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Polarization Study of Swift J151857.0–572147 with IXPE Observation

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Abstract

We present an analysis of the Imaging X-ray Polarimetry Explorer observation from a newly discovered transient source: Swift J151857.0–572147. The obtained polarization degree (PD) and angle are $0.3\% \pm 0.3\%$ and $-24^\circ \pm 26^\circ$ respectively in 2–8 keV within 68% confidence level errors, and polarization results are below MDP_{99} in all energy bins, with the upper limit on PD of 0.8% in the 2–8 keV energy range. No quasi-periodic oscillations (QPOs) are detected in this observation. The polarization and QPO analyses support the hypothesis that the source was in the high soft state, and the results are consistent with predictions for a thin accretion disk model.

Key words: stars: black holes – polarization – X-rays: bursts

1. Introduction

Black hole X-ray binaries (BHXRBs) are binary systems composed of a black hole and a companion star. Mass transfer occurs from the companion to the black hole through Roche-lobe overflow, resulting in the formation of an accretion disk. These accretion disks efficiently convert gravitational potential energy into radiation, thus BHXRBs are among the most luminous X-ray sources. The flux and spectrum of BHXRBs are changing over time, typically transitioning between states of quiescent and outburst. Transients constitute the majority of BHXRBs, and they can only be effectively observed when they are in an outburst state. Described by several states, a complete outburst follows a "q" track in the hardness–intensity diagram (Homan et al. 2001; Fender et al. 2004; Belloni et al. 2005; Belloni & Motta 2016). In the low hard state (LHS), the X-ray spectrum is primarily dominated by non-thermal Comptonization with higher frequencies, while in the high soft state (HSS), the thermal component from the accretion disk becomes relatively strong with lower frequencies. The intermediate state represents a transition between the LHS and the HSS (Belloni et al. 2005; Belloni & Motta 2016). When a black hole is in the LHS, the X-ray spectrum follows a power-law distribution. While in the HSS, the accretion disk reaches the innermost stable circular orbit, and the X-ray spectrum mainly reflects the physical conditions in the inner region of the accretion disk. The effects of general relativity force photons to change their polarization degree (PD) as they travel along geodesics, leading to a net depolarization of the emission observed at infinity (Loktev et al. 2022, 2024). The PD and polarization angle (PA) are associated with spectral states. As detection technologies and simulation models continue to improve, polarization information is becoming increasingly significant, which enable us to gain more insights into the properties of BHXRB systems both in physics and geometry, such as spin, inclination, accretion rate and disk temperature (Li et al. 2005). This comprehensive approach, including polarization, is becoming more prevalent in the field of astrophysics.

The X-ray light curve of some BHXRBs shows stable approximate periodicity, known as quasi-periodic oscillation (QPO), which can be divided into Low Frequency QPO (LFQPO) and High Frequency QPO. The QPOs are strongly correlated with the power-law component of the spectrum. In general, the LFQPO will be detected once the power-law component exceeds 20% in 2–20 keV (Sobczak et al. 2000).

Swift J151857.0–572147, a newly discovered galactic transient, was initially considered as a gamma-ray burst (GRB 240303A; Kennea et al. 2024). The persistent brightness of this source, showing no signs of fading, along with its location in the galactic plane, confirms its classification as a galactic transient. The best localization of the source was provided by Swift/XRT immediate on-board localization, R.A.(J2000) = $15^h18^m57\overset{s}{.}00$, decl.(J2000) = $-57^d21'47\overset{''}{.}9$ (Kennea et al. 2024). The observations by Swift/XRT on 2024 March 10 showed that the X-ray spectrum was softer than a week ago. Spectral fitting results suggested a potential transition from the LHS to HSS (Del Santo et al. 2024). Radio observations with the MeerKAT radio telescope were carried out closely on 2024 March 4, at a central frequency of 1.28 GHz, with a total bandwidth of 856 MHz for 15 minutes (Cowie et al. 2024). A radio source was detected with a highly significant flux density of approximately 10.02 ± 0.04 mJy, within the X-ray uncertainty region of Swift J151857.0–572147. On 2024 March 9, The Australia Telescope Compact

