



Search for Short-timescale Variations in Magnetar Polarization Degree

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Abstract

In this work, we searched for short-timescale variations of polarizations in five magnetars observed by the Imaging X-ray Polarimetry Explorer. Only 4U 0142+61 showed an indication of variations of polarization degree (PD), with the significance of 3.0σ between the highest and lowest PDs, though no significant changes were observed in the polarization angle and emission features during this process. 1RXS J170849.0–40091, SGR 1806–20, 1E 2259+586 and 1E 1841–045 remained stable within the error ranges. To verify these results, we also performed simulations assuming constant polarization over their observation period. The results indicated that the probability of the detected PD of 4U 0142+61, being due to statistical fluctuations is only 5.8%. However, we cannot rule out the possibility of statistical fluctuations for 4U 0142+61, if the observed PD variation is indeed a real physical phenomenon, which would be necessary to be confirmed in future observations.

Key words: stars: magnetars – polarization – X-rays: stars

1. Introduction

Magnetars are young, highly magnetized neutron stars (NSs) with typical spin periods of 2–10 s, whose emission is powered by the decay of enormous internal magnetic fields (see, e.g., Mereghetti 2008; Turolla et al. 2015; Kaspi & Beloborodov 2017). Strong quantum electrodynamic (QED) effects emerge when the magnetic field approaches the critical value ($B_c = 4.4 \times 10^{13}$ G) where the Landau level spacing equals the electron rest energy (Schwinger 1951). The anomalous magnetic fields of magnetars exceed this critical value by up to two orders of magnitude.

The concept of magnetars was first proposed by Duncan & Thompson (1992) to explain the unusual radiative behavior of Soft Gamma Repeaters (SGRs) and Anomalous X-ray Pulsars (AXPs), which distinguishes them from ordinary rotation-powered pulsars. Unlike normal pulsars, magnetars exhibit diverse radiative behaviors, including bursts, outbursts, and giant flares. These observational differences likely arise from their complex magnetic field structures. While the external magnetic fields of typical pulsars are often approximated as simple dipoles, magnetars are thought to have more intricate configurations, featuring both poloidal and toroidal components, as well as higher-order multipole contributions (see, e.g., Rea et al. 2010; Xing & Yu 2011). Compared to a pure dipole configuration, a twisted dipole magnetic field stores additional magnetic energy, the release of which is believed to power the bursting activities of magnetars (Beloborodov 2009).

In the model proposed by Thompson et al. (2002), the magnetosphere is characterized as a self-similar, globally twisted dipolar magnetic field. However, subsequent observational evidence has suggested that magnetar magnetospheres might exhibit localized twists (Pili et al. 2015). For example, changes in the pulse profile (time and energy dependent) and spectrum of SGR 1806-20 around the 2004 December 27 Giant Flare (Woods et al. 2007; Yu 2012), support this notion. Additionally, the detection of a proton cyclotron feature in the X-ray spectrum of the “low-field” magnetar SGR 0418+5729 is consistent with a strong, localized toroidal field on the order of 10^{15} G (Tiengo et al. 2013). Currently, numerous properties of magnetars remain unexplained, and understanding the structure of their magnetic fields remains of critical importance for advancing our knowledge of these enigmatic objects.

X-ray polarimetry offers a unique observational advantage to validate the “twisted magnetosphere” model of magnetars (Aly 1994; Lynden-Bell & Boily 1994; Wolfson 1995; Thompson et al. 2002; Gourgouliatos 2008; Tong et al. 2021; Ntotsikas et al. 2024). From one side, magnetars are expected to exhibit highly polarized emissions, making them ideal targets for polarimetric studies (Harding & Lai 2006). The highly polarized emission is due to the propagation of X-ray photons in two distinct modes, ordinary (*O*-mode) and extraordinary (*X*-mode) modes, within the highly magnetized environment. The *O*-mode is polarized parallel to the plane defined by the local magnetic field and the photon propagation

direction, whereas the X -mode is polarized perpendicular to this plane. In strong magnetic fields, X -mode photons exhibit significantly different interaction properties compared to O -mode ones, with notably lower cross-sections, particularly at energies below the electron cyclotron frequency (Gnedin & Sunyaev 1974; Herold 1979; Meszaros et al. 1988; Pavlov & Zavlin 2000; Lai & Ho 2003). The low cross-section is due to the misalignment of the X -mode electric field with the magnetic field, making it less effective at interacting with the plasma. Because of vacuum birefringence in QED, photons keep the same polarization mode as they move closer to the surface of NS. This phenomenon occurs because the strong magnetic field modifies the vacuum's refractive index, causing the polarization states of photons to evolve differently as they propagate through the magnetosphere (Heyl & Shaviv 2002). Therefore, magnetar emissions are expected to exhibit high levels of polarization up to 70%~80% (Turolla et al. 2024), and such high polarization levels are advantageous for detecting significant polarization signals.

Traditional X-ray spectral analysis supports the presence of a twisted magnetosphere through successful fitting of characteristic spectral features with resonant Compton scattering (RCS) models in globally twisted magnetic fields (Nobili et al. 2008; Rea et al. 2008; Zane et al. 2009), but this approach suffers from inherent degeneracies and limited sensitivity to geometric configurations (Taverna et al. 2014). Polarimetric measurements provide direct constraints on the spatial distribution of magnetospheric currents and the influence of vacuum polarization effects as photons propagate through the magnetosphere (Taverna et al. 2014), by introducing two independent parameters: polarization degree (PD) and polarization angle (PA). Observations of the high-energy X-ray emission from certain magnetars, such as 1RXS J170849.0–40091 (1RXS J170849 hereinafter) and 4U 0142+61, exhibit significant phase-dependent features (Den Hartog et al. 2008a, 2008b), which could be explained by the asymmetric current distribution and viewing-angle modulation of resonant scattering efficiency in localized twist models, such as the shearing of a single lobe in an octupolar field (Pavan et al. 2009). If this scenario holds, phase-resolved polarimetric results should offer more evidence.

We used Imaging X-ray Polarimetry Explorer (IXPE) observational data in this study to look into possible weekly scale changes in PD and how they might be related to local magnetic field twists or untwists in magnetar magnetospheres. The data reduction processes are detailed in Section 2. In Section 3, we report the time-resolved polarization results analyzed for these magnetars. In Section 4, we performed a more detailed analysis of 4U 0142+61 to investigate its variability. Section 5 summarizes the findings and discusses potential causes.

2. IXPE Observations and Data Reduction

IXPE is a joint mission developed by NASA and the Italian Space Agency that was launched on 2021 December 9 (Soffitta et al. 2021; Weisskopf et al. 2022). IXPE is equipped with three identical X-ray telescopes, each comprising a mirror module coupled to an imaging photoelectric polarimeter positioned in the focal plane (Costa et al. 2001; Baldini et al. 2021), hosted by a detector unit (DU). IXPE is the unique observatory capable of measuring linear X-ray polarization with high sensitivity.

