with the pulsed X-ray flux. The polarization angle shows significant variation and makes two complete revolutions during the pulse period resulting in nearly nil pulse-phase averaged polarization. Applying the rotating vector model to the *IXPE* data we obtain the estimates for the rotation axis inclination and its position angle on the sky as well as for the magnetic obliquity. The derived inclination is close to the orbital inclination reported earlier for X Persei. The polarimetric data imply a large angle between the rotation and magnetic dipole axes, which is similar to the result reported recently for the X-ray pulsar GRO J1008−57.

Key words: magnetic fields – polarization – pulsars: individual: X Persei – stars: neutron – stars: oscillations – X-rays: binaries

1 INTRODUCTION

Accretion of matter onto spinning and strongly magnetized neutron stars (NSs) in close binary systems results in a phenomenon of X-ray pulsars (XRPs, see Mushtukov & Tsygankov 2022 for review). The magnetic field strength at the NS surface in XRPs is typically measured to be $\sim 10^{12}$ G and in some sources is confirmed to be as high as $\sim 10^{13}$ G (Staubert et al. 2019; Kong et al. 2022). Such a strong magnetic field affects both geometry of the accretion flow in XRPs and the physical processes of interaction between radiation

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and matter (Harding & Lai 2006; Suleimanov et al. 2022), making XRPs unique labs to study physics under extreme conditions.

The geometry of the emitting regions in XRPs is known to be dependent on the mass accretion rate (Basko & Sunyaev 1976): at relatively low mass accretion rates ($\dot{M} \lesssim 10^{17}\,\mathrm{g\,s^{-1}}$), the accretion flow is decelerated in the atmosphere of a NS (Zel'dovich & Shakura 1969), while a high mass accretion rate ($\dot{M} \gtrsim 10^{17}\,\mathrm{g\,s^{-1}}$) results in the appearance of a radiation dominated shock above the NS surface and extended accretion columns confined by a strong magnetic field and supported vertically by the radiation pressure (Basko & Sunyaev 1976; Wang & Frank 1981).

The influence of the strong magnetic field on the radiative transfer in the atmospheres of NSs has long been discussed in the literature. In particular, it is well known that the transfer of radiation critically depends on the polarization of X-ray photons and the direction of their propagation with respect to the local direction of magnetic field (see Gnedin & Pavlov 1974; Kaminker et al. 1983 and Chapter 6 in Meszaros 1992 for review). Most of the existing models (Meszaros & Nagel 1985a,b; Sokolova-Lapa et al. 2021; Caiazzo & Heyl 2021) predict a polarization degree up to 80% at energies below the cyclotron resonance (i.e., at $E < E_{\rm cyc} \approx 11.6\,B_{12}\,\mathrm{keV}$, where $B_{12} = B/10^{12}\,\mathrm{G}$ is the local magnetic field strength). This makes XRPs one of the main targets for the new generation of X-ray polarimeters.

Thanks to the successful launch of the first highly sensitive space X-ray polarimeter, the *Imaging X-ray Polarimeter Explorer* (*IXPE*, Weisskopf et al. 2022), on 2021 December 9, polarization in X-ray energy band has been discovered in XRPs Her X-1 (Doroshenko et al. 2022), Cen X-3 (Tsygankov et al. 2022), GRO J1008−57 (Tsygankov et al. 2023), and Vela X-1 (Forsblom et al. 2023). Detection of polarization in the X-ray energy band allowed us to determine the geometrical parameters of the NS, and obtain constraints of the magnetic field structure and the structure of the NS atmosphere. Unexpectedly, the observed degree of linear polarization (below 10–15 per cent, even in the phase-resolved data) turned out to be much smaller than that predicted by most theoretical models. To understand the nature of this discrepancy, we need to observe sources with very different parameters determining geometrical and physical conditions of the emission region.

X Persei (4U 0352+309) belongs to the rare class of persistent low-luminosity XRPs with Be optical companions (e.g. Reig & Roche 1999). Pulsations of the flux with a period of 835 s were discovered from the source with the *Copernicus* satellite (White et al. 1976). The pulsar moves around its optical companion, star HD24534, along a moderately eccentric ($e = 0.11 \pm 0.02$) wide orbit with a period of $P_{\rm orb} = 250.3 \pm 0.6$ d, orbital inclination $i_{\rm orb} \approx 30^{\circ}$, a projected semi-major axis of the NS of $a_{\rm x}\sin i = 454 \pm 4$ lt-s, and the mass function $f(M) = 1.61 \pm 0.05 M_{\odot}$ (Delgado-Martí et al. 2001). Additional quasi-periodic variations of the observed flux from the source with a period of about 7 years were reported by Nakajima et al. (2019). Recently, the most accurate distance to X Persei of 600 ± 13 pc was determined from the *Gaia* data (Bailer-Jones et al. 2021). The magnetic field of the NS in X Persei is not known precisely, but all estimates including broad-band X-ray spectral analyses and the observed evolution of spin frequency point to high magnetic field values. In particular, a wide depression in the source spectrum observed at around 30 keV was interpreted by Coburn et al. (2001) and Lutovinov et al. (2012) as a cyclotron resonant scattering feature, equivalent to a magnetic field strength of $\sim 2.5 \times 10^{12}$ G. However, this spectral feature was later proposed to be related to the double-hump continuum shape typical to XRPs at extremely low mass accretion rates (Tsygankov et al. 2019a). This would shift the magnetic field to even higher values: $\gtrsim 10^{13}$ G (e.g. Di Salvo et al. 1998; Tsygankov et al. 2019b; Mushtukov et al. 2021; Sokolova-Lapa et al. 2021). Applying the accretion torque models to the spin frequency evolution of the source, another estimate of the magnetic field strength can be obtained: $B \sim 4 \times 10^{13} - 2.5 \times 10^{14}$ G (Doroshenko et al. 2012; Yatabe et al. 2018), which supports the estimate made from the source spectral shape. Combination of a strong magnetic field and low mass accretion rate in X Persei point to the accretion from cold disc composed of recombined material (see, e.g., Tsygankov et al. 2017). X Persei is the closest low luminosity ($L \sim 10^{35}\,\mathrm{erg\,s^{-1}}$) pulsar known, which provides a unique opportunity to study accretion at low rates with good counting statistics essential for polarimetric observations. Furthermore, the low mass accretion rate in this object implies that it must have a simple geometrical configuration of the emitting regions at the NS surface, so called hot spots, which simplifies interpretation of the results. The magnetic field of X Persei is strong even by the standards of XRPs and makes the source particularly interesting for polarimetric observations as the energy range covered by *IXPE* is much below the cyclotron energy, which again simplifies theoretical interpretation of the results.

