



A Two-week IXPE Monitoring Campaign on Mrk 421

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Abstract

X-ray polarization is a unique new probe of the particle acceleration in astrophysical jets made possible through the Imaging X-ray Polarimetry Explorer. Here we report on the first dense X-ray polarization monitoring campaign on the blazar Mrk 421. Our observations were accompanied by an even denser radio and optical polarization campaign. We find significant short-timescale variability in both X-ray polarization degree and angle, including an $\sim 90^\circ$ angle rotation about the jet axis. We attribute this to random variations of the magnetic field, consistent with the presence of turbulence but also unlikely to be explained by turbulence alone. At the same time, the degree of lower-energy polarization is significantly lower and shows no more than mild variability. Our campaign provides further evidence for a scenario in which energy-stratified shock-acceleration of relativistic electrons, combined with a turbulent magnetic field, is responsible for optical to X-ray synchrotron emission in blazar jets.

Unified Astronomy Thesaurus concepts: [Blazars \(164\)](#); [Jets \(870\)](#); [X-ray astronomy \(1810\)](#); [Shocks \(2086\)](#); [Markarian galaxies \(1006\)](#); [Time domain astronomy \(2109\)](#); [Polarimetry \(1278\)](#); [Radio jets \(1347\)](#)

1. Introduction

Blazars are powerful active galactic nuclei (AGN) with relativistic jets emitting across the electromagnetic (and possibly high-energy particle) spectrum (e.g., R. Blandford et al. 2019; T. Hovatta & E. Lindfors 2019). Their extreme brightness and variability are attributed to relativistic effects dominating their multiwavelength emission due to orientation of the jets toward the line of sight (e.g., I. Liodakis et al. 2018). The broad spectral energy distribution (SED) of high-

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Table 1
Summary of X-Ray Observations

Observatory	Obsid	Start Date	End Date
IXPE	02008199	2023-12-06 21:28:11.792	2023-12-22 07:44:27.400
NuSTAR	60902024002	2023-12-06 23:26:00	2023-12-07 10:31:09
NuSTAR	60902024004	2023-12-11 12:36:00	2023-12-12 00:11:09
NuSTAR	60902024006	2023-12-18 06:41:09	2023-12-18 18:16:09
NuSTAR	60902024008	2023-12-20 19:31:00	2023-12-21 06:41:09
XMM	0902112401	2023-12-07 00:16:39	2023-12-07 03:53:19
XMM	0902112501	2023-12-08 12:53:01	2023-12-08 18:16:21
XMM	0920900201	2023-12-11 12:52:35	2023-12-11 18:08:23
XMM	0920901301	2023-12-14 04:14:29	2023-12-14 10:54:29

synchrotron-peaked (HSP, $\nu_{\text{syn}} > 10^{15}$ Hz) blazars is characterized by a synchrotron component extending from radio to X-rays, plus a high-energy component from X-rays to TeV γ -rays of currently debated origins.

Since its launch in December 2021, the Imaging X-ray Polarimetry Explorer (IXPE; M. C. Weisskopf et al. 2022) has been shaping our view of high-energy processes in the Universe, including jet–disk geometry as well as particle acceleration and emission in astrophysical jets from accreting black hole systems (e.g., H. Krawczynski et al. 2022; S. R. Ehlert et al. 2022; H. L. Marshall et al. 2024). The first IXPE observation of the blazar Mrk 501 measured a factor of ~ 2 higher X-ray polarization than at optical or radio wavelengths, with the electric-vector position angles (EVPAs) at all sampled wavelengths roughly aligned with the jet axis on the sky (I. Liodakis et al. 2022), as measured with Very Long Baseline Array (VLBA) imaging (e.g., Z. R. Weaver et al. 2022). Synchrotron radiation with such an EVPA arises in a plasma with a mean magnetic field direction aligned perpendicular to the jet axis, as expected for a shock-compressed or helical (or toroidal) field. The observed degree of polarization was a factor of $\gtrsim 7$ lower than the maximum value of 70%–75% and time-variable, both of which are characteristics of a turbulent magnetic field (A. P. Marscher 2014). The presence of a shock can explain how the radiating electrons are accelerated. Radiative energy losses as the electrons propagate away from the shock front lead to energy stratification that causes the emission region to be confined closer to the shock front at higher photon energies (A. P. Marscher & W. K. Gear 1985; A. P. Marscher 2014; E. Angelakis et al. 2016; F. Tavecchio et al. 2018). The emission regions at different frequencies are therefore, at most, only partially cospatial, with the larger, lower-frequency regions containing a greater number of cross-polarized turbulent cells, which causes their polarization to be lower. Subsequent IXPE observations of blazars Mrk 421 (L. Di Gesu et al. 2022), 1ES 1959+650 (M. Errando et al. 2024), 1ES 0229+200 (S. R. Ehlert et al. 2023), PG 1553+113 (R. Middei et al. 2023), and PKS 2155-304 (P. M. Kouch et al. 2024) provided further support for this emerging picture.

Arguably, the most interesting X-ray polarization behavior has been found in Mrk 421. While the first observation found a similar trend of X-ray higher polarization than that at longer wavelengths, as for Mrk 501, two subsequent observations revealed the first detection of an X-ray polarization angle rotation (L. Di Gesu et al. 2023). Rotations of the polarization angle are often detected at optical wavelengths (e.g., A. P. Marscher et al. 2008; D. Blinov et al. 2015, 2018; I. Liodakis et al. 2020), with long-term rotations associated

with gamma-ray flaring (D. Blinov et al. 2021). But so far, no clear single cause has been identified. Further change in the X-ray polarization angle was detected in the fourth IXPE observation (D. E. Kim et al. 2024a), which is possibly associated with the ejection of a new moving radio knot found in contemporaneous VLBA images, although the connection between the X-ray rotation and radio ejection requires further investigation. This would, however, be in line with the optical polarization behavior of some blazars with lower synchrotron SED peaks ($\nu_{\text{syn}} < 10^{14}$ Hz, A. P. Marscher et al. 2008, 2010; I. Liodakis et al. 2020) than those of Mrk 421 and Mrk 501, whose SEDs peak at X-ray energies, classifying them as HSP sources (e.g., M. Ajello et al. 2022).

Here we present the first dense X-ray polarization monitoring of a blazar, Mrk 421, with IXPE measurements carried out in four segments during 2023 December 6–22, the last blazar observations during IXPE’s 2 yr prime mission. In Section 2 we describe our X-ray and multiwavelength observations, in Section 3 we present our results, and in Section 4 we discuss our findings.

2. Observations and Data Reduction

2.1. X-Rays

Mrk 421 was observed by IXPE in 2023 between December 6 and 22, as well as by NuSTAR and XMM-Newton over multiple epochs during this time period. The observations used in our analysis are listed in Table 1.

2.1.1. NuSTAR

NuSTAR observed Mrk 421 four times during the IXPE campaign, on 2023 December 6 for a net focal plane module A/B exposure time (respectively) of 21.29/21.13 ks⁷³ (ObsID: 60902024002), on 2023 December 11 for a net exposure time of 21.2/21.1 ks (ObsID: 60902024004), on 2023 December 18 for a net exposure time of 17.4/17.4 ks (ObsID: 60902024006), and on 2023 December 20 for a net exposure time of 20.6/20.4 ks (ObsID: 60902024008). The NuSTAR spectra were extracted using a circular 1′ radius source region and a circular 100′′ radius background region. The spectral extraction was accomplished with HEASOFT version 6.33, NUSTARDAS version 2.1.2, and CALDB version 20240229. Each spectrum was grouped to have a minimum of 30 counts per bin. Above 50 keV the background became stronger than the source, so we limit NuSTAR photon energies to 3.0–50.0 keV in spectral fits that incorporate NuSTAR data

⁷³ The focal plane module A & B (FPMA, FPMB respectively) exposure times are written as FPMA/FPMB.