Array also conducted observations at frequencies of 5.5 and 9 GHz. The source's inverted radio spectrum and photon index were consistent with an LHS X-ray binary, suggesting it could be a neutron star or black hole. Additionally, a significant radio flare was observed, consistent with galactic BHXRBs that emit relativistic ejecta during state transitions (Carotenuto & Russell 2024; Cowie et al. 2024). This bright radio flare was found to be fading rapidly on 2024 March 10, and its H I absorption constrained the distance of Swift J151857.0–572147 between 4.48 and 15.64 kpc (Burridge et al. 2024). Observations of optical and near-infrared (NIR) frequencies were done by the Robotic Eye Mount telescope (Baglio et al. 2024). In the optical band, the source was likely undetectable due to the extreme extinction ($N_{\rm H} = (5.6 \pm 0.1) \times 10^{22}\ {\rm cm}^{-2}$). On the contrary, the NIR counterpart was clearly detected in the same position as the radio's at the coordinates of R.A.(J2000) = $15^{\rm h}18^{\rm m}57\overset{\rm s}{.}138$, decl.(J2000) = $-57^{\rm d}21'47\overset{''}{.}30$, with an error of 2″. The transient was observed to be brightening in the NIR, aligning with the expected behavior of a low-mass X-ray binary during the initial stage of an outburst (Baglio et al. 2024).

In this work, we use IXPEOBSSIM (Baldini et al. 2022) to analyze the Imaging X-ray Polarimetry Explorer (IXPE) data of Swift J151857.0–572147 and study its properties from the perspectives of the light curve, power density, spectrum, and polarization. Observations and data reduction are introduced in Section 2. Polarization data analysis and detection result of LFQPOs are discussed in Section 3, then conclusions are drawn in Section 4.

2. Observations and Data Reduction

The IXPE (Weisskopf et al. 2022), an observatory in space that was launched on 2021 December 9, is a project of NASA and the Italian Space Agency (ASI). It has three co-aligned X-ray telescopes, with each telescope equipped with an imaging photoelectric polarimeter detector unit (DU) based on a gas pixel detector (Costa et al. 2001; Baldini et al. 2021), which can observe in the 2–8 keV energy range. BHXRBs are one of the scientific targets of IXPE, which led to the observation (ObsID: 03250201) of Swift J151857.0–572147 on 2024 March 18 with a total exposure time of 96 ks.

Level-2 event files of this observation were downloaded from the HEASARC archive, and filtered for source and background regions by SAOImage DS9 (DS9; Joye & Mandel 2003) version 7.5. The source regions were selected for DUs as circles with a radius of 100″, and we did not select the background region since the source is bright, following the prescription of Di Marco et al. (2023). The astronomical coordinates of the center are R.A.(J2000) = $15^{\rm h}18^{\rm m}57\overset{\rm s}{.}0$, decl.(J2000) = $-57^{\rm d}21'47\overset{''}{.}9$ after world coordinate system correction.

IXPEOBSSIM (Baldini et al. 2022) is a Python based simulation and analysis framework specifically developed for IXPE. Given a source model and the response functions of the telescopes, it is designed to produce realistic simulated observations. These simulations are in the form of event lists in FITS format, containing a strict superset of the information. The IXPEOBSSIM software version 31.0.1 and response matrix version 013 were used to analyze the IXPE data, and unweighted polarization parameters were derived using the PCUBE tool integrated inside IXPEOBSSIM.