Here we present the results of *IXPE* observations of X Persei performed in August and September 2022. In Section 2, we present the *IXPE* data as well as the accompanying observations by *SRG*/ART-XC. Section 3 is devoted to the results of the X-ray polarimetric observations. We discuss the structure of the atmosphere and the constraints obtained on the geometry in Section 4, and we summarize our findings in Section 5.

2 DATA

2.1 *IXPE*

X Persei was observed with the Imaging X-ray Polarimetry Explorer (*IXPE*) over the periods of 2022 Aug 19–22 and Sep 16–19 with a total effective exposure of ≃225 ks. *IXPE* is a joint effort of NASA and the Italian Space Agency, launched by a Falcon 9 rocket on 2021 December 9. The observatory consists of three grazing incidence telescopes, each equipped with an X-ray mirror assembly and a polarization-sensitive detector unit (DU) (Soffitta et al. 2021; Baldini et al. 2021). It provides imaging polarimetry over a nominal 2–8 keV band. The time resolution and accuracy is <10 μs, far better than what is needed for our analysis. A detailed description of the instrument and its performance is given in Weisskopf et al. (2022).

The data have been processed with the publicly available IXPEOBSSIM package[1] version 30.2.2 (Baldini et al. 2022) using CalDB released on 2022 November 17. Source photons were

[1] https://github.com/lucabaldini/ixpeobssim

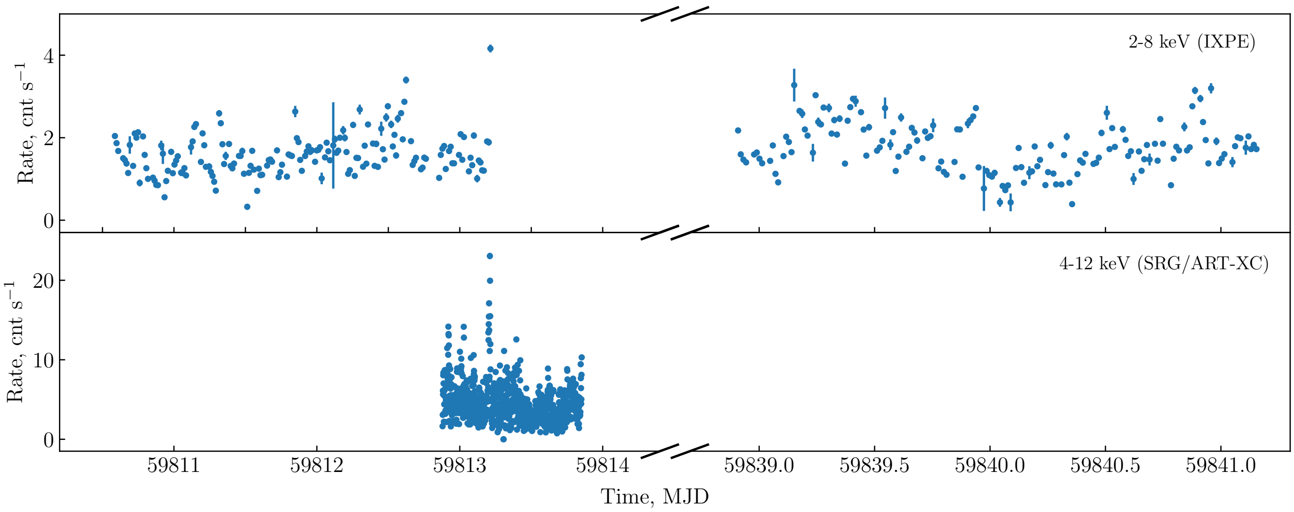

Figure 1. *Top:* The light curve of X Persei in the 2–8 keV energy band summed over three modules of *IXPE*. Both observations performed in Aug and Sep 2022 are shown. *Bottom:* The light curve of the source in the 4–12 keV band obtained during the quasi-simultaneous *SRG*/ART-XC observation.

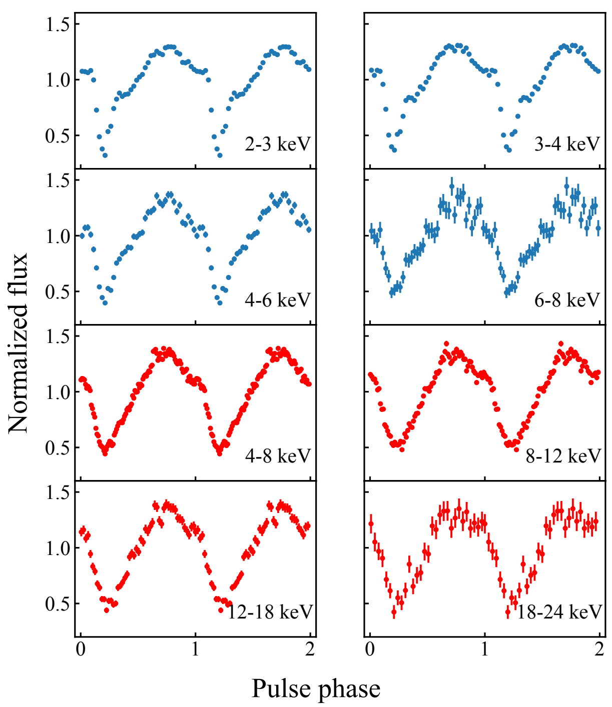

Figure 2. Pulse profile of X Persei in different energy bands as seen by *IXPE* (upper four panels in blue) and ART-XC telescope (bottom four panels in red). Data from the three and seven *IXPE* and ART-XC units, respectively, were combined.