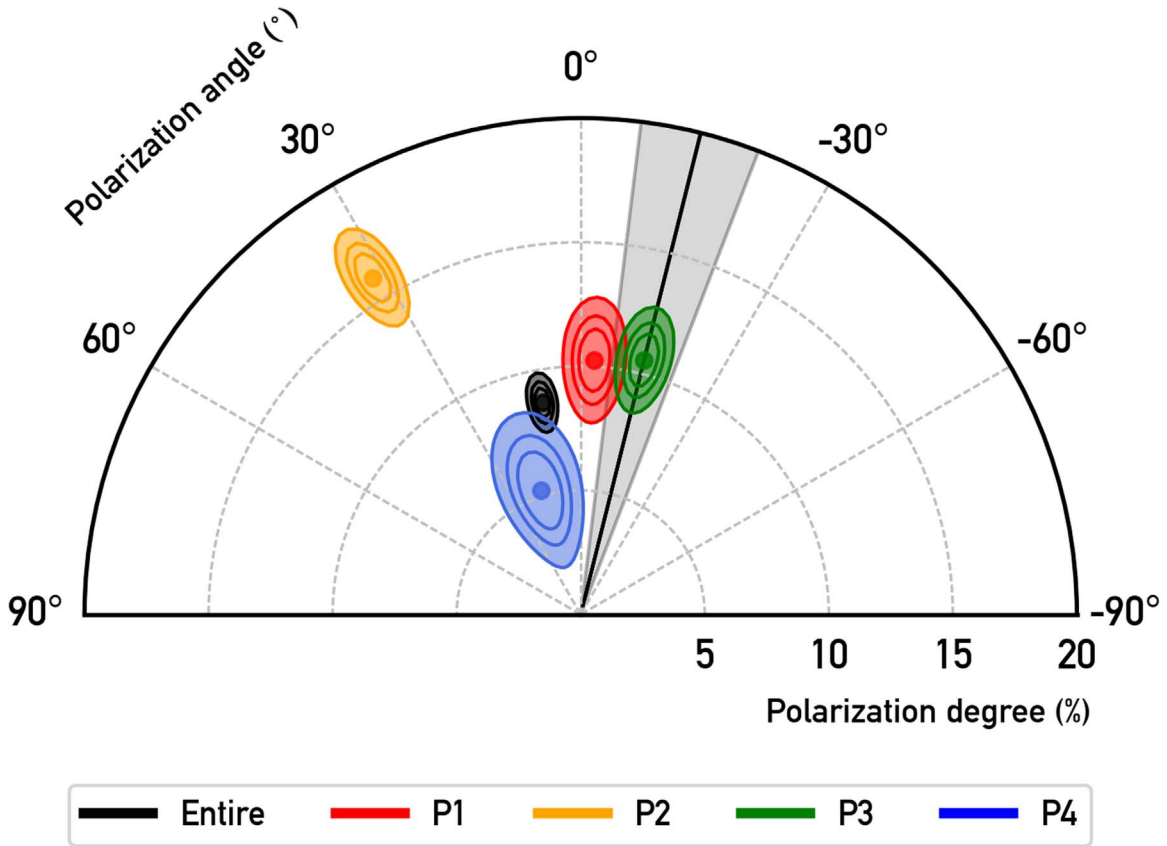


Figure 1. Time-averaged X-ray polarization contours for each of the four IXPE epochs for this campaign, labeled P1 (red), P2 (yellow), P3 (green), and P4 (blue), respectively, in order of time. “Entire” (black) represents all data for the campaign. Radial offset from the origin corresponds to polarization degree Π , and angle corresponds to polarization angle ψ . Contours are drawn at 68.27%, 90.00%, and 99.00% confidence levels, according to a χ^2 test with two degrees of freedom. The black line and gray shading in the unified plot represents the position angle of the jet on the sky in degrees, as observed by the VLBA at 43 GHz.

(see Section 2.1.3). The instrumental cross-normalization constant for FPMB was set to be 1.04 times the normalization constant for FPMA, as in K. K. Madsen et al. (2015).

2.1.2. XMM-Newton

XMM-Newton observed Mrk 421 four times during the IXPE campaign: on 2023 Dec 7 for a duration of 13.0 ks (Obsid: 0902112401), on 2023 December 8 for a duration of 19.4 ks (Obsid: 0902112501), on 2023 December 11 for an exposure time of 20.0 ks (Obsid: 0920900201), and on 2023 Dec 14 for an exposure time of 24.0 ks (Obsid: 092091301). All observations used the timing data mode and thick filter for the EPIC instrument. We reprocessed the observations using XMM SAS release 20230412_1735-21.0.0 and filtered the light curves for background flares.

MOS1 data were unavailable for analysis. We initially extracted spectra from the full timing window for both MOS2 and PN cameras using standard timing mode threads. To test for photon pile-up, we used the *epatplot* tool, and found a $\sim 20\%$ excess of double events. We fit NuSTAR spectra to an absorbed power law and used *WebPIMMS*⁷⁴ to predict PN pile-up. The predicted PN count rate was well below pile-up thresholds and predicted pile-up rates were negligible. As a precaution against pile-up, we used only single events and excised the brightest “core” rows by iteratively masking them from the spectral extraction. We increased the size of the mask

by one pixel in each direction per iteration, until the best fit to a simple absorbed power law produced negligible ($< 1\%$) change in n_H , power-law index, and normalization. Given the low expected pile-up, the actual goodness of the power-law model fit is irrelevant for determining the exclusion zone, only the variation in the model approximation in order to determine the row-specific impact of pile-up.

2.1.3. IXPE

IXPE observed Mrk 421 during four separate pointings from 2023 December 6 to 22, spanning 15.4 days (ObsID: 02008199). The pointings cover Mrk 421 for 927 ks, of which 514 ks is exposure (after accounting for factors such as Earth eclipses). The four observation periods are simultaneous with the four NuSTAR observations. Using the same methods as D. E. Kim et al. (2024a), we calculated the polarization angle and degree for each pointing. These are shown in Figure 1. The I , Q , and U spectra were extracted using *ixpeobssim* (L. Baldini et al. 2022) version 30.6.3, within a circular source region of $1'$. The background was subtracted from an annular region with inner radius $2'$ and outer radius $5'$. The CALDB IRF version 13 (date 2023 July 2) in *ixpeobssim* was used for calibration. The spectra were weighted according to instrumental response. The I spectrum was grouped with a minimum of 30 counts/bin, while the Q and U spectra were grouped within equal 0.2 keV width bins. The polarization measurements were performed using the *pcube* algorithm (L. Baldini et al. 2022) and were background subtracted with a

⁷⁴ <https://heasarc.gsfc.nasa.gov/cgi-bin/Tools/w3pimms/w3pimms.pl>

Table 2
Results of spectropolarimetric fitting for the `constant*tbabs*polconst*zlogpar` model

	Int 1	Int 2	Int 3	Int 4
PD(%)	12 ± 2	19 ± 1	12 ± 1	6 ± 2
PA(°) ^a	−2.6 ± 3.9	32 ± 2.2	−14 ± 3.2	19 ± 9.7
α	2.8 ± 0.01	2.8 ± 0.01	2.9 ± 0.01	2.9 ± 0.01
β	0.170 ± 0.05	0.37 ± 0.02	0.23 ± 0.02	0.33 ± 0.02
Flux ^b	1.85 ^{+0.01} _{−0.01}	2.27 ^{+0.03} _{−0.03}	2.90 ^{+0.01} _{−0.01}	2.64 ^{+0.03} _{−0.03}
$\chi^2/\text{d.o.f.}$	2122/1583	1416/1245	1355/1253	1438/1215

Notes. We note that the values for α and β are those from NuSTAR.

^a Measured counterclockwise from west to east, -90° to $+90^\circ$.

^b The 2–8 keV observed flux in units of 10^{-10} erg cm $^{-2}$ s $^{-1}$.

backscale ratio of 1/20. The spectra used in the spectropolarimetric fit were also background subtracted. The energy range 2.0–8.0 keV was used for the entire IXPE analysis.

Spectropolarimetric Fitting. For each IXPE observation, we jointly fit the I , Q , and U spectra together with the corresponding simultaneous NuSTAR and XMM-Newton observations.

We started with a `constant*tbabs*polconst*zlogpar` model, where `constant` is the instrumental cross-normalization constant, `tbabs` represents Galactic absorption, and `zlogpar` is a redshifted log-parabolic model similar to what has been used in the past to fit Mrk 421’s X-ray spectrum (E. Massaro et al. 2004; L. Di Gesu et al. 2022). The spectral distribution is expressed in the form

$$N(E) = K(E(1+z)/E_p)^{(\alpha-\beta \log(E(1+z)/E_p))}. \quad (1)$$

In this equation, E_p is the pivot energy, α is the spectral slope at the pivot energy, and β is an indicator of spectral curvature at the peak. K is a normalization constant with units of photons/(cm 2 s keV). We fix the pivot energy to 5 keV (e.g., M. Baloković et al. 2016; L. Di Gesu et al. 2022; R. Middei et al. 2022). We attempted to add a `zphabs` model to take into account absorption at the source, but it did not improve the fit, so it was dropped. We therefore fit all four IXPE observations with a `constant*tbabs*polconst*zlogpar` model.