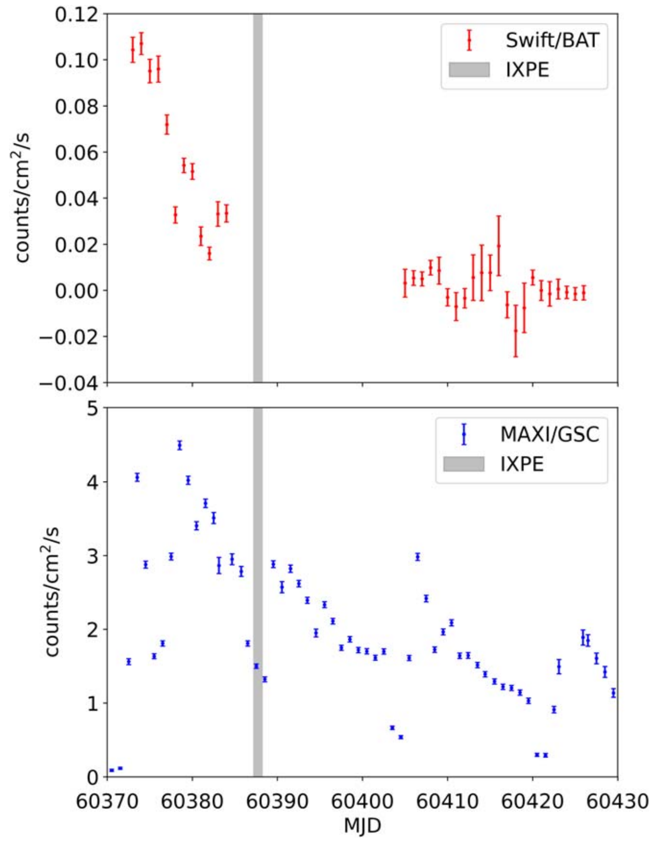

Figure 1. The light curve of Swift J151857.0–572147 from Swift/BAT (top) in 15–50 keV, MAXI/GSC (bottom) in 2–6 keV and IXPE observations. It shows a relatively long-term observation of Swift/BAT and MAXI/GSC with a gray strip marking the period of IXPE observation.

3. Results and Discussion

The light curves from Swift/BAT,[6] MAXI/GSC (Matsuoka et al. 2009) and IXPE observations of Swift J151857.0–572147 are shown in Figures 1 and 2. In the early stage of Swift/BAT observation, the flux presented a significant decrease, and after around 20 days, it turned into a quiet and stable state. The observation of IXPE lies in the period that Swift/BAT lacked data, providing a good supplement to its light curve. As shown in Figure 2, top panel, there is a dramatic flux drop on MJD