collected in a circular region with radius $R_{\rm src} = 60''$ centered on the X Persei position. Following recommendations from Di Marco et al. (2023) for bright sources, the background was not subtracted from the data, because it appears to be negligible ($\sim$1% of the total signal). The event arrival times were corrected to the Solar system barycenter using the standard **barycorr** tool from the FTOOLS package and accounting for the effects of binary motion using the orbital parameters by Delgado-Martí et al. (2001). The resulting light curve of X Persei in the 2–8 keV band is shown in the upper panel of Fig. 1. Because the source does not demonstrate significant difference in the average count rate in the two observational segments, the subsequent scientific analysis was performed using the joint dataset.

The same extraction procedure was applied to all three Stokes parameters I, Q and U. In order to use the χ^2 statistics, the flux (Stokes parameter I) energy spectra were rebinned to have at least 30 counts per energy channel. The energy binning obtained for the Stokes parameter I was also applied to the spectra of the Stokes parameters Q and U. The subsequent spectral fitting was performed with the XSPEC package (Arnaud 1996) using the instrument response functions of version 10. Taking into account the high count statistic and negligible background level, the unweighted approach has been applied. The uncertainties are given at the 68.3 per cent confidence level for a single parameter of interest unless stated otherwise.

2.2 *SRG*/ART-XC

To control the temporal and spectral properties of X Persei in the broader energy band, the quasi-simultaneous observations with the *Spectrum-Roentgen-Gamma observatory* (*SRG*, Sunyaev et al. 2021) Mikhail Pavlinsky ART-XC telescope (Pavlinsky et al. 2021) were carried out on MJD 59813 with an $\sim$84 ks net exposure. The ART-XC telescope includes seven independent modules and provides imaging, timing and spectroscopy in the 4–30 keV energy range. ART-XC data were processed with the analysis software ARTPRODUCTS v1.0 and the CALDB version 20220908. The corresponding light curves of X Persei in the 4–24 keV band is shown in the lower panels of Fig. 1.

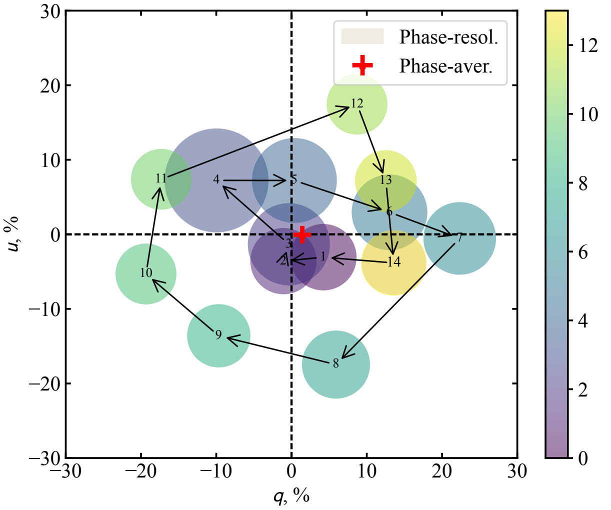

Figure 3. Variations of the phase-resolved normalized Stokes parameters $q = Q/I$ and $u = U/I$ (from using `pcube`) over the spin phase of X Persei in the 3–8 keV energy band averaged over three DUs. Colour coding and the size of the corresponding circle correspond to the phase bin number and 1σ uncertainty, respectively. The phase-averaged value is shown with the red cross.

Table 1. Spectral parameters of the best-fitting model for the phase-averaged *IXPE* data on X Persei in the 3–8 keV band using XSPEC.

Parameter	Value	Units
$N_{\rm H}$	$0.15^{\rm fixed}$	10^{22} cm^{-2}
const$_{\rm DU2}$	0.95±0.01	
const$_{\rm DU3}$	0.91±0.01	
Photon index	1.72 ± 0.02	
PD	1.8±1.0	%
PA	−1.3±16.0	deg
Flux (2–8 keV)	2.76±0.04	10^{-10} erg cm^{-2} s^{-1}
Luminosity (2–8 keV)	1.2×10^{34}	erg s^{-1} at $d = 600$ pc
χ^2 (d.o.f.)	1044 (1038)	

Note. Quoted uncertainties are at the 68.3 per cent confidence level. Systematic uncertainty of 5% was added in order to obtain the reliable errors on the model parameters.

3 RESULTS

Considering that the main goal of our investigation is pulse-phase resolved spectro-polarimetric analysis, we first determined pulsation period for the period covered by *IXPE* data. The pulse period was first approximately determined as 833.14 s using the event data (with event arrival times corrected for effects of orbital motion of the satellite and neutron star as described above) and Z^2 statistics (Buccheri et al. 1983). This value was then refined using the phase-connection technique (Deeter et al. 1981) to $P_{\rm spin} = 833.214(10)$ s (the uncertainty is reported at 1σ confidence level). The folded pulse profile in different energy bands based on the *IXPE* and ART-XC data (see Fig. 2) demonstrates a typical shape for the source with only minor dependence on energy.