Since the launch of IXPE, five magnetars have been observed: 4U 0142+61 (Taverna et al. 2022), 1RXS J170849 (Zane et al. 2023), SGR 1806–20 (Turolla et al. 2023), 1E 2259+586 (Heyl et al. 2024), and 1E 1841–045 (Rigoselli et al. 2025; Stewart et al. 2025). Their basic information is shown in Table 1. Although magnetars are expected to exhibit high PDs up to ~80%, observed PDs in most sources fall below this value, with the exception of 1RXS J1708, whose PD reaches $85\% \pm 15\%$ in the 6–8 keV. The discrepancy arises mainly from different origins of thermal emission: emission from a condensed surface (expected $PD \leq 30\%$) rather than a magnetized atmosphere (expected $PD \sim 70\% \sim 80\%$), suggesting the likely presence of solid surfaces in magnetars (Turolla et al. 2024). To perform the time-dependent analysis, we used the Level 2 data distributed in the HEASARC archive.⁶ All data were processed with the following steps: (1) energy correction (based on the onboard calibration data) in the case of 4U 0142+61, while for the other magnetars data has already undergone this calibration prior to download; (2) particle and instrumental background events were removed according to the Di Marco et al. (2023) algorithm; (3) the time intervals of high background is also removed by filtering on the count rates in the 2–8 keV energy band, deleting intervals where the count rate in any DU with a 300 s time bin exceeded the mean value by over 3 times the standard error (see Figure A1 for 4U 0142+61 as an example) (Kaaret et al. 2024); (4) since we report detailed analysis results only for 4U 0142+61, barycenter corrections were performed using the *barycorr* tool in HEASoft V6.30.1, the JPL-DE421 solar system ephemeris; (5) phase folding performed with *xpphase* for 4U 0142+61 (pepoch = 59850.0, $f = 0.115079336$ Hz, and $\dot{f} = -2.1 \times 10^{-14}$ Hz s⁻¹ (Taverna et al. 2022).), while event selection was done using the *xpselect* tool; (6) source and background regions were selected using SAOImage DS9 (DS9; Joye & Mandel 2003) version 7.5.

Observations of 4U 0142+61, SGR 1806–20, and 1E 1841–045 were partially affected by solar particles, whereas those of 1RXS J170849 and 1E 2259+586 remained unaffected. We computed polarization using the *xpbin* tool and *pcube* methods. We adopt a uniform selection of source and

⁶ <https://heasarc.gsfc.nasa.gov/docs/ixpe/archive>

Table 1
Basic Information about the Five Magnetars Observed by IXPE

Parameters	4U 0142+61	1RXS J170849	SGR 1806–20	1E 2259+586	1E 1841–045
Obs ID	01003299	01003199	02002899	02007899	03250499
Start time	2022/1/31	2022/9/19	2023/3/22	2023/6/2	2024/9/28
Stop time	2022/2/27	2022/10/8	2023/4/13	2023/7/6	2024/10/10
Exposure (ks)	840	837	945	1208	292
R.A.	01 ^h 46 ^m 22 ^s	17 ^h 08 ^m 46 ^s	18 ^h 08 ^m 39 ^s	23 ^h 01 ^m 08 ^s	18 ^h 41 ^m 19 ^s
decl.	+61°45′03″	−40°08′52″	−20°24′39″	+58°52′44″	−04°56′11″
Distance (kpc)	3.6 ± 0.4	3.8 ± 0.5	8.7 ^{+1.8} _{−1.5}	3.2 ± 0.2	8.5 ^{+1.3} _{−1.0}
B_c (10^{14} G)	1.3	4.7	20	0.59	7
P (s)	8.7	11.0	7.5	7.0	11.8
$\dot{P}$ (10^{-11} s/s)	0.20	1.95	49.5	0.05	4.1
PD (%)	13.5 ± 0.8 ^a	35.1 ± 1.6 ^b	~5.7 ^c	5.6 ± 1.4 ^d	25.8 ± 3.1 ^e

Notes. Parameters, including R.A., decl., distance, magnetic field strength, and spin period P and its derivative $\dot{P}$, are taken from <https://www.physics.mcgill.ca/pulsar/magnetar/main.html#tab2> and Olausen & Kaspi (2014).

^a Taverna et al. (2022).

^b Zane et al. (2023).

^c Turolla et al. (2023).

^d Heyl et al. (2024).

^e Rigoselli et al. (2025). The PDs are calculated in the 2–8 keV energy range, among which the PD of SGR 1806–20 is below the MDP (~20%).

background regions for all the considered targets except 1E 1841–045. Specifically, the source regions are defined as circles with a radius of 60″, while the background regions are defined as annuli with inner and outer radii of 150″ and 300″, respectively. For 1E 1841–045, the source region was defined as a circle with a radius of 48″, and the background region as an annulus with inner and outer radii of 60″ and 240″, respectively. This adjustment was made to maximize the number of source events while minimizing contamination from the surrounding supernova remnant (SNR) Kes 73. We chose the smaller background region to accurately account for the SNR’s contribution and ensure a more accurate subtraction of the background flux. Their corresponding DS9 images are presented in Figure A2.

To study polarization on a short timescale, we used *ixpeobssim* version 31.0.1 to perform simulations and data analysis; this software was specifically developed for IXPE (Baldini et al. 2022). The analysis was performed by using the PCUBE algorithm in the *xpbin* tool with response matrices version 013 in the proper date period and the unweighted approach (Di Marco et al. 2022).

3. Time Resolved Analysis of Magnetars

We perform time-resolved analysis of the reported magnetars observed by IXPE, as listed in Table 1.

1. *4U 0142+61*. IXPE observed 4U 0142+61 during two periods: the first one is from 2022 January 31 to February 7 (exposure time: 714 ks) and the second one is from 2022 February 21 to 27 (exposure time: 118 ks).

Taverna et al. (2022) reported that 4U 0142+61 exhibits a characteristic $\sim 90^\circ$ PA rotation between low and high energies. The finding suggests that different polarization-mode photons likely dominate at these energy bands. We divided the first segment into six ~ 60 hr time bins, while the second segment was left as it is, given its relatively short duration. Even if an energy-dependent PD was reported for this source (Taverna et al. 2022), here we performed a time-resolved analysis across the entire 2–8 keV energy band, and the results are reported in Figure 1 and Table 2, where the seven time bins are sequentially labeled as T1–T7. We observe a maximum difference of polarization between the fourth time bin (T4) and the sixth time bin (T6), which is $10\% \pm 3\%$. A simple significance estimation using the standard Gaussian equation:

$$\sigma = \frac{|PD_{T4} - PD_{T6}|}{\sqrt{\sigma_{T4}^2 + \sigma_{T6}^2}}, \quad (1)$$

yields a significance level of $\sim 3\sigma$. The PA remains consistent within the errors ($5^\circ \pm 10^\circ$), and no significant changes in the count rate were observed between these periods, as illustrated in Figure 1 (c).