[6] https://swift.gsfc.nasa.gov/results/transients/weak/SwiftJ1518-5721/

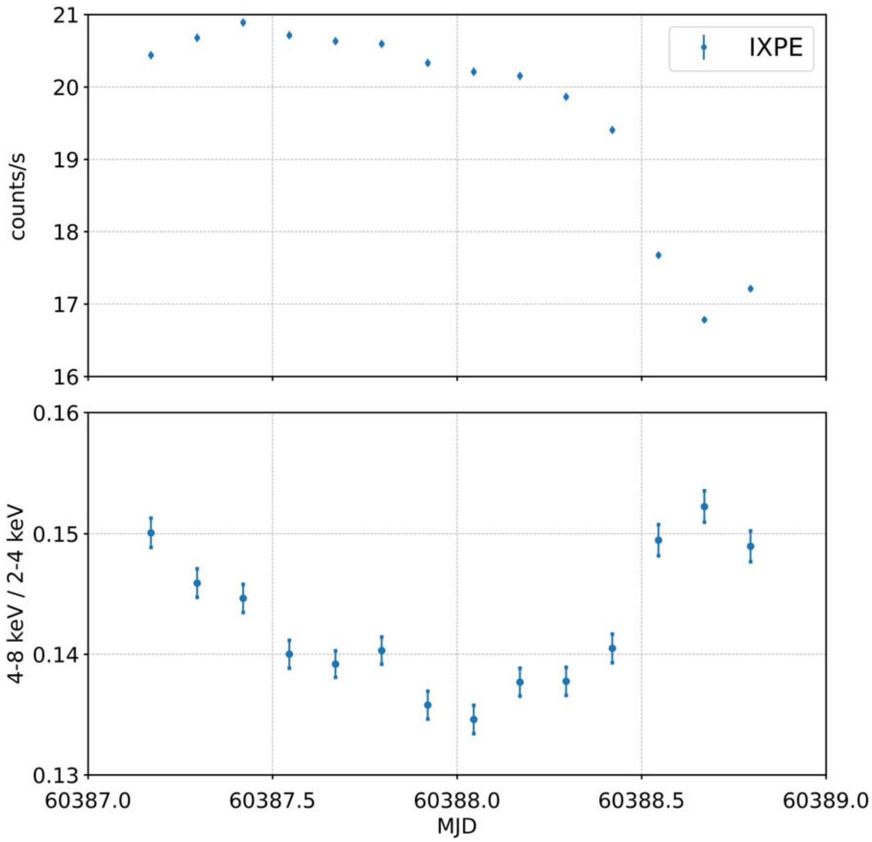

Figure 2. The light curve (top) and the hardness diagram (bottom) from IXPE observation. Hardness is defined as the counts of photons in the 4–8 keV range divided by the counts in the 2–4 keV range. Each point is averaged over three hours and three DUs.

Table 1
Polarization Properties in Six Different Energy Bands and in the Full IXPE 2–8 keV Band

	2–3 keV	3–4 keV	4–5 keV	5–6 keV	6–7 keV	7–8 keV	2–8 keV
U/I(%)	0.2±0.4	−0.3 ± 0.3	−0.1 ± 0.5	−1.4 ± 0.9	−0.9 ± 1.5	−1.3 ± 3.1	−0.2 ± 0.3
Q/I(%)	0.6 ± 0.4	−0.1 ± 0.3	−0.7 ± 0.5	0.6 ± 0.9	−1.6 ± 1.5	4.5 ± 3.1	0.2 ± 0.3
PA(°)	10 ± 17	−53 ± 34	−87 ± 23	−33 ± 17	−75 ± 23	−8 ± 19	−24 ± 26
PD(%)	0.6 ± 0.4	0.3 ± 0.3	0.7 ± 0.5	1.5 ± 0.9	1.8 ± 1.5	4.6 ± 3.1	0.3 ± 0.3
MDP $_{99}$(%)	1.1	1.0	1.6	2.7	4.5	9.3	0.8

60388.5. In the bottom panel, an upward trend in hardness is observed when the flux decreases, which indicates that the source was likely in the HSS during IXPE observation, a state in which the hardness of a black hole undergoes irregular changes.

We searched the LFQPO for Swift J151857.0-572147 from IXPE observation data, which tend to appear more frequently in the LHS (Sobczak et al. 2000). Barycentric corrections for the IXPE events were made using the barycorr tool in HEASoft version 6.30.1. The JPL-DE430 solar system ephemeris was utilized, with the position of the source set at R.A.(J2000) = $15^{h}18^{m}57\overset{s}{.}0$, decl.(J2000) = $-57^{d}21'47\overset{''}{.}9$. The power density spectrum, a diagram widely used for QPO searching, generated using the Stingray software (Huppenkothen et al. 2019), is shown in Figure 3. We specifically focused on the frequency range of 0.1–30 Hz, which is known to be the typical frequency range for LFQPOs. It is evident that the power density remains almost constant, and no significant peak is detected.