Following standard procedures for *IXPE* data analysis of XRPs (Doroshenko et al. 2022; Tsygankov et al. 2022), we performed polarimetric analysis of the data using the formalism of Kislat et al. (2015) implemented in the `pcube` algorithm in the `xpbin` tool as a part of the IXPEOBSSIM package (Baldini et al. 2022) as well as using spectro-polarimetric analysis with the the XSPEC package (Strohmayer 2017). At the first step we explored the energy dependence of the polarimetric properties of X Persei. We found that polarization is undetectable below 3 keV in the pulse phase-averaged as well as in the phase-resolved data. At the same time, above 3 keV the polarization degree (PD) and the polarization angle (PA, measured from north to east) can be significantly measured and are consistent within the uncertainties. Therefore, we excluded the 2–3 keV data from the following analysis .

Pulse-phase averaged polarimetric analysis using the `pcube` algorithm in the 3–8 keV band resulted in a very low, consistent with zero, polarization with the normalized Stokes parameters of $q = Q/I = 1.4 \pm 1.2\%$ and $u = U/I = 0.0 \pm 1.2\%$ (see red cross in Fig. 3). However, similarly to the others XRPs studied with *IXPE*, phase-resolved analysis revealed a very strong variability of q and u over the pulse phase (Fig. 3). We see that the PD= $\sqrt{q^2 + u^2}$ varies from being consistent with zero to ~ 20 per cent. The non-detection in the phase-averaged data can be thus attributed to a rotation of the PA with the pulse phase.

At the next step, we performed spectro-polarimetric analysis with XSPEC to account for the energy dispersion and the spectral shape. We fitted jointly the I, Q and U spectra prepared with the PHA1, PHA1Q, and PHA1U algorithms in the `xpbin` tool. To avoid problems with the mismatch in spectral calibrations of *IXPE* and ART-XC telescopes and the fact that observations only partly overlap, for the following analysis only data from *IXPE* were used.

The spectrum of X Persei is relatively simple and below 10 keV can be well described with an absorbed power law. The interstellar absorption was accounted for using the `tbabs` model with abundances adopted from Wilms et al. (2000). Moreover, the fit appeared to be insensitive to the $N_{\rm H}$ value and it was fixed at 0.15×10^{22} cm^{-2} (see e.g. Di Salvo et al. 1998). The PD and PA values were derived from the `polconst` model assuming their independence of the energy. A cross-calibration multiplicative constant (`const` in XSPEC) was introduced to the model in order to take into account possible discrepancies in the DU's effective areas (with DU1 constant fixed to unity). The quality of the phase-averaged spectrum approximation can be seen in Fig. 4 with the best-fitting parameters presented in Table 1. Replacing `polconst` model with `pollin` and `polpow`, which correspond to a linear and a power-law dependence of PD and PA on energy, respectively, did not improve quality of the fit.

The same spectral model was applied to the phase-resolved data. All the spectral parameters were allowed to vary, except the cross-calibration constants, which were fixed to values obtained from the phase-averaged fit. The obtained results are summarized in Figs 5, 6 and Table 2. The PD is correlated with the pulsed flux, similarly to what was recently found in another XRP with luminosity much below the critical value, GRO J1008−57 (Tsygankov et al. 2023). The PA varies from -90° to $+90^\circ$, covering the widest range among the XRPs observed until now with *IXPE*. During the pulse period, the PA makes two complete revolutions.

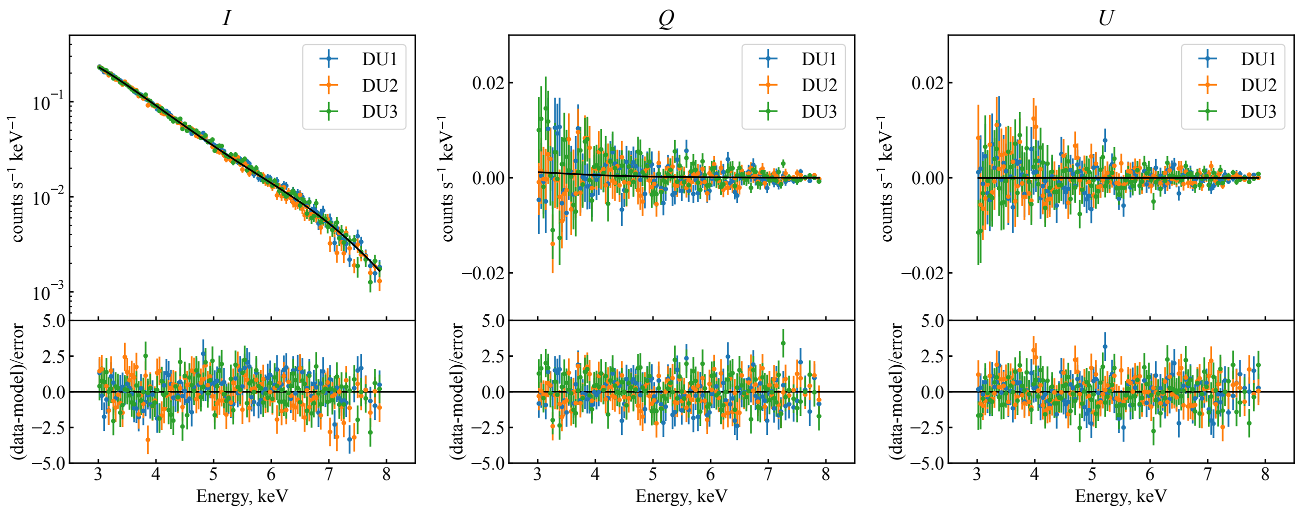

Figure 4. Energy distributions of the Stokes parameters I, Q and U averaged over the spin phase of X Persei obtained with *IXPE* in the 3–8 keV band. The best-fitting model is shown with the black solid line. Bottom panels of each plot represent the residuals between the data and the model normalized for the error. Data from the three *IXPE* detectors are shown with different colours: DU1 in blue, DU2 in orange and DU3 in green.