The results of the fits are tabulated in Table 2. The columns sort the results by the corresponding IXPE observation, while the rows represent the time-averaged PD, the time-averaged PA, α , β , the rest frame 2–10 keV flux, and the reduced χ^2 for each observation. The reduced χ^2 values of the fits range between 1.08 and 1.34, suggesting that while our model may be a reasonable first approximation, there is a need for additional model complexity. The XMM spectra in particular have notably strong residuals at some energies. The PD varies from $6 \pm 2\%$ to $20 \pm 1\%$ between observations, while the PA ranges from $-14 \pm 3^\circ$ to $+32 \pm 2^\circ$. Comparable results have been found in A. M. Bharathan et al. (2024), averaging over the first 70 ks of the IXPE exposure. These spectra and fits are plotted in Appendix A.

Time Variability. We investigated polarization variability over time by applying the χ^2 test of the constant model on different timescales of binning over the entire observation period, following D. E. Kim et al. (2024a). This test examines the statistical significance of the variability by estimating the null hypothesis probability (P_{Null}) of each constant model fitting on the normalized q and u Stokes parameters, while taking into account the uncertainty of each measurement. We divided the entire observation period into 10–35 subperiods,

corresponding to ~ 130 ks to ~ 40 ks, respectively. As a result, we obtained less than 1% for the null hypothesis probability of the constant model for all cases of time binning of q and u Stokes parameters. The highest null hypothesis probability for q was 2.2×10^{-8} , which corresponds to an out-of-range value of $\sim 5.5\sigma$ ($\sim 5.0\sigma$ for ≥ 1 bin of 31), and we measured zero probability for the u Stokes parameter. Hence, we found evidence of statistically significant polarization variability over time from this observing period. Figure 2 shows the polarization measurements split in 31 bins (of size ~ 43 ks per bin), which provided the largest number of statistically significant polarization variations.

In order to compare polarimetric variability with changes in the X-ray flux and spectral shape, we calculate the hard (H; 4–8 keV) and soft (S; 2–4 keV) fluxes, as well as a hardness ratio HR as a proxy for spectral shape, using the same ~ 43 ks binning scheme as with time-resolved polarimetry. We define the hardness ratio $\text{HR} = (H - S)/(H + S)$, where H is the 4–8 keV flux and S is the 2–4 keV flux. The variation in these quantities is shown in Figure 3. We note a flare in both H and S by a factor of ~ 2 at MJD ~ 60299 , after which the flux gradually decays over the next $\gtrsim 10$ days, with significant variability on ~ 43 ks scales but remains elevated. The trend on timescales of days (most notably including the large flare) is broadly consistent with harder-when-brighter (as with L. Di Gesu et al. 2023). But there are obvious deviations from this trend on timescales of ~ 8 hr. Another notable deviation is that the softest points (at MJD ~ 60297) occur during this elevated, decaying state, after which the hardness (but not flux) becomes comparable to preflare conditions.

2.2. Optical Observations

Mrk 421 was observed by several telescopes in BVRI bands during all four segments of the IXPE observations. These facilities included the Kanata telescope using the Hiroshima Optical and Near-InfraRed camera (HONIR; K. S. Kawabata et al. 1999; H. Akitaya et al. 2014), the Liverpool Telescope using the Multicolour OPTimised Optical Polarimeter (MOP-TOP; H. Jermak et al. 2016; M. Shrestha et al. 2020), the LX-200 telescope of St. Petersburg State University (V. M. Larionov et al. 2008), the Nordic Optical Telescope (ALFOSC, analysis described in T. Hovatta et al. 2016 and K. Nilsson et al. 2018), Boston University’s 1.8 m Perkins Telescope (with the PRISM camera, S. G. Jorstad et al. 2010), the Sierra Nevada Observatory (DIPOL-1; J. Escudero & D. Morcuende 2023; J. Otero-Santos et al. 2024; J. Escudero Pedrosa et al. 2024), the Skinakas Observatory (RoboPol, A. N. Ramaprakash et al. 2019), and the T-60 telescope at the

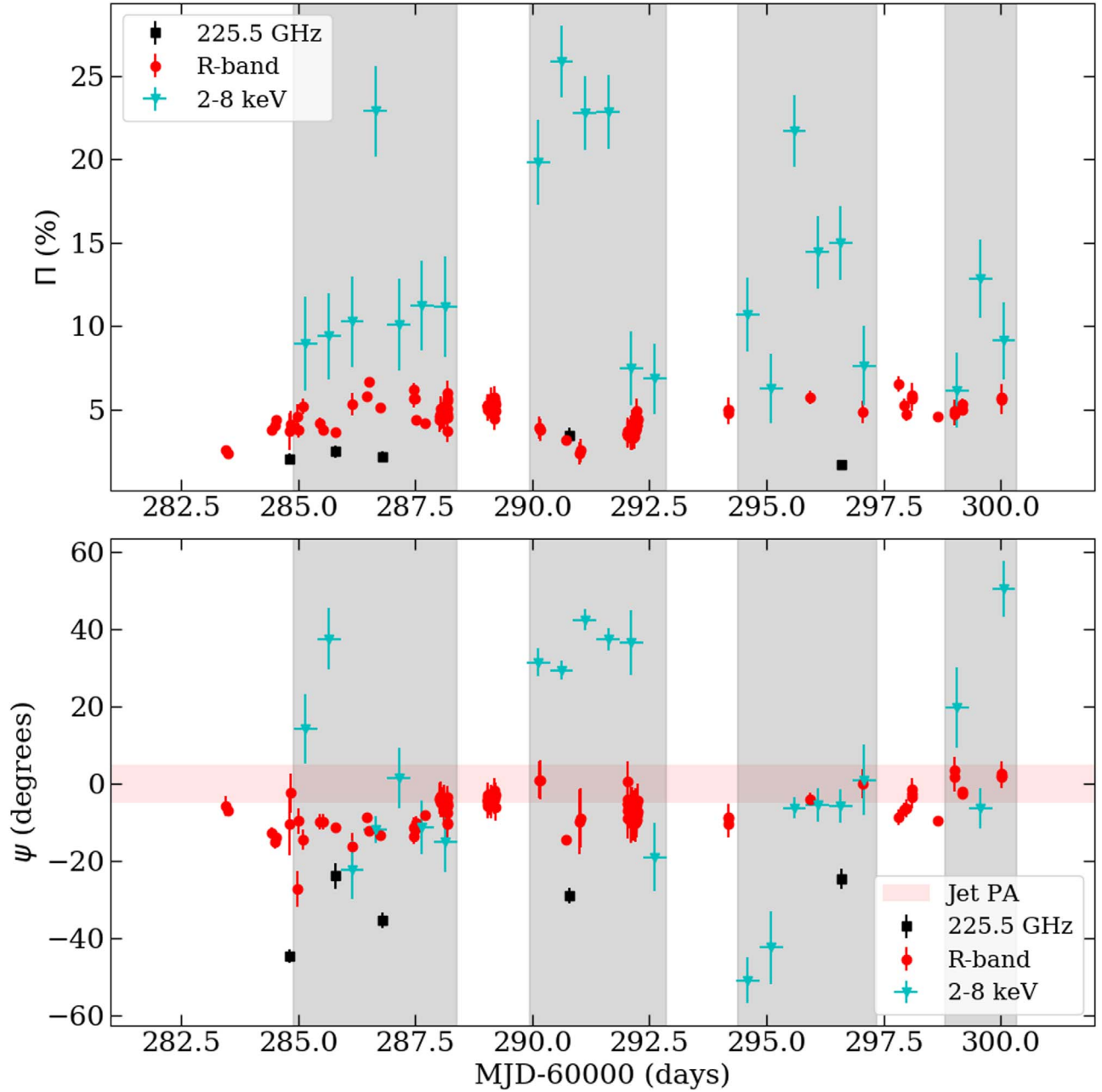


Figure 2. Time-resolved multiwavelength polarization observations. The top panel shows the polarization degree and the bottom panel shows the polarization angle, relative to the jet. The gray shaded areas in both panels mark the duration of the IXPE exposures, and the red shaded area in the bottom panel indicates the direction of the jet on the plane of the sky. We only show bins where the X-ray polarization degree is detected at the $>3\sigma$ level.