The IXPE observation data of Swift J151857.0–572147 was processed with `IXPEOBSSIM`, and the polarization results are

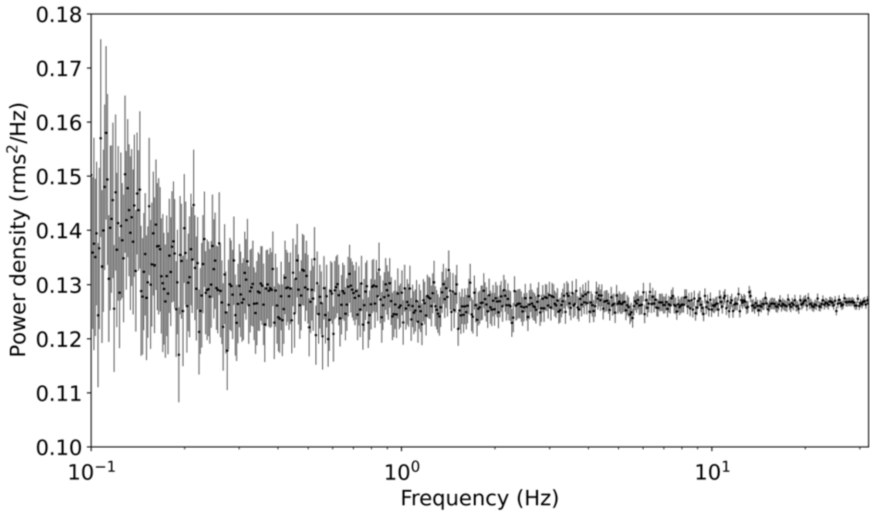

Figure 3. The power density spectrum of Swift J151857.0–572147 from IXPE observation in the 0.1–30 Hz frequency range with Poisson noise.