Table 2. Spectral parameters for the phase-resolved spectro-polarimetric analysis of the X Persei data with XSPEC.

#	Phase	Photon index	PD (%)	PA (deg)	χ^2 (d.o.f.)
1	0.000–0.071	1.64±0.04	5.3±3.5	−25.5±21.0	563 (569)
2	0.071–0.143	1.73±0.04	3.3±3.3	...	522 (550)
3	0.143–0.214	1.69±0.04	$3.1^{+4.4}_{-3.1}$	...	501 (460)
4	0.214–0.286	1.37±0.04	14.9±5.6	74.4±11.0	345 (362)
5	0.286–0.357	1.79±0.04	$3.7^{+4.5}_{-3.7}$	...	435 (449)
6	0.357–0.429	1.70±0.04	15.6±4.0	6.5±7.4	536 (488)
7	0.429–0.500	1.58±0.04	17.6±3.9	3.9±6.2	545 (517)
8	0.500–0.571	1.60±0.04	17.4±3.6	−35.5±6.0	524 (544)
9	0.571–0.643	1.67±0.04	17.2±3.3	−62.9±5.6	667 (597)
10	0.643–0.714	1.63±0.04	17.6±3.2	−84.8±5.3	590 (611)
11	0.714–0.786	1.56±0.04	17.4±3.2	75.7±5.2	624 (612)
12	0.786–0.857	1.59±0.04	14.6±3.1	31.0±6.2	666 (620)
13	0.857–0.929	1.67±0.04	16.3±3.3	12.4±5.7	622 (602)
14	0.929–1.000	1.59±0.04	12.6±3.4	−1.6 ± 7.8	532 (581)

Note. The cross-normalization constants as well as the $N_{\rm H}$ value are frozen at the values derived from the phase-averaged analysis. The missing values of the PA correspond to non-detection of the polarization.

4 DISCUSSION

4.1 Atmospheric structure and polarization mechanism

We estimate the bolometric accretion luminosity of X Persei to be below $\sim 5\times10^{34}$ erg s^{-1}. For the surface magnetic field of about 10^{13} G, this luminosity is well below the critical value $L_{\rm crit} \approx 3\times10^{37}$ erg s^{-1} (Basko & Sunyaev 1976; Mushtukov et al. 2015), above which the radiative force becomes high enough to stop the accretion flow above the NS surface. Under the condition of $L \ll L_{\rm crit}$, the influence of radiation pressure on the dynamics of the accretion flow is negligible and the accretion results in a hot spot geometry of the emission region. The observed two-component structure of the broadband X-ray energy spectrum and the luminosity of X Persei indicate that the X-rays are emitted from the atmosphere under the conditions where the upper optically thin layer are overheated by the deceleration of accreting gas (Zel'dovich & Shakura 1969; Suleimanov et al. 2018). In this case, the low-energy component of the X-ray spectrum is produced by the thermal emission of underlying cold atmospheric layers, while the high-energy component is shaped by the cyclotron emission and subsequent multiple Compton resonant scatterings in the hot electron gas (Mushtukov et al. 2021; Sokolova-Lapa et al. 2021).

It is expected that a NS atmosphere with an inverse temperature profile produces a pencil beam emission pattern, which is suppressed along the NS surface normal: the hot upper layers contribute more to the X-ray energy flux leaving the NS atmosphere at larger angles with respect to the local normal. In the case of a hot spot geometry, the PD below the cyclotron resonance is expected to be higher for photons leaving the atmosphere at larger angles to the local magnetic

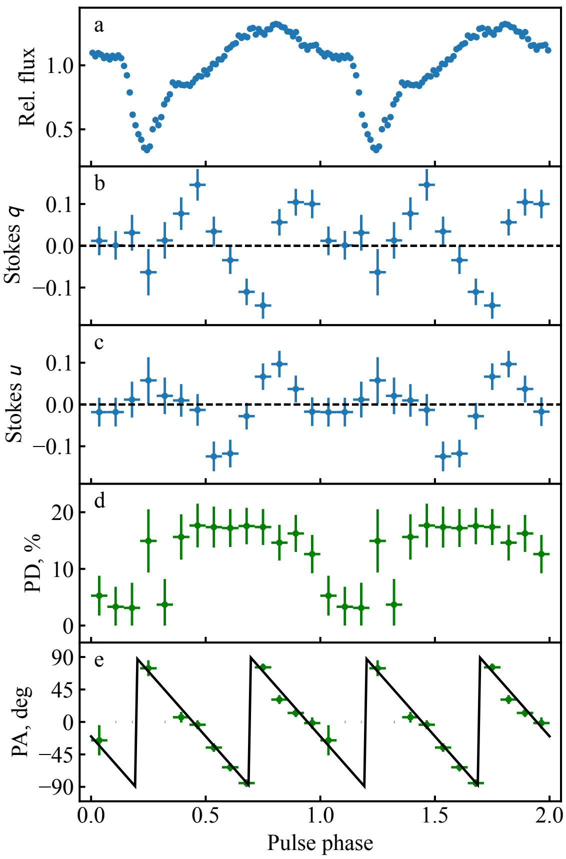

Figure 5. Dependence of the normalized flux (*panel a*), normalized q and u Stokes parameters (*panels b and c*), PD and PA (*panels d and e*) on the pulse phase in the 3–8 keV energy band. Data from the three *IXPE* telescopes are combined. Data for three phase bins are missing the PA values because they are not constrained. The black solid line in the bottom panel corresponds to the best-fitting RVM with the following parameters: $i_{\rm p} = 162^\circ$, $\theta = 90^\circ$, $\chi_{\rm p} = 70^\circ$, and $\phi_0/2\pi = 0.75$.

field direction because of a stronger dependence of scattering and absorption cross-sections on polarization (Meszaros et al. 1988). Thus, the expected correlation between the flux and the PD is in agreement with the observations (compare panels a and d in Fig. 5). It means that the minimal X-ray energy flux and PD correspond to the smallest angle between NS magnetic axis and line of sight. A similar correlation between the variations of X-ray energy flux and PD was detected recently in the XRP GRO J1008−57, where strongly magnetized accreting NS was also observed below the critical luminosity (Tsygankov et al. 2023).