2. *1RXS J170849*. IXPE observed 1RXS J170849 during two periods: the first one is from 2022 September 19 to 2022 September 29 (exposure time: 720 ks) and the second one is from 2022 September 30 to 2022 October 8 (exposure time: 117 ks). Zane et al. (2023) reported that 1RXS J170849 exhibited a high degree of polarization ($\sim 35\%$ in the 2–8 keV energy band) with the PA

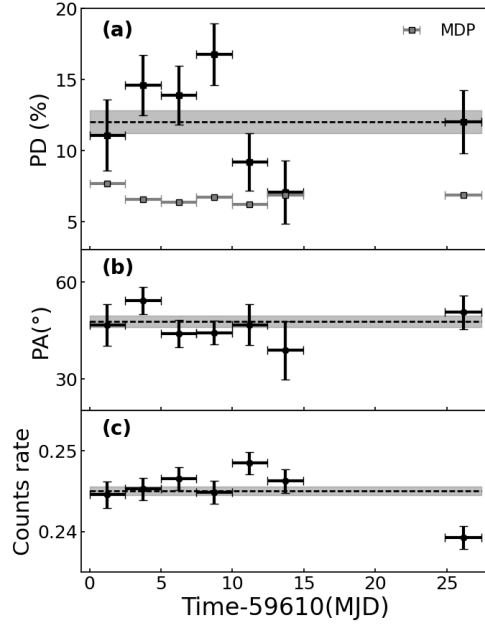


Figure 1. Time-resolved polarization result of 4U 0142+61 in the 2–8 keV band. Panels (a) and (b) show the time-resolved PD and PA, respectively, with their weighted averages indicated by dashed horizontal lines. Panel (c) shows the IXPE light curve averaged over 3DUs. The gray shading indicates the 1σ error range of the average. See Table 2 for numerical values.

remaining largely constant across different energy bands. Due to the high significance of the polarization measurement, we divided the observation into eight ~ 58 hr time bins, with results shown in Figure 2(I) and Table 2. 1RXS J170849 shows quite stable behavior for PD, PA and count rate, that values in each time bin are consistent with their averages within the uncertainties.

3. *SGR 1806–20*. IXPE observed SGR 1806–20 during two periods: the first one is from 2023 March 22 to 2023 April 1 (exposure time: 475 ks) and the second one is from 2023 April 3 to 2023 April 13 (exposure time: 471 ks). For SGR 1806–20, the extremely low flux of the source during the observation, coupled with the influence of solar activity, resulted in low statistical significance for the polarization measurements. However, a significant PD $31.6 \pm 10.5\%$ was detected in the 4–5 keV energy band (Turolla et al. 2023). We divided the first and second observations into two equal time bins of ~ 126 hr and ~ 125 hr, respectively. The results were shown in Figure 2(II) and Table 2. None of the time bins yielded PD values exceeding minimum detectable polarization (MDP), precluding a statistically meaningful time-resolved analysis.
4. *1E 2259+586*. IXPE observed 1E 2259+586 during two periods: the first one is from 2023 June 2 to 19 (exposure time: 879 ks) and the second one is from 2023 June 30 to July 6 (exposure time: 329 ks). Heyl et al. (2024)

reported that 1E 2259+586 showed phase-dependent PD and PA behaviors, with PD anticorrelating with the count rate. Two emission regions on the NS surface explain this, with a plasma loop partially blocking one’s radiation during certain phases. Due to the low significance of the polarization measurement, we divided the first segment into two equally spaced time bins, each spanning ~ 209 hr, while the second segment was treated as a single time bin, with results shown in Figure 2(III). Similar with the integrated result, no significant polarization is detected in any of the three time bins; despite that, no hint of variability with respect to the average values for PD, PA and count rates is shown.

5. *1E 1841–045*. IXPE observed 1E 1841–045 during two periods: the first one is from 2024 September 28 to October 1 (exposure time: 165 ks) and the second one is from 2024 October 7 to 10 (exposure time: 127 ks). Stewart et al. (2025) and Rigoselli et al. (2025) reported that the IXPE observation of 1E 1841–045 after its 2024 outburst revealed an energy-dependent PD increasing from $\sim 15\%$ at 2–3 keV to $\sim 55\%$ at 5–8 keV, with the PA remaining nearly constant at $\sim 0^\circ$. The broad X-ray data was analyzed using spectropolarimetry, which pointed to a synchrotron or curvature radiation source for the hard power-law component. We divided the first and second observations into two equal time bins of ~ 44 hr and ~ 34 hr, respectively. The time-resolved analysis in Figure 2(IV) shows insignificant variability in PD, PA, or counts rate across the time bins, with the maximum PD variation at 1.3σ , we come to the conclusion that the current data set does not allow for a more in-depth study of short-timescale polarimetric evolution in this source.

4. Detailed Analysis of 4U 0142+61

In this section, we conduct a detailed polarization study of 4U 0142+61 to investigate the potential polarization variability.

4.1. Fluctuation Analysis

In Section 3, we reported hints of possible time-dependent PD variations, with the most notable difference appearing between epochs T4 and T6. If such variations reflect intrinsic physical changes, using excessively large time bins could induce depolarization effects. To mitigate this depolarization effect while capturing the underlying variations, we dig into this by applying different time binnings, obtaining a variation significance up to 3.9σ when a time interval, designated as T_s (MJD 59618.549–59620.207; PD = 0.21 ± 0.03), is considered to compare with T6.

We used a Bayesian approach to assess the significance of the polarization variations between T4 or T_s with respect to