Haleakala observatory (V. Piirola 1973; A. V. Berdyugin et al. 2018; A. Berdyugin et al. 2019; V. Piirola et al. 2021). We corrected for dilution of the polarization by unpolarized host-galaxy light in the R-band by estimating the flux density of the host within a given aperture and subtracting from the total flux density following K. Nilsson et al. (2007) and T. Hovatta et al. (2016). Details of the data reduction and analysis of the different participating telescopes can be found in I. Liodakis et al. (2022), A. L. Peirson et al. (2023), and P. M. Kouch et al. (2024). The optical flux and polarization measurements are shown along with the IXPE results in Appendix B. The points labeled as R-band with a “†” correspond to R-band observations that we were unable to correct for the host-galaxy contribution, but are provided here for relative comparison.

2.3. Radio Observations

Radio observations covered frequencies from 4.8 to 225.5 GHz using the Effelsberg 100 m radio telescope (A. Kraus et al. 2003), the Korean VLBI Network (KVN), and the Submillimeter Array (SMA) polarimeter (D. P. Marrone & R. Rao 2008). The Effelsberg 4.8 and 14.2 GHz observations are part of the program Monitoring the Stokes Q , U , I , and V Emission of AGN jets in Radio (QUIVER, I. Myserlis et al. 2018). The KVN provided 25 GHz observations using the Yonsei and Tamna antennas in single-dish mode (S. Kang et al. 2015), and the SMA observations were performed as part of the SMA Monitoring of AGNs with POLarization (SMAPOL, I. Myserlis et al. 2024, in preparation) program at 225.5 GHz. Data from all radio observations are shown in Appendix B.

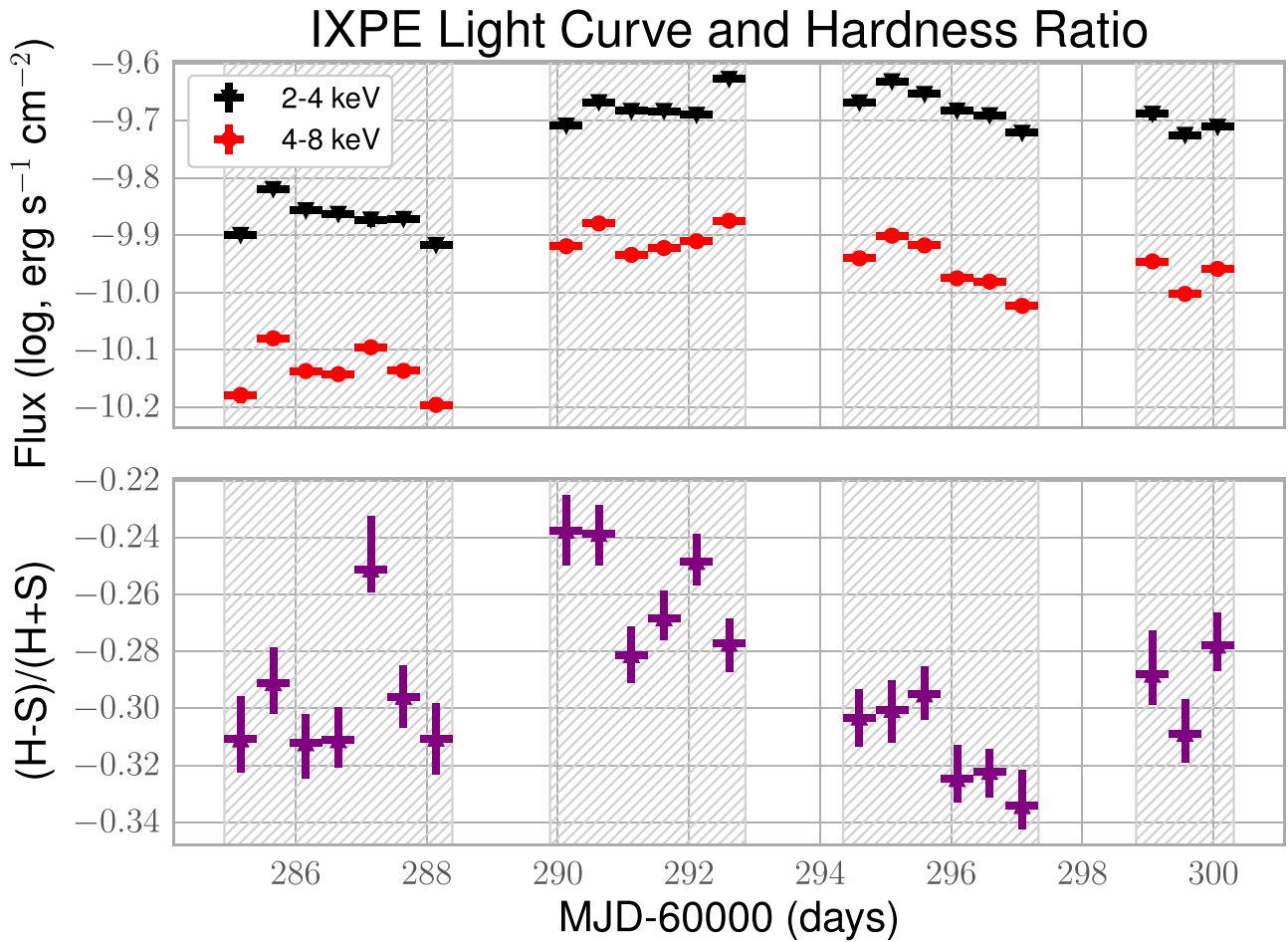


Figure 3. Top: light curves of the log₁₀ IXPE flux for soft (2–4 keV, black triangles) and hard (4–8 keV, red dots) bands. Bottom: hardness ratios calculated from the soft and hard flux.

In the beginning of the second IXPE pointing, 2023 December 12 (RJD = 289, where RJD = JD – 2460000.0), we obtained total and polarized intensity images of Mrk 421 with the Very Long Baseline Array (VLBA) at 43 GHz under the Boston University BEAM-ME project.⁷⁵ The data reduction was performed using the Astronomical Image Process System (AIPS) and Difmap software packages, as described in S. G. Jorstad et al. (2017). Figure 4 displays the total intensity image with the polarized intensity superposed, along with line segments indicating the EVPA. We have modeled the total intensity image by components with circular Gaussian brightness distributions. We measured the Stokes Q and U flux densities of these components (knots) and derived their PD and EVPA at 43 GHz. Table 3 lists the total intensity and polarization parameters of the three brightest components (A0, J1, and J2). This model fits the uv data very well, with a reduced χ^2 of 0.86. The location and size of each component is marked in Figure 4 by green circles. Knot A0, located at the southern end of the jet, represents the VLBI core of the jet, while the jet component nearest to the core, J2, defines the innermost jet direction as $\text{PA}_{\text{jet}} = 1^\circ \pm 5^\circ$. This is, within the uncertainties, parallel to the parsec-scale jet direction of Mrk 421, $\text{PA}_{\text{jet}} = -14^\circ \pm 14^\circ$, estimated based on 92 epochs of observations from 2007 to 2018 (Z. R. Weaver et al. 2022).

3. Results

To probe short-term variability, we divide the IXPE observations into 31 bins as discussed above. Figure 2 shows the significantly detected X-ray polarization bins. Only one bin does not have a significant detection. We find rapid variability in both the polarization degree and angle. Between the second and third observations we also detect a significant rotation of the polarization angle by $\sim 90^\circ$. This is significantly less than the previously detected rotation in Mrk 421 of about 400° (L. Di Gesu et al. 2023). The direction of the polarization vector seems to vary about the jet axis, which is typically of HSP blazars (A. P. Marscher & S. G. Jorstad 2021, C.-T. J. Chen et al. 2024, L. Lisalda et al. 2025, submitted). We discuss the origin of the rotation below.

On the other hand, at radio wavelengths the degree of polarization of Mrk 421 is low (1%–3%), with a median of $\sim 2\%$. In the past, the millimeter-radio polarization angle has been fairly stable along $-29^\circ \pm 8^\circ$, consistent with the jet axis on the sky over long timescales, $-14^\circ \pm 14^\circ$ (see above). However, the direction of both the jet and the EVPA at 43 GHz in the innermost regions was $1^\circ \pm 5^\circ$ on 2023 December 12 (MJD = 60290) during the IXPE campaign (see Figure 4), identical with the optical EVPA. The EVPA of SMAPOL and QUIVER data exhibits a relatively stable frequency dependence across centimeter and millimeter wavelengths, suggestive of a Faraday screen with rotation measure $\text{RM} \sim -250 \text{ rad/m}^2$ (R. N. Manchester 1972).