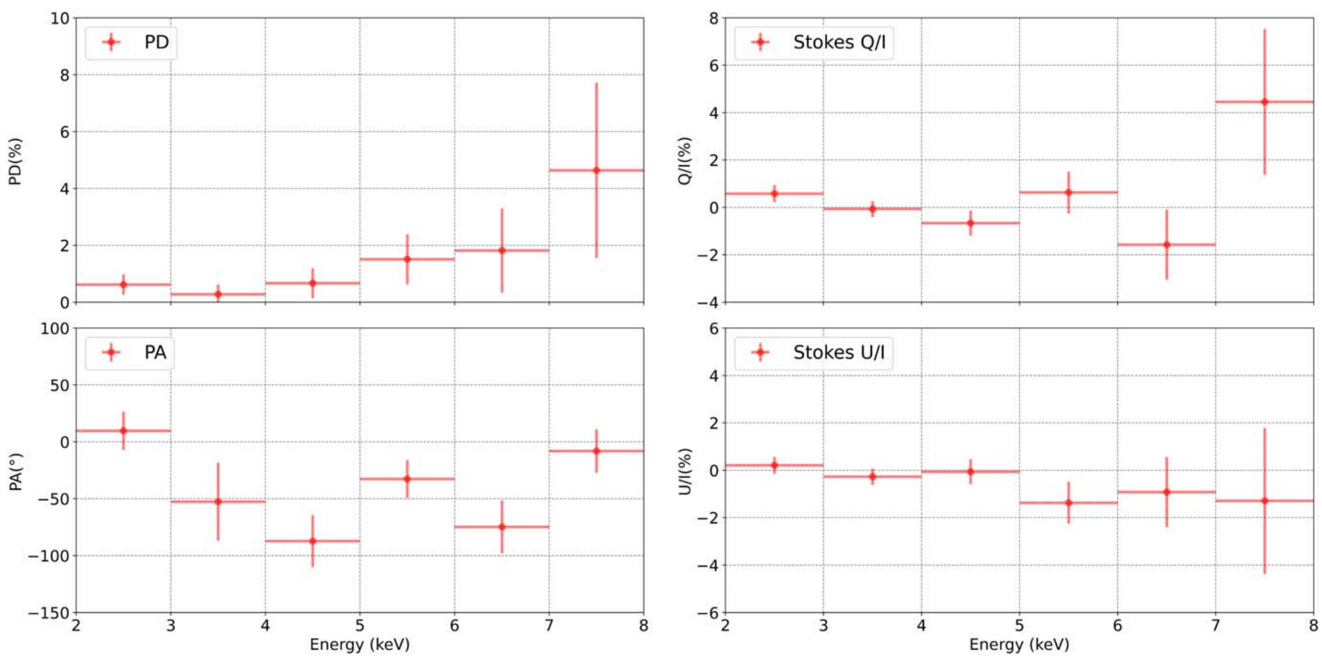

Figure 4. The average PD (upper left) and PA (lower left) of Swift J151857.0–572147 as a function of energy in 2–8 keV. The PD and PA are not statistically significant in all energy bins, and the results are from the joint analysis of three DUs with uncertainties calculated at a 68.3% confidence level. The normalized Stokes parameters Q/I (upper right) and U/I (lower right) are calculated under the same conditions.

summarized in Table 1. No significant PD is detected in the 2–8 keV energy range, giving an upper limit of 0.8% for the minimum detectable polarization at the 99% confidence level (MDP_{99}). The normalized Stokes parameter U/I is $-0.2\% \pm 0.3\%$ and Q/I is $0.2\% \pm 0.3\%$, calculated at a 68% confidence level and averaged over the three DUs. We also studied the polarization as a function of energy, as shown in Figures 4 and 5, and listed in Table 1 with errors at the 68% confidence level; the PD values in all of the energy bins are lower than their MDP_{99}, and no polarization is detected in any bin. This hints that the intrinsic PD of this source is low. If we consider a constant PD and each energy bin as an independent data set, the statistical significance of this observation in any single bin can be evaluated. The confidence level for the

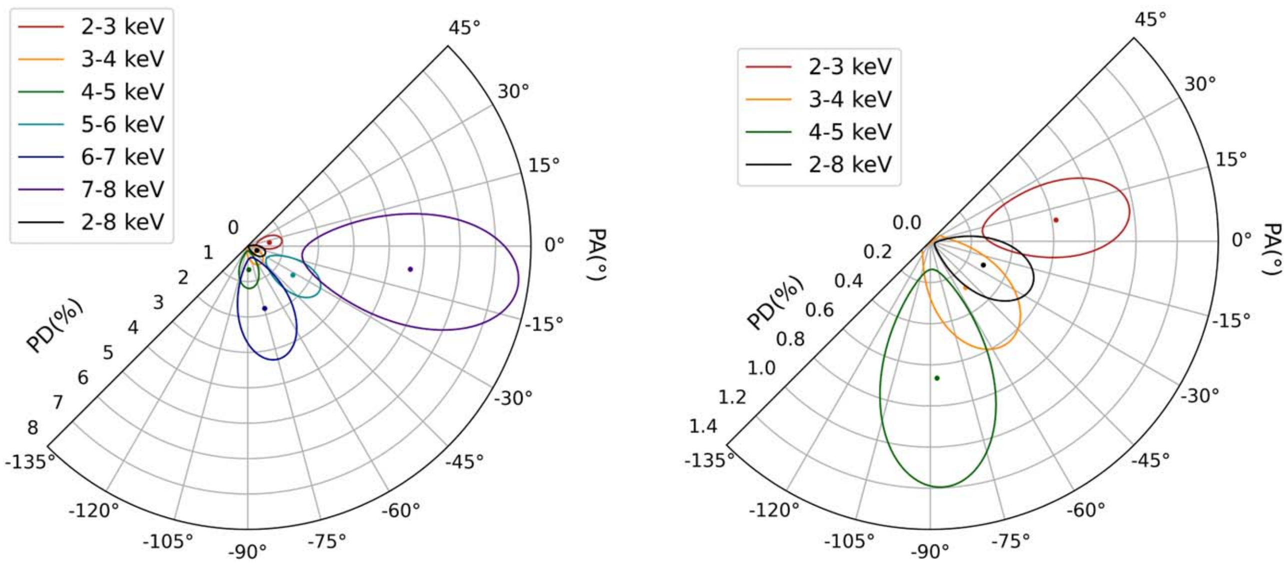

Figure 5. The energy-dependent polar plot of Swift J151857.0–572147. The right panel is an enlargement of the left one, only with less statistical bins. Contours show the 68% confidence level errors.