Table 2
Time-resolved Polarization Results of Magnetars

Bin	Tstart (MJD)	Tstop (MJD)	PD	PA (°)	MDP	Exposure (ks)	Counts
4U 0142+61							
T1	59610.318	59612.815	0.11 ± 0.02	47 ± 6	0.077	88	66,295
T2	59612.815	59615.312	0.15 ± 0.02	54 ± 4	0.065	128	97,103
T3	59615.312	59617.809	0.14 ± 0.02	44 ± 4	0.064	125	95,102
T4	59617.809	59620.305	0.17 ± 0.02	44 ± 4	0.067	121	91,108
T5	59620.305	59622.802	0.09 ± 0.02	47 ± 6	0.062	135	101,458
T6	59622.802	59625.299	0.07 ± 0.02	39 ± 9	0.069	116	89,709
T7	59635.194	59637.783	0.12 ± 0.02	51 ± 5	0.068	118	90,685
Total	59610.318	59637.783	0.120 ± 0.008	47 ± 2	0.025	832	631,460
1RXS J170849							
T1	59841.215	59843.622	0.37 ± 0.04	−60 ± 3	0.139	88	22,035
T2	59843.622	59846.029	0.32 ± 0.04	−66 ± 4	0.126	108	27,122
T3	59846.029	59848.436	0.38 ± 0.04	−67 ± 3	0.119	114	28,656
T4	59848.436	59850.843	0.35 ± 0.04	−63 ± 3	0.116	115	28,830
T5	59850.843	59853.250	0.33 ± 0.05	−56 ± 5	0.180	65	15,973
T6	59853.250	59855.657	0.31 ± 0.04	−64 ± 4	0.119	117	29,244
T7	59855.657	59858.064	0.34 ± 0.04	−60 ± 3	0.118	114	28,872
T8	59858.064	59860.471	0.36 ± 0.04	−59 ± 3	0.118	117	29,515
Total	59841.215	59860.471	0.34 ± 0.01	−62 ± 1	0.044	837	210,246
SGR 1806-20							
T1	60025.520	60030.520	0.2 ± 0.2	73 ± 28	0.507	236	3158
T2	60030.520	60035.790	0.3 ± 0.2	26 ± 19	0.539	239	3012
T3	60037.488	60132.745	0.2 ± 0.2	−30 ± 33	0.571	235	2694
T4	60132.745	60047.932	0.1 ± 0.2	−8 ± 73	0.600	236	2608
Total	60025.520	60047.932	0.06 ± 0.09	23.4 ± 43	0.276	946	11,472
1E 2259+586							
T1	60097.969	60106.663	0.07 ± 0.02	−71 ± 10	0.073	467	86,162
T2	60106.663	60115.357	0.04 ± 0.03	−81 ± 18	0.087	412	74,896
T3	60124.051	60132.745	0.06 ± 0.03	−77 ± 15	0.100	329	59,789
Total	60097.969	60132.745	0.06 ± 0.02	−75 ± 8	0.050	1208	220,847
1E 1841-045							
T1	60581.064	60582.881	0.27 ± 0.06	−4 ± 6	0.171	83	14,114
T2	60582.881	60584.710	0.25 ± 0.06	12 ± 7	0.181	82	13,598
T3	60590.371	60591.800	0.37 ± 0.07	1 ± 5	0.211	64	10,080
T4	60591.800	60593.217	0.14 ± 0.07	−9 ± 14	0.214	64	10,398
Total	60581.064	60593.217	0.25 ± 0.03	1 ± 4	0.096	293	48,190

T6, following the methodology described in Feng et al. (2020). The posterior distributions provided the best estimates and confidence intervals for PD and PA, as shown in Figure 3. The left subfigures illustrate the significance levels between T4 and T6, while the right subfigures show the comparison between Ts and T6. The Bayesian analysis shows that the PD difference between Ts and T6 is inconsistent at a level of 3.0σ , where the difference between T4 and T6 is inconsistent at a level of 2.2σ .

To avoid possible underestimation of the uncertainty when the pcube errors are considered, we account for the error correlation between PD and PA by employing a PD-PA protractor plot (see Figure 4) (see, e.g., Di Marco et al. 2022). The results from Figure 4 are consistent with those from the Bayesian analysis, indicating that the PD difference between Ts and T6 reaches a significance level of approximately 3σ . Meanwhile, aiming to verify the possibility that such a

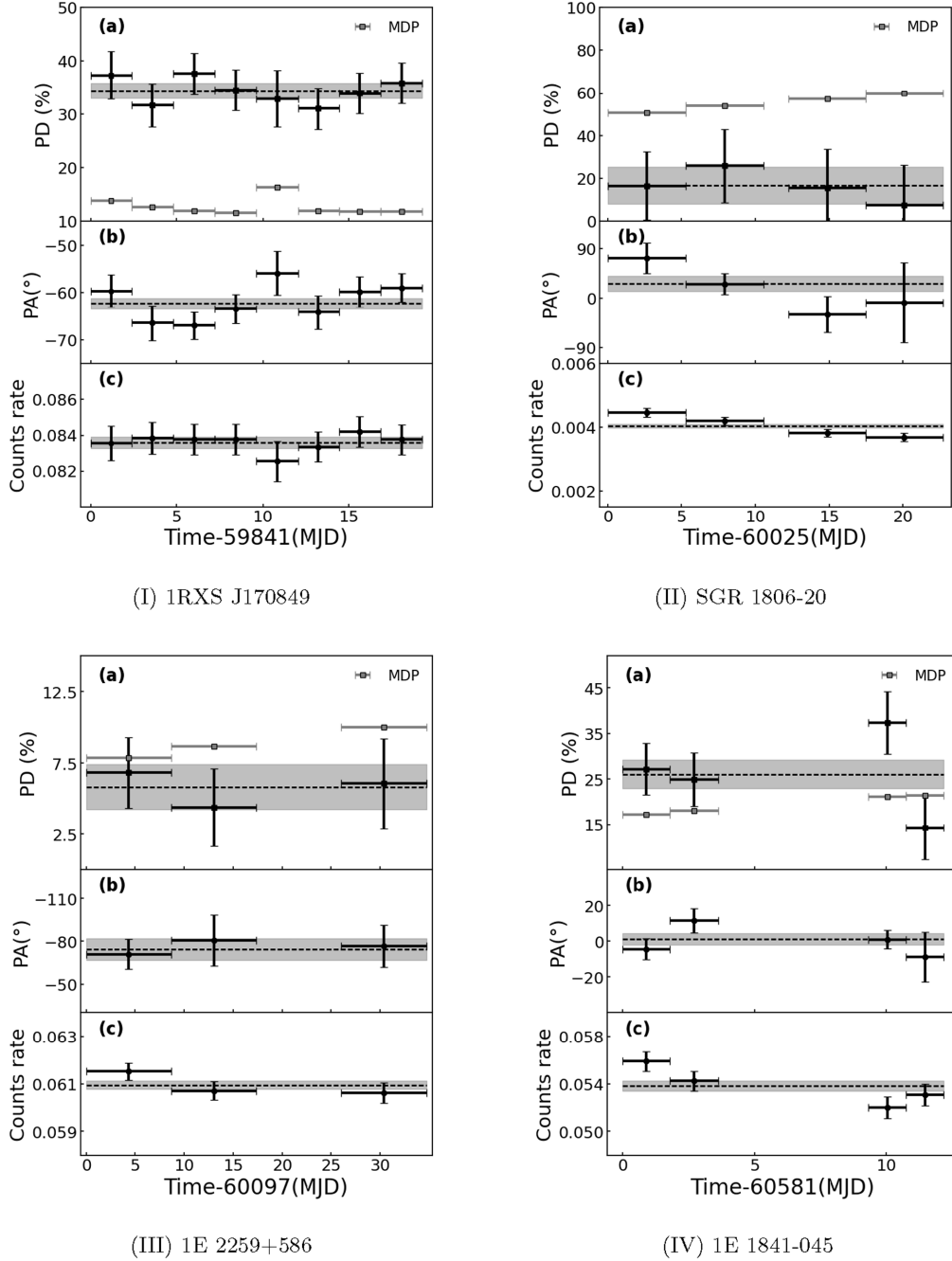


Figure 2. Time-resolved polarization result of four magnetars in the 2–8 keV band: (I) 1RXS J170849, (II) SGR 1806–20, (III) 1E 2259+586, and (IV) 1E 1841–045. For each subfigure, panels (a) and (b) show the time-resolved PD and PA, respectively, with their weighted averages indicated by dashed horizontal lines. Panel (c) shows the IXPE light curve averaged over 3DUs. The gray shading indicates the 1σ error range of the average. The detailed values are tabulated in Table 2.