The low polarization degree observed in X Persei is probably related to the inverse temperature profile in NS the atmosphere. In this case, two effects come into play. On one hand, the upper atmosphere in local thermodynamic equilibrium emits many photons for which the absorption and scattering cross sections are larger. Because the emission occurs in an optically thin upper layer, these photons freely leave the atmosphere and equalize the difference between the fluxes in the two polarization modes (Mushtukov et al. 2021). On the other hand, the estimates show that the temperature between the upper overheated layer and the lower cold atmosphere changes rapidly and there is a region with a large temperature gradient (Suleimanov et al. 2018). Under the condition of hydrostatic equilibrium, the temperature jump is associated with a jump in mass density and a large density range is present at the boundary between the cold atmosphere and the overheated upper layer. If the vacuum resonance density

$$\rho_{\rm V} \approx 10^{-4}\, B_{12}^2 E_{\rm keV}^2 \ {\rm g\,cm^{-3}}, \quad (1)$$

where B_{12} is the field strength in units of 10^{12} G and $E_{\rm keV}$ is the photon energy in keV (Lai & Ho 2003), falls into this density range, a polarization mode conversion is expected at the lower boundary of the overheated upper atmospheric layer. It has been shown previously that mode conversion in an overheated upper atmospheric layer leads to flux equalisation in the two polarization modes and a corresponding reduction in the linear PD (see Supplementary Materials in Doroshenko et al. 2022).

4.2 Constraints on the geometry

The PA makes two complete turns during the pulsation period (see Fig. 3 and Fig. 5e). Polarization of X-ray photons with respect to the local direction of the magnetic field is conserved in the NS magnetosphere within the adiabatic radius $R_{\rm ad} \approx 7.6\times10^6\, B_{12}^{0.4} E_{\rm keV}^{0.2}$ cm (Heyl & Shaviv 2000; González Caniulef et al. 2016). Thus, it is expected that the PA follows the projection of the magnetic field axis in the sky (or is perpendicular to this projection, depending on the polarization composition of the X-rays leaving the NS atmosphere). A full turn of the magnetic axis projection during the pulse period becomes possible under the condition

$$i_{\rm p} < \theta, \quad (2)$$

where $i_{\rm p}$ is the pulsar spin inclination angle and θ is the magnetic obliquity, i.e. the angle between the rotation and the NS magnetic field axis. Interaction of the accretion flow with NS magnetosphere leads to the alignment of the NS spin with the orbit on a time scale (Biryukov & Abolmasov 2021)

$$\tau \approx 600\, I_{45} \left(\frac{\dot M}{\dot M_{\rm Edd}}\right)^{-6/7} \left(\frac{M}{M_\odot}\right)^{-9/7} \mu_{30}^{-2/7}\ {\rm yr}, \quad (3)$$

where I_{45} is the NS moment of inertia in units of 10^{45} g cm^2, $\dot M_{\rm Edd} \approx 1.6\times10^{18}\,{\rm g\,s^{-1}}$ is the Eddington mass accretion rate onto a NS, and μ_{30} is the NS magnetic moment in units of 10^{30} G cm^3. For the observed mass accretion rate in X Persei and under the assumption of a surface magnetic field $B\sim10^{13}$ G, we get the time scale required for the alignment $\tau\sim4\times10^5$ yr. The estimated time scale of spin axis alignment is much smaller than the age reported for the optical companion in X Persei by Lyubimkov et al. (1997): $\sim 5\times10^6$ yr and sufficiently small to assume that the magnetic field of the NS has not experienced a significant decay (see Pons & Viganò 2019 for review and Fig. 20 there). Thus, the rotational axis of the NS in X Persei is likely aligned with the orbital axis of the binary system. In this case, one would expect $i_{\rm p}\sim i_{\rm orb}\approx30^\circ$ and the condition (2) can be easily satisfied.

To determine the geometry of X Persei, we follow the procedure applied earlier to Her X-1 (Doroshenko et al. 2022), Cen X-3 (Tsygankov et al. 2022) and GRO J1008−57 (Tsygankov et al. 2023) and fit the rotating vector model (RVM,