polarization detection was tested assuming the ensemble of bins against the null hypothesis of assuming a null polarization in every bin. We obtained a polarization detection at confidence level of 93.7%, which means there is a 6.3% chance that the observed polarization signal is due to random fluctuations.

We also studied the time-dependent polarization properties of this source. As affirmed in Figure 2, top panel, there is a significant flux decrease at the tail of IXPE observation. We thus divided the events into two parts by setting MJD = 60388.5 as the boundary. The PD values are 0.2 ± 0.3 and 0.8 ± 0.6 within 68% confidence level errors, given the upper limits MDP_{99} of 0.9% and 1.8% in 2–8 keV energy band before and after the boundary, respectively.

Since the launch of IXPE in 2021, several BHXRBs have been observed in the HSS, including Cyg X-1 (Steiner et al. 2024), LMC X-1 (Podgorný et al. 2023), 4U 1630–47 (Ratheesh et al. 2024), 4U 1957+115 (Marra et al. 2024) and Swift J1727.8–1613 (Veledina et al. 2023). X-ray polarization is sensitive to the geometric structure of the inner accretion disk, and also associated with spin and inclination. The classic theory of thin accretion disks posits that a geometrically thin and optically thick disk will produce multi-colored thermal radiation with low polarization. This theory aligns well with the results of Swift J151857.0–572147, whose PD is below 0.8%, and also consistent with Cyg X-1 (Steiner et al. 2024), LMC X-1 (Podgorný et al. 2023) and Swift J1727.8-1613 (Svoboda et al. 2024), whose PDs are around 2%, less than 1.1%, and less than 1%, respectively. However, the PD of 4U 1630–47 (Ratheesh et al. 2024) generally increases with energy, reaching $11.8\% \pm 2.5\%$ in the 7.5–8 keV range. The returning radiation is thought to importantly contribute to the high PD of 4U 1630–47, particularly when the black hole is in the HSS. In this state, the X-ray primarily originates from the inner accretion disk, and strong gravity will alter polarization properties. The impact of returning radiation is also being considered for 4U 1957+115 (Marra et al. 2024), whose PD increases with energy in 2–6 keV as well, but no significant polarization signal was detected in the 6–8 keV range. The PD of Swift J151857.0–572147, which is studied in this paper, is lower than the MDP_{99}, making it insufficient to confirm the correlation between PD and energy.

4. Summary

We analyzed the IXPE observation data for Swift J151857.0–572147. This newly discovered transient source was observed by IXPE on 2024 March 18. Our conclusions are summarized below:

1. The source was in the HSS and no LFQPOs were detected in the observation data from IXPE on 2024 March 18.
2. The PD and PA are respectively $0.3\% \pm 0.3\%$ and $-24° \pm 26°$ in 2–8 keV within 68% confidence level errors, but polarization results are below MDP_{99} and the upper limit PD is 0.8%. The normalized Stokes parameters U/I and Q/I are $-0.2\% \pm 0.3\%$ and $0.2\% \pm 0.3\%$ respectively within the same confidence level errors.

This work has examined the polarization properties of Swift J151857.0–572147 based on IXPE observations. The PD is not statistically significant but has a typically low upper limit, which aligns with the predicted outcomes of the thin accretion disk model in the HSS. IXPE has observed several BHXRBs with similar polarization properties in the same state before. Further research necessitates additional analyses to ascertain the nature of this source by multiple detectors. More observations could potentially provide a more nuanced understanding of its polarization properties and facilitate a more thorough examination of the thin accretion disk model.

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