variation is simply due to statistical fluctuations, we test this hypothesis here.

We performed simulations of observations by using *ixpeobssim* assuming a constant PD throughout the entire observation period equal to 12.0% (the weighted average value in 2–8 keV energy range). In the simulations, we adopted the same spectral model reported in Taverna et al. (2022). Each

simulation has an exposure time corresponding to one-seventh of the total observation, similarly to the time bins reported in the time-resolved analysis. Analyzing the results from a total of 16,000 simulated observations, we found, as expected, a Gaussian distribution for PD centered on 12.0%, with a standard deviation of 2.3%. The PDs of T4 and T6 are consistent with a random fluctuation at 2.2σ as reported in the

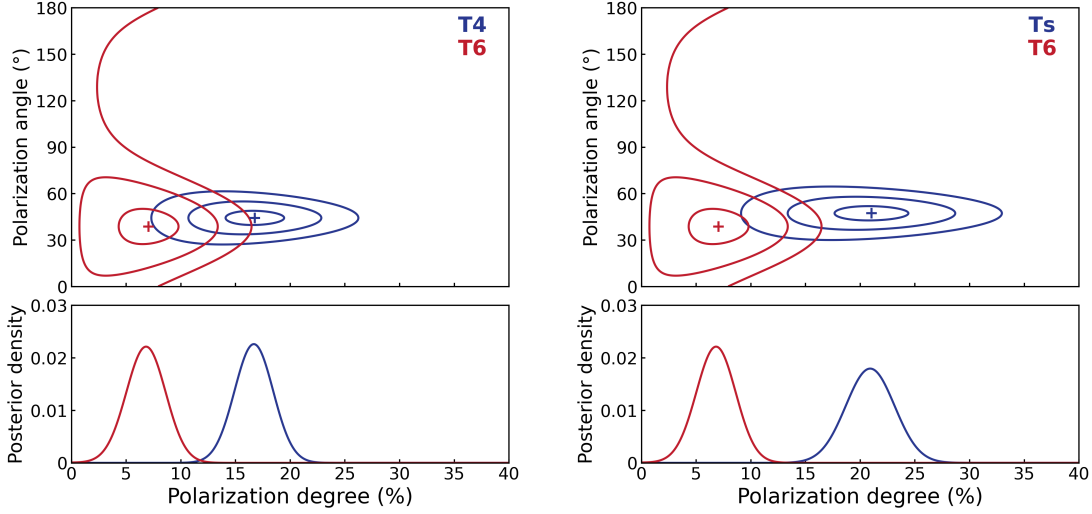


Figure 3. Top: Posterior distributions of PD and PA using data from T6 (in red) compared with data from T4 (left, in blue) and Ts (right, in blue) in the 2–8 keV. The contours represent 1 σ , 3 σ , and 5 σ from inner to outer. Bottom: Marginalized posterior distribution of PD over PA.

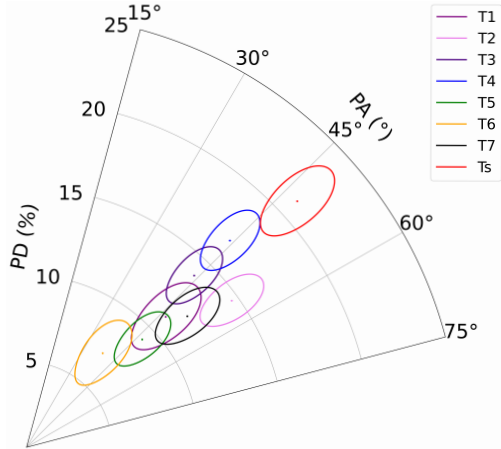


Figure 4. The time-resolved 2–8 keV band polarization characteristics of 4U 0142+61 are presented in the PD-PA polar plane, with uncertainties determined at a 68% CL. The analysis incorporates eight temporal bins, following the same configuration as shown in Table 2.

previous section. This confirms, also with simulations, that at a 94.2% CL the PD difference between T4 and T6 could be due to statistical fluctuations.

To determine the probability that two independent measurements of the same variable, following a Gaussian distribution having a standard deviation of 2.3%, can differ by more than 9.7%, we consider the properties of normally distributed random variables. Let X_1 and X_2 be the independent and identically distributed random variables following the normal distribution with mean μ and $\sigma = 2.3\%$. The difference between these two variables, $D = X_1 - X_2$, will also follow a normal distribution but with a mean of zero, as derived in Equation (1). We can standardize D to a standard normal variable Z . Being

interested in finding the probability $P(|D| \geq 9.7\%)$, we translate it into: $P\left(|Z| \geq \frac{9.7\%}{\sqrt{2} \times 2.3\%}\right) = P(|Z| \geq 2.98)$. Due to the symmetry of the standard normal distribution, this probability can be expressed as $2 \times P(Z \geq 2.98)$. Therefore, $P(|Z| \geq 2.98)$ is roughly $2 \times 0.0014 = 0.0028$. This indicates that there is only a 0.28% chance that two randomly sampled values from the given Gaussian distribution will differ by 9.7% or more. This means that the significance is at the level of 99.7% that is $\sim 3\sigma$ as reported in Section 3.

When all the possible combinations of time bins are accounted for, the probability of observing at least one PD difference $\geq 9.7\%$ in 21 comparisons is:

$$P_{\text{global}} = 1 - (1 - 0.0028)^{21} \approx 5.8\% \quad (1.9\sigma)$$

For a single bin (e.g., T4 or T6), the probability of observing a 5.0% deviation from the mean is $p = 0.057$. When accounting for all seven bins, the probability of detecting at least two such deviations due to statistical fluctuations becomes:

$$P_{\text{global}} = 1 - (1 - 0.057)^7 - 7 \cdot 0.057 \cdot (1 - 0.057)^6 \approx 8.5\% \quad (1.7\sigma).$$

It means that the adopted time binning gives a significance for this deviation at the level of 94.2%, i.e., $\sim 2\sigma$ as previously reported in the discussion about simulations. In conclusion, with the present data, it is not possible to exclude at high significance that such a variation is due to statistical fluctuations. Further investigations could be useful to verify, with greater significance, possible variability on timescales longer than the spin period in this class of sources.