⁷⁵ www.bu.edu/blazars/BEAM-ME.html

Table 3
Parameters of Jet Components at 43 GHz

Knot (1)	S, mJy (2)	R, mas (3)	$\text{PA}_{\text{jet}}, \text{deg}$ (4)	Size, mas (5)	$\text{PD}_{43 \text{ GHz}}, \%$ (6)	$\text{EVPA}_{43 \text{ GHz}}, \text{deg}$ (7)
A0	335 ± 15	0.0	...	0.05 ± 0.02	3.0 ± 0.4	2 ± 4
J2	37 ± 8	0.21 ± 0.05	1 ± 5	0.17 ± 0.03	7.0 ± 1.5	-25 ± 6
J1	25 ± 10	0.52 ± 0.09	-38 ± 7	0.47 ± 0.10	18.0 ± 7.5	-12 ± 10

Notes. Column identification: (1) name of component; (2) flux density, S , millijanskys; (3) distance from the core, R , milliarcseconds (mas); (4) position angle of the knot with respect to the core, PA_{jet} , degrees; (5) FWHM size of the component, mas; (6) degree of polarization, percentage; (7) position angle of polarization, degrees. All uncertainties are 1σ .

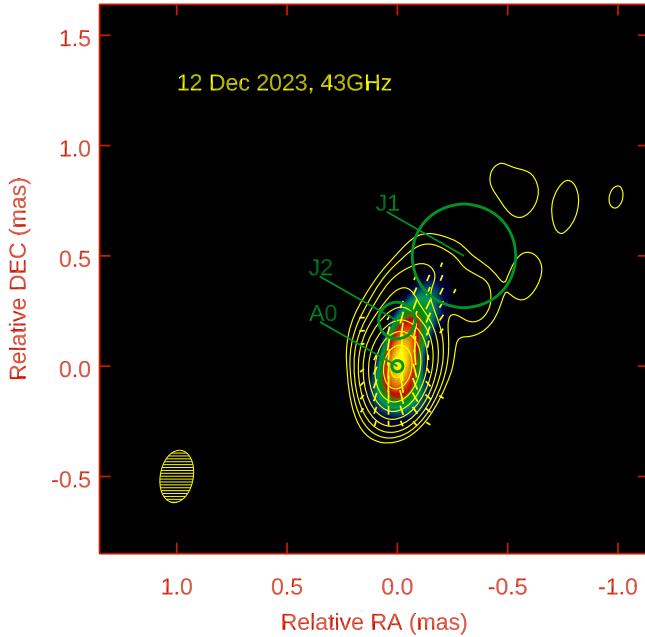


Figure 4. Total (contours) and polarized (color scale) intensity images of Mrk 421 at 43 GHz, convolved with an elliptical Gaussian beam of dimensions $0.24 \times 0.15 \text{ mas}^2$ with major axis along $\text{PA} = -10^\circ$. The global total intensity peak is $321 \text{ mJy beam}^{-1}$ and the global polarized intensity peak is $9.6 \text{ mJy beam}^{-1}$. Yellow line segments within the image indicate the direction of polarization, while the length of each segment is proportional to the polarized intensity. Green circles designate the core, A0, and jet components, J1 and J2, according to model fitting to the uv data.

We find a similar behavior at optical wavelengths: there are no large variations in either flux, polarization degree, or polarization angle. The polarization degree smoothly changes from 2% to 6% with a median of about 4.5%. The polarization angle is roughly stable and along -7° , a bit offset from the jet axis. Compared to previous observations contemporaneous with IXPE, the source maintains consistent behavior at radio and optical wavelengths (D. E. Kim et al. 2024a).

The 31-bin light curve of the IXPE soft and hard flux is matched to the polarimetric binning and within any given epoch is consistent with increased spectral hardness at high flux, with the exception of epoch 2 ($290 < \text{MJD} - 60000 < 293$), where there is no obvious correlation over a timescale of $\sim$ days. After the first epoch ($284 < \text{MJD} - 60000 < 289$), the flux increases by a factor of ~ 2 and remains comparably high for the remainder of the campaign. This flare corresponds to an increase in hardness, $\sim 6\sigma$ above the mean value for the IXPE campaign ($\text{HR} \sim 0.295$), as well as an increase in polarization degree from $\sim 10\%$ to $\sim 25\%$, which is sustained over ~ 2 days. The most extreme deviations

of polarization angle from the jet value seem to be associated with either very hard ($\text{MJD} - 60000 \sim 290$) or very soft ($\text{MJD} - 60000 \sim 296$) spectra. Epochs 2 ($290 < \text{MJD} - 60000 < 293$) and 3 ($294 < \text{MJD} - 60000 < 298$) show a trend of decreasing HR, to below preflare levels, and the $\sim 90^\circ$ rotation in X-ray polarization angle occurs during this trend, such that the softest HR values are associated with a return to the jet angle, a moderate degree of polarization ($\sim 7\%$ – 15%), and rapid variability ($\lesssim$ day) of the polarization degree.

4. Discussion and Conclusions

We have presented the first dense monitoring of the X-ray polarization of a blazar with IXPE. We find large variations in the polarization degree and a rotation in the polarization angle. The origin of these rotations requires us to consider models varying from shocks moving along a helical magnetic field down the jet (A. P. Marscher et al. 2008), bent jets (A. A. Abdo et al. 2010), turbulence (A. P. Marscher 2014), shock–shock interactions (I. Liodakis et al. 2020), kink instabilities (H. Zhang et al. 2017), and magnetic reconnection (D. N. Hosking & L. Sironi 2020; H. Zhang et al. 2020), among others. S. Kiehlmann et al. (2017) concluded that relatively small ($\sim 90^\circ$) rotations are likely to result from random walks of the magnetic field due to turbulence or emission originating in multiple zones. They also found that larger ($> 180^\circ$) rotations are often associated with γ -ray activity (A. P. Marscher et al. 2010; D. Blinov et al. 2015, 2018), particularly for long-term optical rotation (D. Blinov et al. 2021).

We test the random-walk scenario following S. Kiehlmann et al. (2017) and S. Kiehlmann et al. (2021), in a similar manner as in our previous analysis of the X-ray EVPA rotation detected in Mrk 421 (L. Di Gesu et al. 2023). We generate a large number of simulated polarization light curves by exploring the parameter space of number of cells and number of cells that change per day ($N_{\text{cell}}, N_{\text{var}}$, respectively). We then identify the simulations that produce similar polarization properties as those observed.

We apply the test to both the entire IXPE data set as well as to only the period of rotation between the second and third observational segments. For the former case, we use the median and interquartile range of the polarization degree and the interquartile range of the polarization angle. We require that the simulations produce values within 10% of those observed for the individual quantities. We are able to achieve a $> 50\%$ success rate between simulations and observations, with the median polarization degree succeeding at a higher rate than the interquartile range of the polarization angle. However, when we require all conditions to be satisfied at the same time, the maximum success rate is only 1%. This is because the observed

quantities are better reproduced from different regions of the N_{cell} , $N_{\text{V ar}}$ parameter space, with little overlap. This is consistent with the findings of the larger statistical study of the optical RoboPol sample (S. Kiehlmann et al. 2017). For segments 2–3, we again require that the median and interquantile range of the polarization degree for the simulations be within 10% of that observed and that the simulations produce a rotation of the polarization angle that has an equal or larger amplitude. Figures showing the success rate of the simulations for the N_{cell} , $N_{\text{V ar}}$ parameter space are presented in Appendix C. For the polarization degree, we find similar results as in the entire data set. For the polarization angle, we find that more than 80% of the simulations are able to produce a rotation that has an amplitude that is equal to, or larger than, the observed value. However, similar to the entire data set, when we demand that all conditions are met, we can only achieve a success rate of $\sim 2\%$. Based on both tests, we conclude that a simple, pure random-walk model has only a low probability to reproduce the observed behavior.

Although at least some level of turbulence appears to be present, evident by the lower than theoretically expected polarization degree (see below), turbulence is unlikely to be the primary cause of the EVPA rotation. The observed behavior is likely more akin to a scenario where turbulent plasma passes through a more ordered magnetic field region, such as a shock (A. P. Marscher 2014).