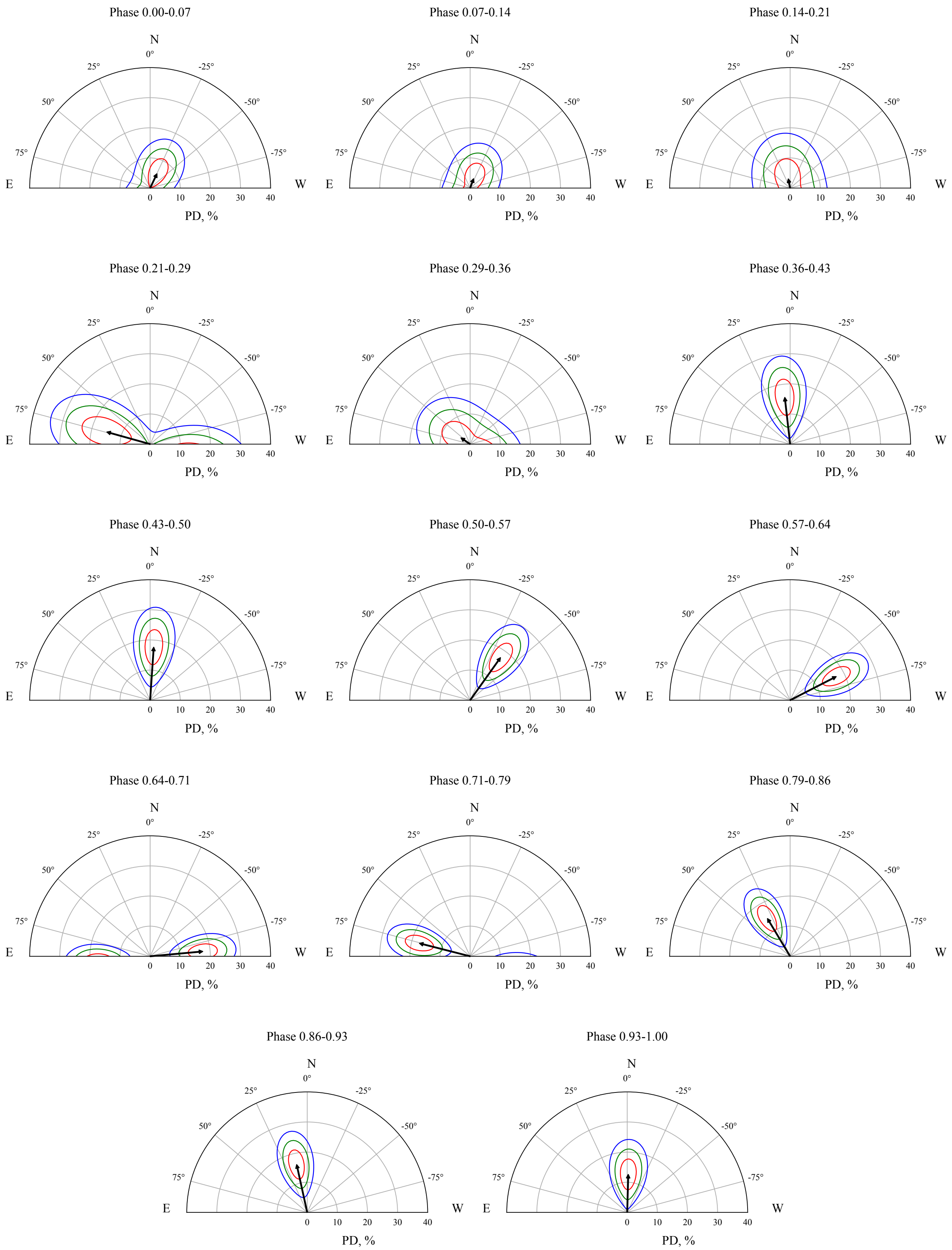

Figure 6. Polarization vector of X Persei as a function of the pulse phase based on the spectro-polarimetric analysis. The PD and PA at 68.27, 95.45 and 99.73 per cent confidence levels (in red, green and blue colour, respectively) are shown for 14 phase intervals.

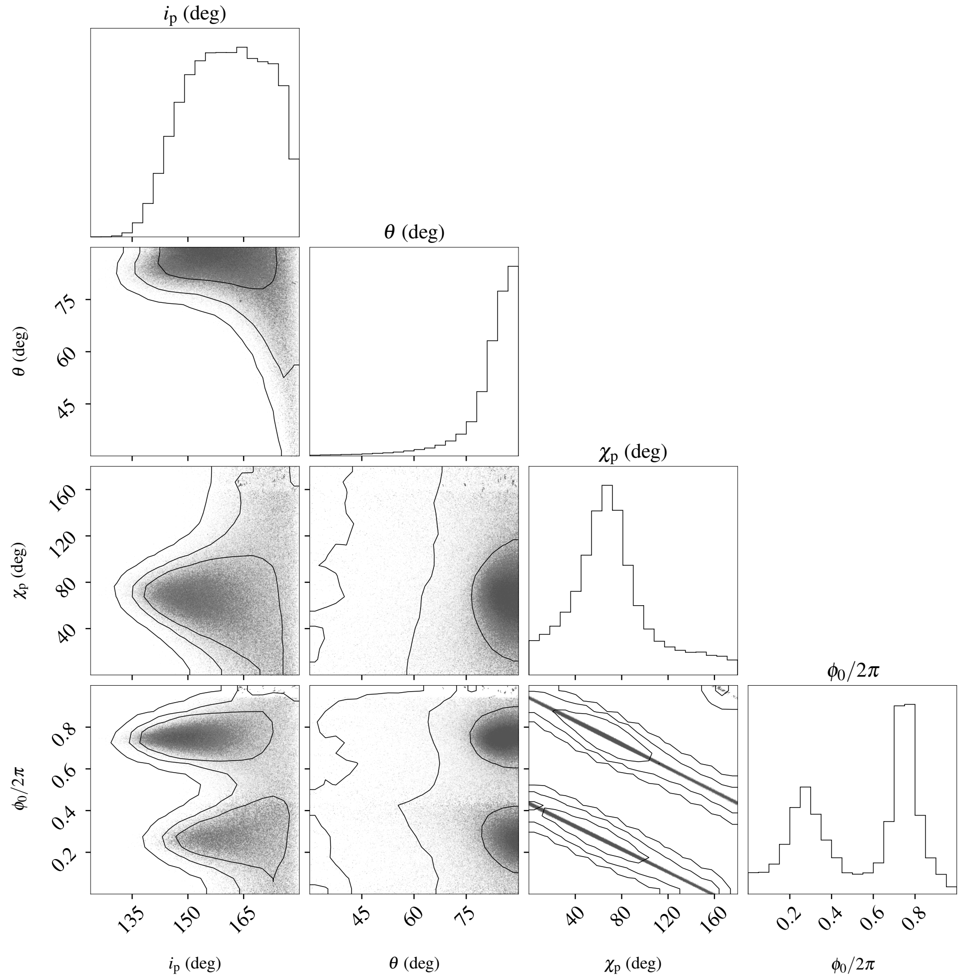

Figure 7. Corner plot of the posterior distribution for the RVM parameters using the PA dependence on the spin phase. The two-dimensional contours correspond to 68.27, 95.45 and 99.73 per cent confidence levels.