We performed simulations adopting exposure times as Ts and consistent model inputs as described previously. We generated 56,000 simulated observations reporting a standard

deviation (σ) of 2.6%. The 3σ upper limit for statistical fluctuations is 19.9%. The PD value of Ts (21.1%) exceeds the 3σ upper limit, corresponding to a significance of 3.5σ , in line with $\sim 4\sigma$ previously reported. To account for multiple testing (11 independent time bins, each with a duration of 77 ks), we calculated the global probability of observing at least one such deviation due to statistical fluctuations:

$$P_{\text{global}} = 1 - (1 - 0.00023)^{11} \approx 0.25\% \quad (3.0\sigma).$$

This result indicates that the observed PD enhancement in Ts is unlikely to arise from statistical fluctuation, supporting the hypothesis of intrinsic physical changes in the source.

The PDs of T4 and T6 both deviate significantly from the weighted average PD, with a difference of 5% in opposite directions. The significance of these deviations is approximately 2.3σ . Additionally, the probability that at least one of these deviations arises purely from statistical fluctuations is 2.1σ . Similarly, we adopted the Bayesian approach previously discussed and found that the polarization results from T4, T6, and Ts are all consistent with the integrated 2–8 keV measurements within a 3σ CL. These results imply that statistical fluctuations could plausibly explain the observed deviations.

4U 0142+61, being brighter than the other observed magnetars, shows smaller uncertainties; despite this, only marginal variations of polarization with time are reported. No significant polarimetric variations are observed in the other four sources, indicating that such variations, if present, cannot be detected with the present data.

4.2. Pulse and Spectral Analysis

We compared the pulse profiles of T4 and T6, as shown in Figure 5. The pulse profiles of T4 and T6 are well consistent within uncertainties. To exclude edge effects, we filtered out the truncated phase cycle in each good time intervals (GTI). We divided the quantity of photons in each bin by the average value to make the comparison easier.

We conducted a phase-resolved polarization analysis for the T4–T6. However, the phase-resolved PD during T6 was below the MDP, making reliable analysis impossible. Given that PD was low in both T5 and T6, data from these two time bins next to each other that had low PD were combined and analyzed as one (T56). To enhance the significance, events in the 2–5 and 5–8 keV energy ranges with different PA orientations were separated. The results in 2–5 keV are shown in Figure 6. The analysis reveals that in the T4 time interval, the PD reaches its highest value in the 0.2–0.4 phase bin, and there are noticeable changes in the PA across different phase bins, particularly a significant increase in the 0.2–0.4 and 0.6–0.8 phase bins. In contrast, the PD in the T56 time interval remains stable, and the PA changes relatively smoothly, though it still exhibits some phase dependence. Additionally, the PA differences

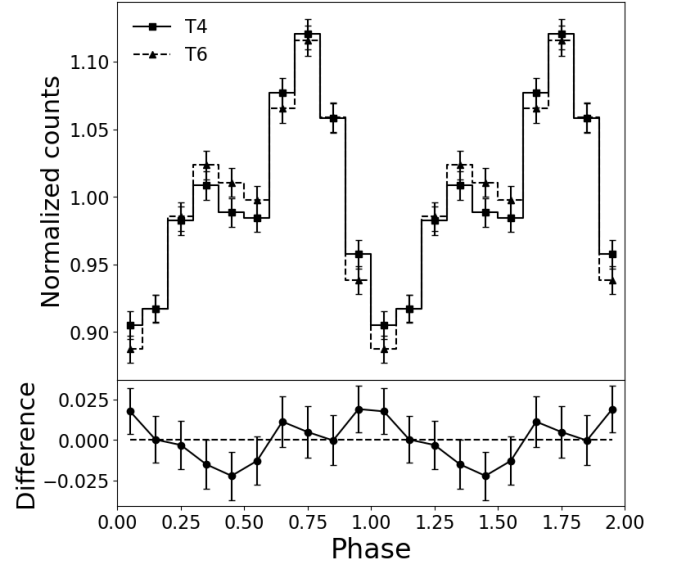


Figure 5. The pulse profiles observed in T4 and T6 in the 2–8 keV band are consistent within the given uncertainties. Error bars are reported at a 68% CL.

between T4 and T56 in the same phase bins are not significant, which could also be due to statistical fluctuations. Although we fitted the PA using the rotating vector model (RVM; Radhakrishnan & Cooke 1969), with the resulting curve displayed in Figure 6, we ultimately refrain from reporting the best-fit parameters due to both the intrinsic parameter degeneracy of the RVM and their large uncertainties, which preclude meaningful physical interpretation.

We plotted the Stokes parameters Q and U as a function of phase for the T4 and T56, as shown in Figure 7. The plots reveal distinct differences in Q and U between these two short time intervals.

Using XSPEC, we performed spectral fitting for the time intervals Ts, T4, T6, and T56, using the model $w \times \text{tbabs} \times (\text{bbody} + \text{powerlaw})$, obtaining the best-fitting spectral parameters as shown in Table 3. The table indicates that the spectra across the specified time intervals are essentially consistent, suggesting no significant changes in the spectra throughout these periods.

To sum up, the pulse profiles and spectra do not change much between the time intervals. However, the phase-resolved polarization analysis shows that PD and PA behave differently between the time intervals. These differences suggest potential changes in the local magnetic field configuration, despite the absence of noticeable alterations in the pulse structure or spectral properties.

5. Discussion

From the analysis of IXPE observations, we concluded that there is no evidence for time variations of polarization in