During the period of the highly variable X-ray polarization ($\Delta\Pi > 10\%$), the radio and optical polarization is at most mildly variable ($\Delta\Pi < 4.5\%$ for R -band, $< 2.5\%$ for all radio bands observed). The X-ray polarization degree reaches a maximum of 25%, $8\times$ higher than the simultaneous optical polarization. Throughout our campaign, the X-rays remain consistently more polarized than the radio and optical emission, although there are time bins within which the ratio of X-ray to optical polarization is close to unity (such as MJD $-60000 \sim [292.5, 295.0, 297.0, 299.0]$, all of which occupy local X-ray flux maxima within the elevated flux after MJD $-60000 \sim 290$, except MJD $-60000 \sim 297.0$ which is at a local flux minimum). This, along with the time variability of the polarization, suggests that even in the X-ray emission region there is a significant turbulent component. The large deviation from the jet axis could occur if a new jet component is ejected from the core. In such a case, shock–shock interactions could induce turbulence that depolarizes the emission. Alternately, if the new component is differently polarized from the core, the overall polarization can cause a change in EVPA from the jet axis and a net drop in polarization (see, e.g., P. M. Kouch et al. 2025, for similar behavior). A new shock is not strictly necessary, though; a blob of electrons crossing the standing shock might also cause such behavior.

In general, a role for turbulence is suggested by the fact that we see only 25% polarization, compared to $\sim 70\%$ – 75% expected for synchrotron radiation in a perfectly ordered magnetic field. Some steady jet models would permit such a low polarization (e.g., F. Bolis et al. 2024), but would not explain the erratic variability.

Also in general, the most extreme variability of the X-ray polarization degree during this campaign is observed to occur on shorter timescales (~ 12 – 48 hr over the entire campaign) than for the most extreme flux variability. The flare beginning MJD $-60000 \sim 290$ is associated with some of the strongest sustained X-ray polarization observed in Mrk 421 (typically

$\lesssim 15\%$; L. Di Gesu et al. 2022, L. Di Gesu et al. 2023, D. E. Kim et al. 2024a), and afterwards the X-ray flux evolves little within a $\pm 12\%$ range over > 10 days. Given that this large PD coincides with the beginning of the X-ray rotation, it is likely that the high degree of polarization is due to shock compression as the moving feature/blob crosses the standing core. That momentarily increases the polarization degree followed by a rapid drop and EVPA rotation as has been observed in low-peaked blazars in the optical. Such a scenario is expected to be analogous to high-peaked sources in X-ray polarization (I. Liodakis et al. 2020).

In comparison to flux variability, polarization variability timescales are shorter by a factor of > 5 and possibly much more. This is due in part to the vector nature of polarization: for example, N_{cell} regions of equal flux but randomly directed polarizations could maintain a steady total flux, while the polarization degree varies about a mean value of $\langle \Pi \rangle \sim 75 N_{\text{cell}}^{-1/2} \%$ with a standard deviation of $0.5 \langle \Pi \rangle$ (A. P. Marscher & S. G. Jorstad 2021). The polarized emission could also occupy a region that subtends only a fraction of the X-ray emitting region. The 90° rotation occurs over an intermediate timescale (~ 5 days). Harder-when-brighter behavior has previously been observed during 2022 June IXPE observations of polarization angle rotation in Mrk 421. This is consistent with shock acceleration, which may explain increased polarization in such a case (L. Di Gesu et al. 2023).

The maximum departure of the EVPA from the jet axis is observed between ~ 2 and ~ 5 days after the flare beginning no later than $\sim \text{MJD} \sim 60290.0$, during a period of relatively slow flux decay that also coincides with a trend of spectral softening. The hardening of the spectrum during the flare maximum and softening thereafter are consistent with shock acceleration. This fits well the interpretation that shock compression leads to high PD, particle acceleration and hardening of the spectrum, followed by the rapid change of the EVPA, depolarization, and the eventual electron cooling that will soften the spectrum.

The significantly higher polarization and variability strongly points to the X-ray emission originating in a smaller region closer to the acceleration site, where the magnetic field is less disordered, than is the case for lower frequencies. Variations of the polarization angle about the jet axis give further evidence for particle acceleration in shocks (I. Liodakis et al. 2022). The evidence therefore supports the persistent emerging picture of energy-stratified shock acceleration in the jets of HSP blazars (e.g., D. E. Kim et al. 2024b).

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Software: XSPEC (K. A. Arnaud 1996).

Appendix A Spectropolarimetric Fit

Here we present figures showing the X-ray spectra from IXPE, XMM-Newton, and NuSTAR, as well as best-fit log-parabolic models. The first and second IXPE observations are shown in Figure 5, and third and fourth IXPE observations in Figure 6.

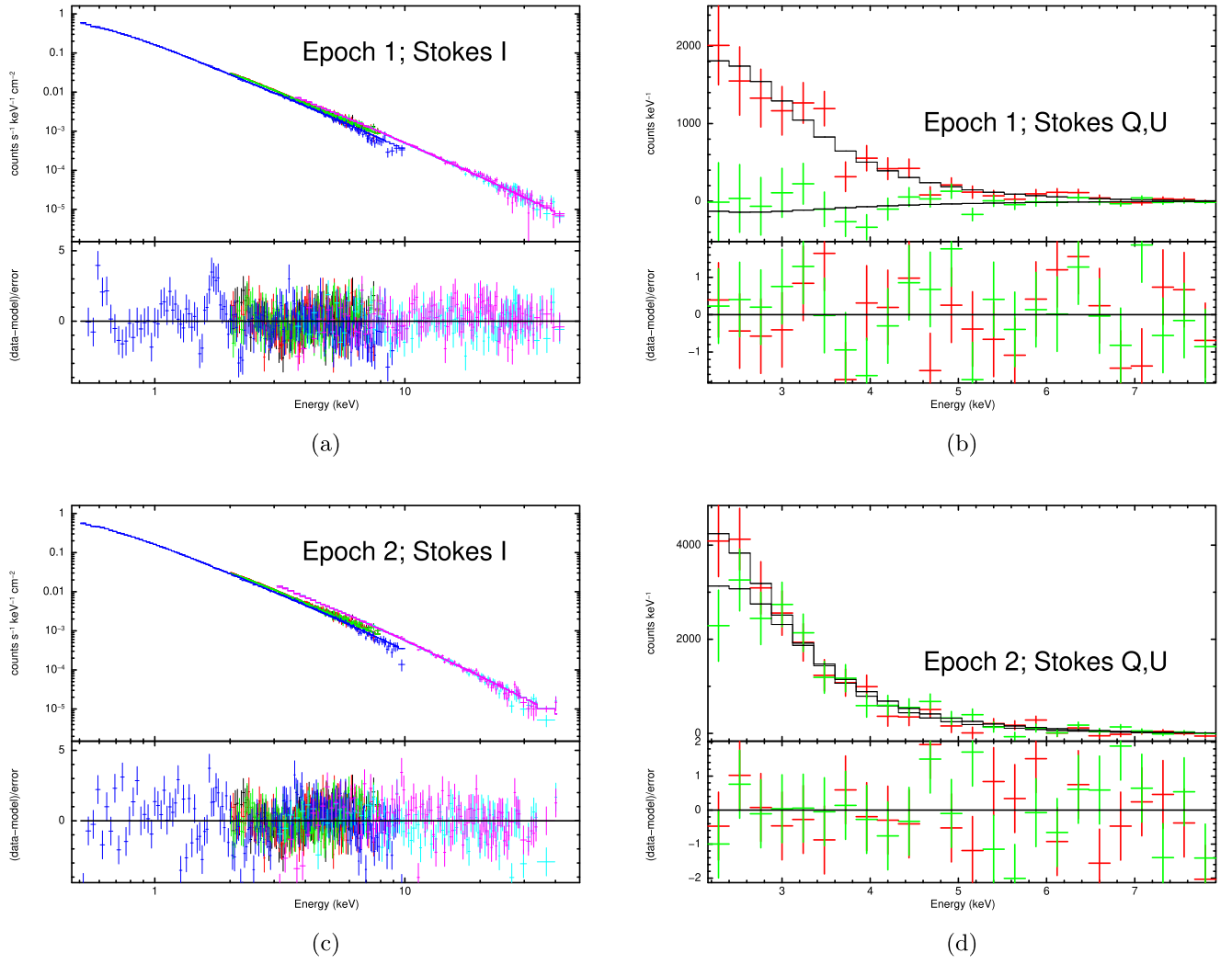


Figure 5. Unfolded I spectra (left) and Q and U spectra (right) for the first (a and b) and second (c and d) IXPE observations. In the unfolded spectra, dark blue is XMM, green, red, and black are IXPE, and pink and light blue are NuSTAR. In the Q and U spectra, red is Q and green is U . Data points are shown as error bars, the model is shown as a solid black step curve.