Radhakrishnan & Cooke 1969; Poutanen 2020),

$$\tan(\mathrm{PA}-\chi_\mathrm{p}) = \frac{-\sin\theta\ \sin(\phi-\phi_0)}{\sin i_\mathrm{p}\cos\theta - \cos i_\mathrm{p}\sin\theta\cos(\phi-\phi_0)}, \quad (4)$$

to the observed variation of the PA with phase ϕ. Here χ_p is the position angle of the pulsar's rotation axis (assuming that radiation escapes predominantly in the O-mode). We use the affine invariant Markov chain Monte Carlo ensemble sampler EMCEE package of PYTHON (Foreman-Mackey et al. 2013). All the parameters in equation (4) were left free. Because polarization is sensitive to the sense of rotation, the prior for the pulsar inclination i_p is $[0°, 180°]$ with the probability density $\propto \sin i_\mathrm{p}$. The inclination is constrained at $i_\mathrm{p} = 162° \pm 12°$ at a 68 per cent confidence level and $i_\mathrm{p} > 135°$ at a 99 per cent confidence level. This is consistent with the orbital inclination $i_\mathrm{orb} \in [26°, 33°]$ reported by Delgado-Martí et al. (2001) using the X-ray pulse arrival times and measured mass function (note that these constraints are equivalent to $i_\mathrm{orb} \approx 150°$ as the sense of rotation cannot be determined from such data). The probability distribution of the position angle χ_p has a broad peak at $\chi_\mathrm{p,O} \approx 70°$ with a 1σ width of about 30°. We note here that there is an alternative solution $\chi_\mathrm{p} = \chi_\mathrm{p,O} + 180° = 250°$, because only the orientation of the polarization plane can be measured. Furthermore, if radiation is dominated by the X-mode, then the pulsar spin orientation is $\chi_\mathrm{p} = \chi_\mathrm{p,X} = \chi_\mathrm{p,O} \pm 90°$.

The spin phase ϕ_0 when the closest pole is directed towards the observer has two maxima at $\phi_0/(2\pi) \approx 0.25$ and 0.75, because the two rotations of the PA are shifted by nearly exactly half a period. Finally, the magnetic obliquity tends to values close to 90°, with the lower limit being 75° at a 68 per cent confidence level. However, an orthogonal magnetic dipole in X Persei (i.e. $\theta \approx 90°$), contradicts the behaviour of the normalized Stokes parameters q and u during the pulse period (see Fig. 3) and a proper analysis of the data requires assumptions on the beam patterns in both polarization modes.

A sharp dip observed in the pulse profile at phase ~ 0.25 (Fig. 5), when the normal to one of the poles is close to the line of sight, can be related to an eclipse of the hot spot by the accretion stream above the NS surface. However, the mass accretion rate in X Persei is very low and the optical thickness of the accretion stream above NS surface seems to be too small to support this hypothesis. Yet, the suggestion of a spot eclipse at this phase is also supported by observations of a sharp spike of the X-ray flux in the centre of the dip seen, for example, in the *Suzaku* data (Maitra et al. 2017) with the corresponding increase of the hardness ratio already observed with *EXOSAT* (Robba & Warwick 1989) and *Ginga* (Robba et al. 1996), which implies that here we are looking directly along the magnetic dipole axis.

5 SUMMARY

The results of polarimetric studies of XRP X Persei can be summarized as follows:

(i) Linear polarization was not detected in the phase-averaged date from X Persei. However, the phase-resolved polarimetry revealed variable PD and PA. The PD at its maximum reaches ∼20 per cent, while the PA makes two complete revolutions during the pulsation period. The PD is detected to be positively correlated with variations of the X-ray energy flux during the observed pulse period (see panels a and d in Fig. 5). A positive correlation between the flux and the PD was already reported in the low-luminosity XRP GRO J1008−57 (Tsygankov et al. 2023), and probably is a typical feature for XRPs at a luminosity well below the critical one.

(ii) The observed variations of the PA, making two full turns per spin period, become possible under the condition that the magnetic obliquity is larger than the inclination of the NS rotation axis. Application of the rotating vector model to the data gives the following set of geometrical parameters: the inclination is constrained $i_{\rm p} = 162^\circ \pm 12^\circ$ ($> 135^\circ$) at 68 (99) per cent confidence level, consistent with the orbital inclination reported in X Persei. The position angle has been determined as $70^\circ \pm 30^\circ$ or $250^\circ \pm 30^\circ$ (assuming that the observed photons were polarized in the O-mode), with alternative solutions rotated by 90°, if radiation escapes in the X-mode. The magnetic obliquity has a preference towards 90° with the lower limit being 75° at a 68 per cent confidence level. High magnetic obliquity potentially makes X Persei the second discovered orthogonal rotator after GRO J1008−57.

(iii) Similarity of the determined NS inclination and the orbital inclination supports the hypothesis of a strong NS magnetic field in X Persei, which would make the relaxation period of the NS towards spin equilibrium and alignment with the orbital axis relatively fast even under conditions of a rather low mass accretion rate.

(iv) The low PD and its correlation with the X-ray flux during the pulse period is consistent with the expected inverse temperature profile in the NS atmosphere at low mass accretion rates. Under this condition, the beam pattern of X-ray radiation leaving the NS surface is expected to be suppressed along the normal to the surface. Thus, a smaller X-ray flux within the pulse period can be related to a smaller angle between the line of sight and the magnetic dipole.

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DATA AVAILABILITY

The *IXPE* data used in this paper are publicly available in the HEASARC database.

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