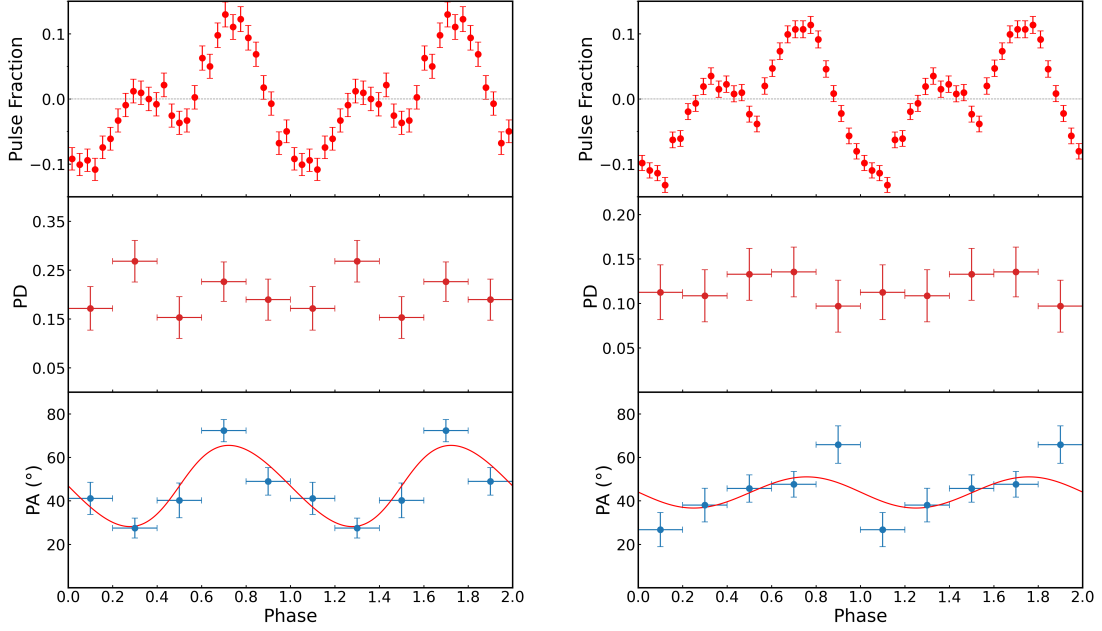


Figure 6. The study focuses on the phase-dependent X-ray flux and polarization properties. The left panel shows the results for T4, while the right panel shows the results for T56. (Upper) Energy-integrated (2–5 keV) IXPE counts as a function of the spin phase. (Center) PD as a function of the spin phase. (Lower) Information similar to that in the center, but it pertains specifically to the PA. The red curve shows the best-fitting RVM. Error bars are at the 1σ confidence level. All measured PDs are above the MDP_{99} . PD and PA are measured in the 2–5 keV band.

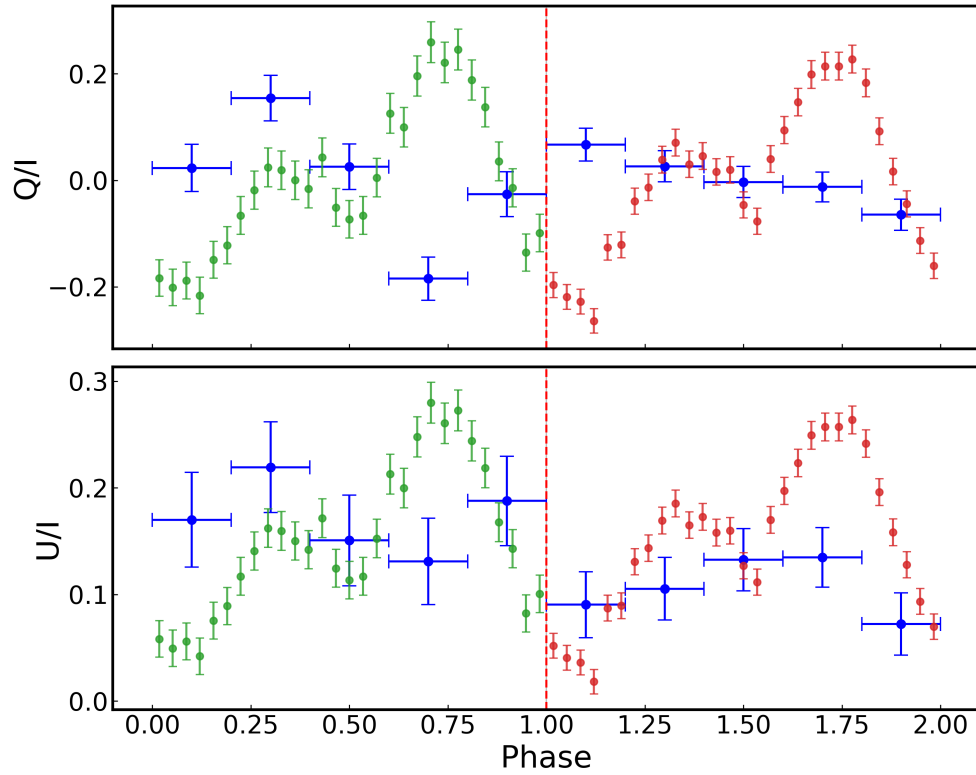


Figure 7. The top and bottom panels show the normalized Stokes parameters Q and U , respectively, as a function of the spin phase. Left of the dividing line (phase 0–1) shows T4 results with green error bars representing its 2–5 keV pulse profile; right (phase 1–2) displays T56 with red error bars. All error bars indicate 1σ uncertainties.

Table 3

Best-fit Parameters of the Phase-averaged IXPE Data on 4U 0142+61 Obtained from Spectral Analysis Using Model^a $w \times tbabs \times (bbody + powerlaw)$ in the 2–8 keV Band

Time	kT_{BB} (keV)	$norm_{BB}^b$ ($\times 10^{-3}$)	Γ	$norm_{PL}^c$ ($\times 10^{-1}$)	W_{DU2}	W_{DU3}	χ^2/dof
T4	0.464 ± 0.009	1.3 ± 0.1	3.3 ± 0.2	0.7 ± 0.2	1.038 ± 0.009	0.963 ± 0.008	197.4/199
Ts	0.48 ± 0.02	1.2 ± 0.1	3.6 ± 0.2	0.9 ± 0.3	1.03 ± 0.01	0.97 ± 0.01	172.9/174
T6	0.460 ± 0.001	1.2 ± 0.1	3.4 ± 0.2	0.9 ± 0.2	1.014 ± 0.009	0.950 ± 0.008	200.7/203
T56	0.450 ± 0.004	1.38 ± 0.09	3.1 ± 0.1	0.6 ± 0.1	1.029 ± 0.006	0.957 ± 0.006	265.6/240

Notes. Errors are given at the 1σ confidence level.

^a The column density parameter was frozen to $N_H = 0.57 \times 10^{22} \text{ cm}^{-2}$, consistent with Den Hartog et al. (2008b), and the constant parameter 1 was frozen to $W_{DU1} = 1$.

^b $norm_{BB}$ units: $10^{39} \text{ erg kpc}^{-2}$.

^c $norm_{PL}$ units: photons/keV/cm²/s at 1 keV.

1RXS J170849, SGR 1806–20, 1E 2259+586 and 1E 1841–045. Only 4U 0142+61 shows marginal indications for time variations.

One possible explanation is that the magnetosphere of 4U 0142+61 undergoes a localized reconfiguration during the T4–T6 period. The high PD in T4 could correspond to a region of the magnetosphere where the magnetic field is more twisted, leading to enhanced RCS and higher polarization (Rea et al. 2008). As the twist relaxes or shifts to another part of the magnetosphere in T5 and T6, the PD decreases, while the PA remains relatively stable due to the global magnetic field structure remaining largely intact. This scenario aligns with the idea that magnetar magnetospheres can sustain localized twists (Beloborodov 2009).