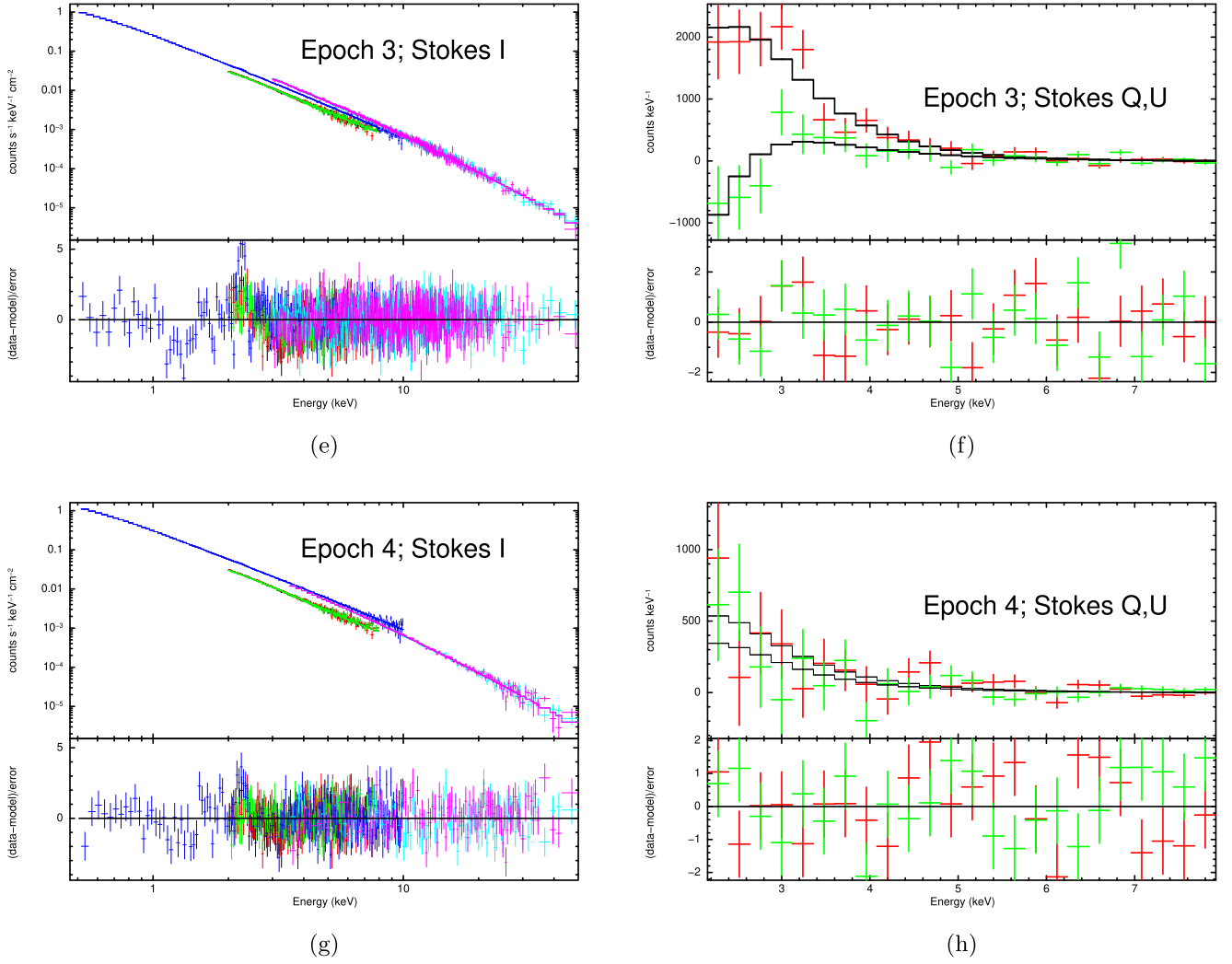


Figure 6. Unfolded I spectra (left) and Q and U spectra (right) for the third (e and f) and fourth (g and h) IXPE observations. In the unfolded spectra, dark blue is XMM, green, red, and black are IXPE, and pink and light blue are NuSTAR. In the Q and U spectra, red is Q and green is U . Data points are shown as error bars, the model is shown as a solid line.

Appendix B Multiwavelength Polarization Observations

Here we present Figures 7 and 8, which show the flux density or magnitude of radio and optical observations (respectively) in comparison with the per-epoch time-averaged polarization degree and angle IXPE data for this campaign.

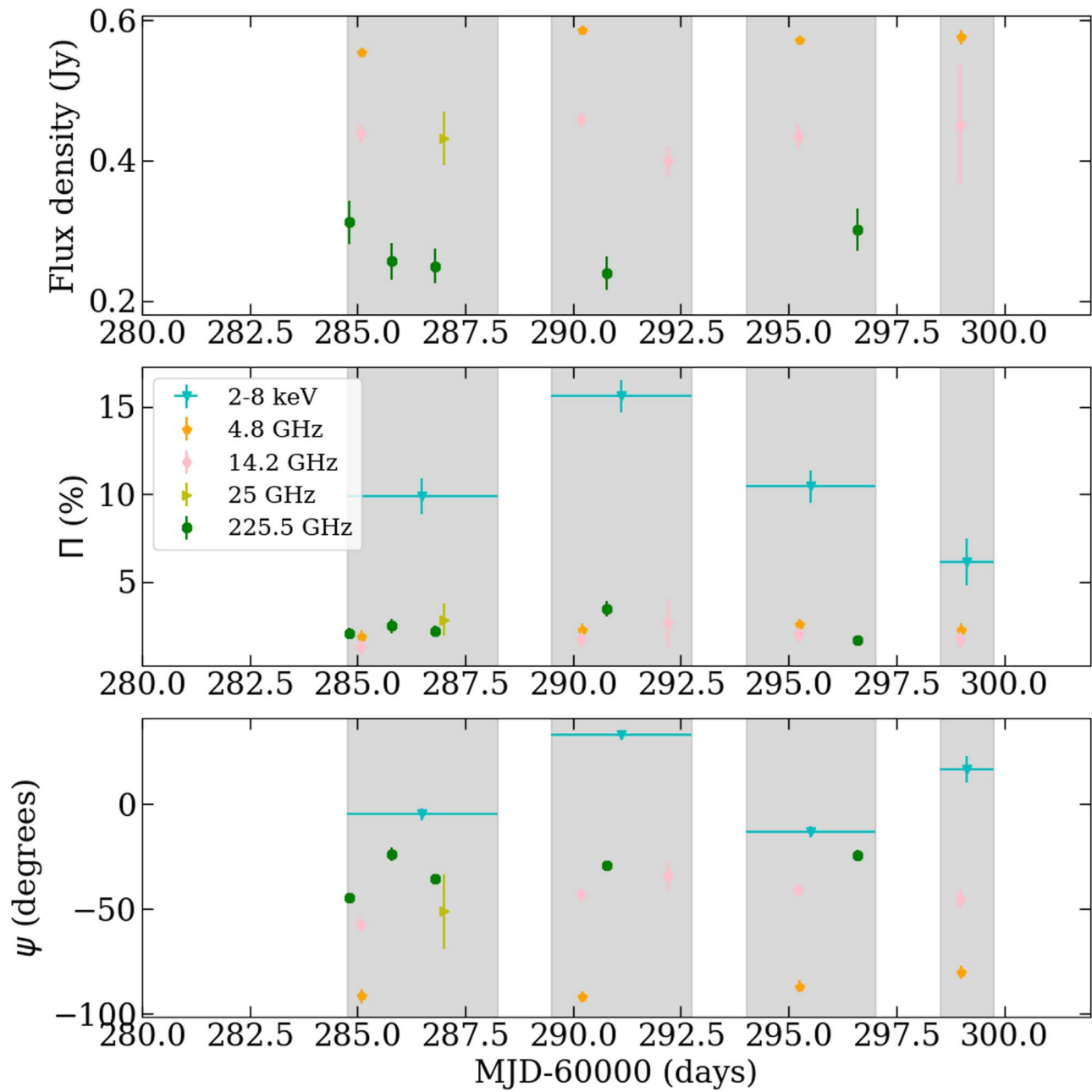


Figure 7. Integrated IXPE and simultaneous radio polarization observations of Mrk 421. The panels show flux density in Janskys (top), polarization degree in % (middle), and polarization angle in degrees (bottom). The gray shaded areas mark the duration of the IXPE observations. The symbols and colors for the different bands are marked in the legend and are the same for all panels.