However, the lack of significant changes in the spectrum poses a challenge to this interpretation. In twisted magnetosphere models, changes in the twist angle or current distribution typically lead to variations in the spectral properties, particularly in the non-thermal tail (1–100 keV) (Fernández & Thompson 2007). The unchanged spectrum suggests that the observed PD variations might be due to a more subtle rearrangement of the magnetospheric currents, possibly confined to a region that does not strongly influence the overall spectral properties. Consequently, the observations of 4U 0142+61 suggest that more complex, localized, and dynamic magnetic field configurations may be at play. Future phase-resolved polarization studies, combined with detailed spectral and timing analyses, will be crucial for disentangling these effects and providing a more complete understanding of magnetar magnetospheres.

We note that the observed variation, at present CL, could be due to statistical fluctuations. However, the measured change in PD when focusing on a more constrained time interval supports a marginal possibility of PD evolution during the observation. To further investigate this behavior, we eagerly anticipate future observations by the Enhanced X-ray Timing and Polarimetry (eXTP) mission (Zhang et al. 2019). With its significantly larger effective area, eXTP is

poised to deliver high-significance detections that can robustly resolve potential short timescale evolutionary behaviors in 4U 0142+61. With its advanced features, eXTP will be able to look deeper into the changing features of this magnetar, providing us important information for understanding its dynamic polarization properties.

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Appendix Extended Data

We provide supporting figures related to our data reduction process in this appendix. Figure A1 displays the average 2–8 keV light curve of 4U 0142+61 from IXPE observations, showing data before (top) and after (bottom) filtering as described in Section 2. Figure A2 displays the source and background regions adopted in our analysis for the five magnetars. The regions were specially adjusted for 1E 1841–045 (e) to avoid contamination from SNR Kes 73, while all other targets show identical circular source regions and annular background regions.

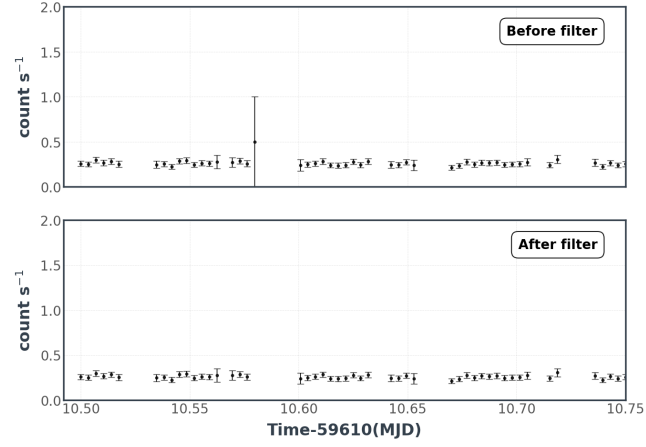


Figure A1. Average light curves of 4U 0142+61 observed by IXPE before and after data filtering (top and bottom panels, respectively).

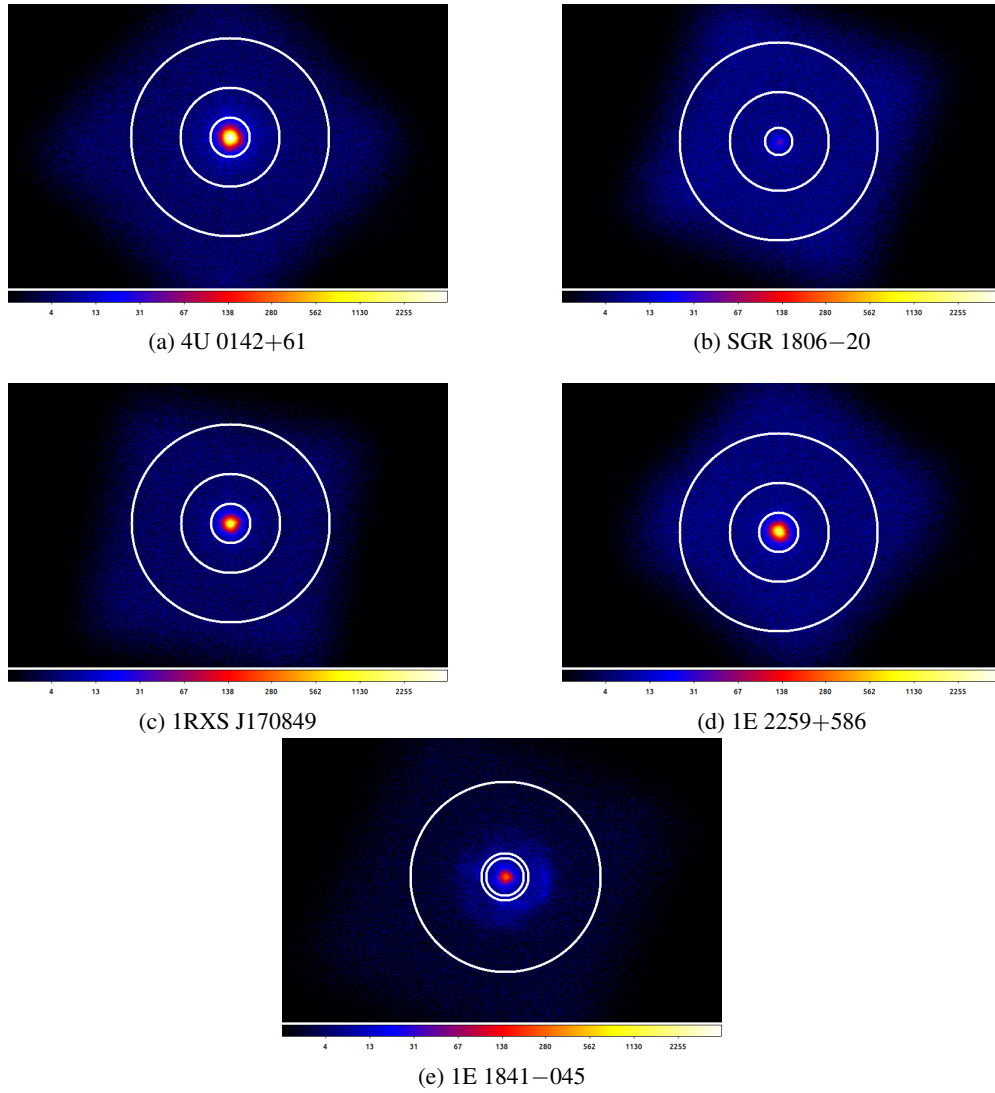


Figure A2. Five magnetars source and background regions shown on images from DU1. All panels share identical color scale parameters.

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