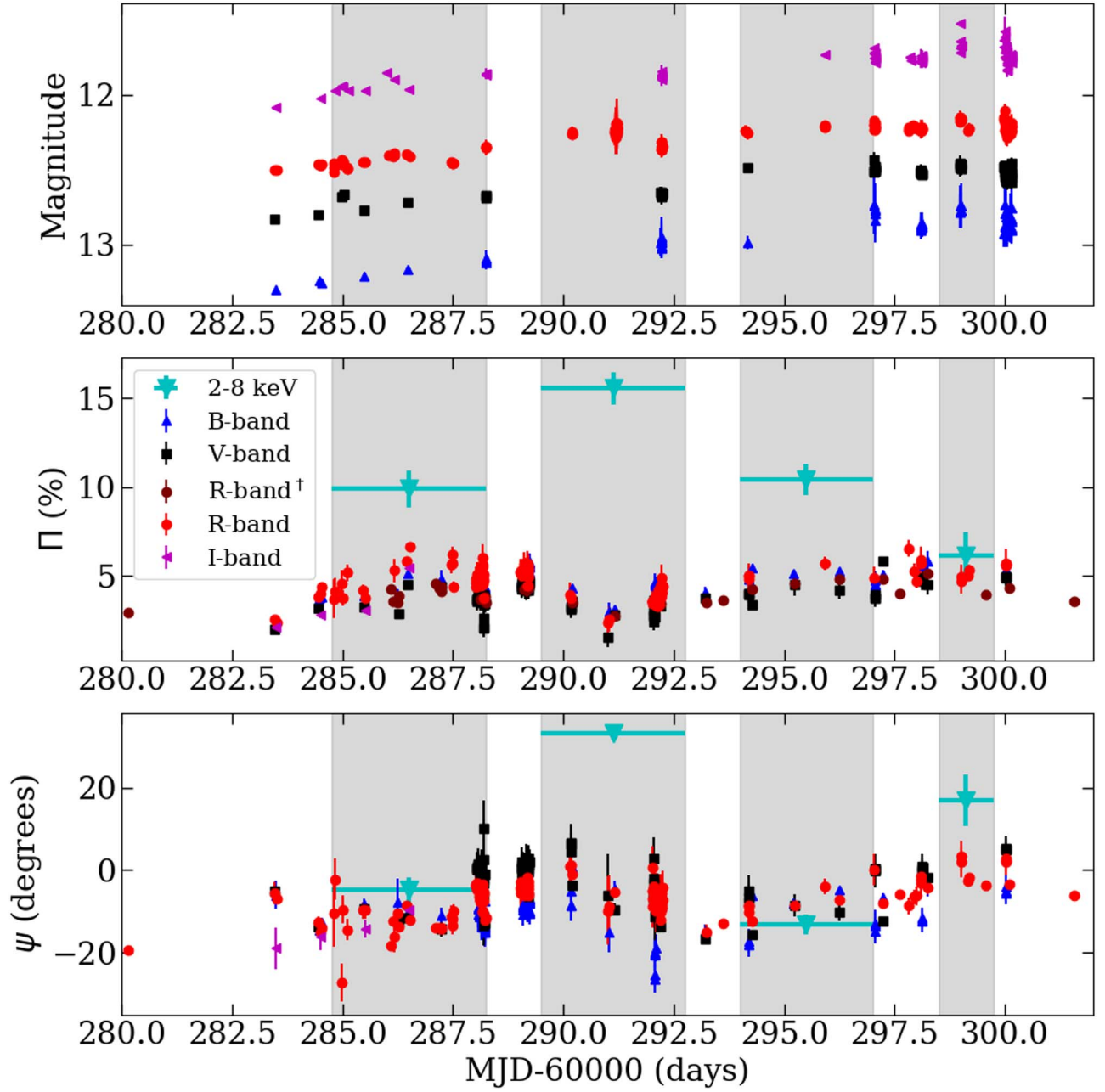


Figure 8. Integrated IXPE and simultaneous optical polarization observations of Mrk 421. The panels show brightness in magnitudes (top), polarization degree in % (middle), and polarization angle in degrees (bottom). The gray shaded areas mark the duration of the IXPE observations. The symbols and colors for the different bands are marked in the legend and are the same for all panels. [†] refers to *R*-band polarization degree that is uncorrected for host-galaxy dilution.

Appendix C Random-walk Simulations

Here we present Figures 9, 10, 11, and 12, which show the success rate of the simulations for the N_{cell} , N_{var} parameter space.

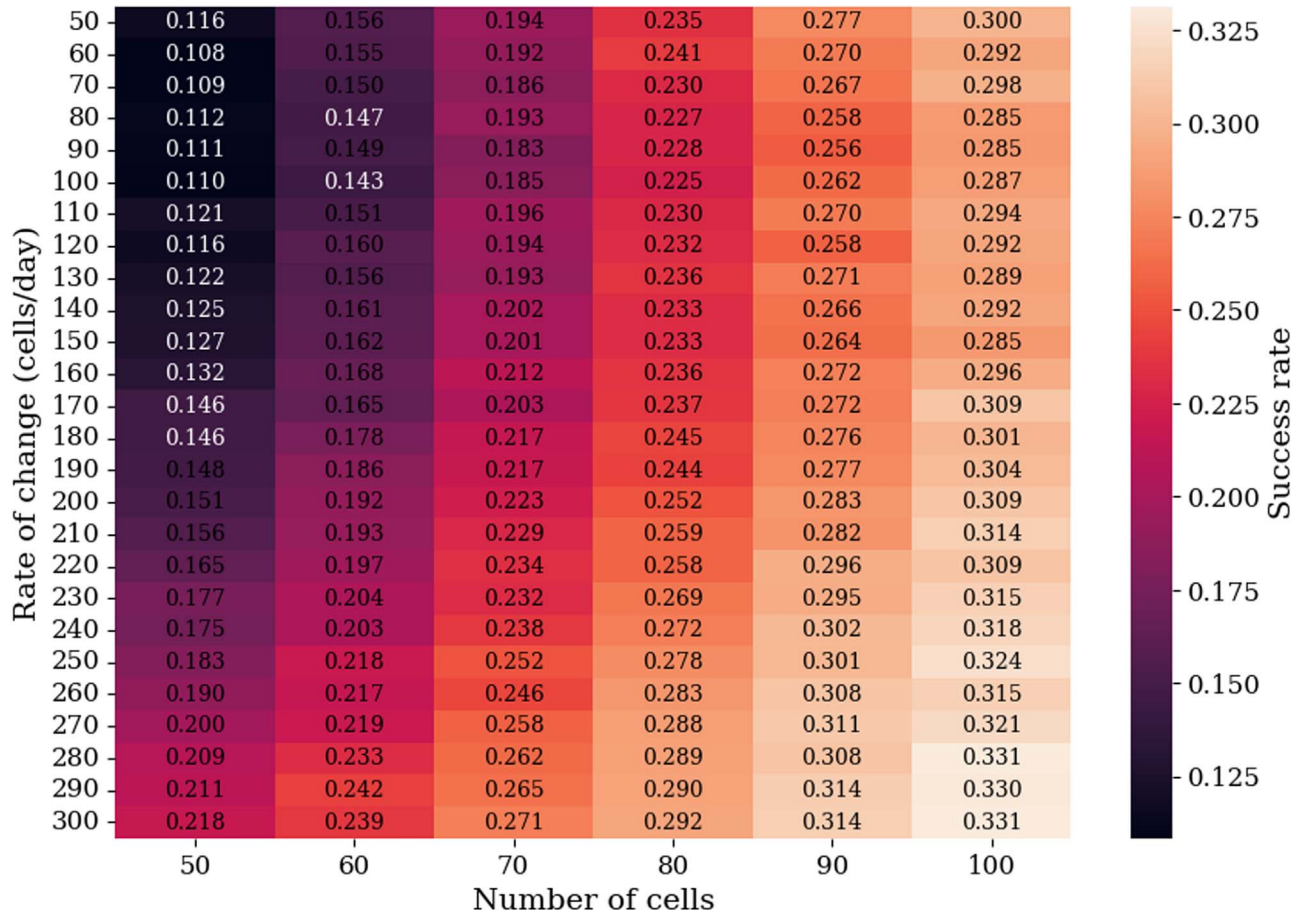


Figure 9. Parameter space of the random-walk simulations. The color bar shows the fraction of successful simulations that reproduce the median polarization degree within 10% of the observed value.

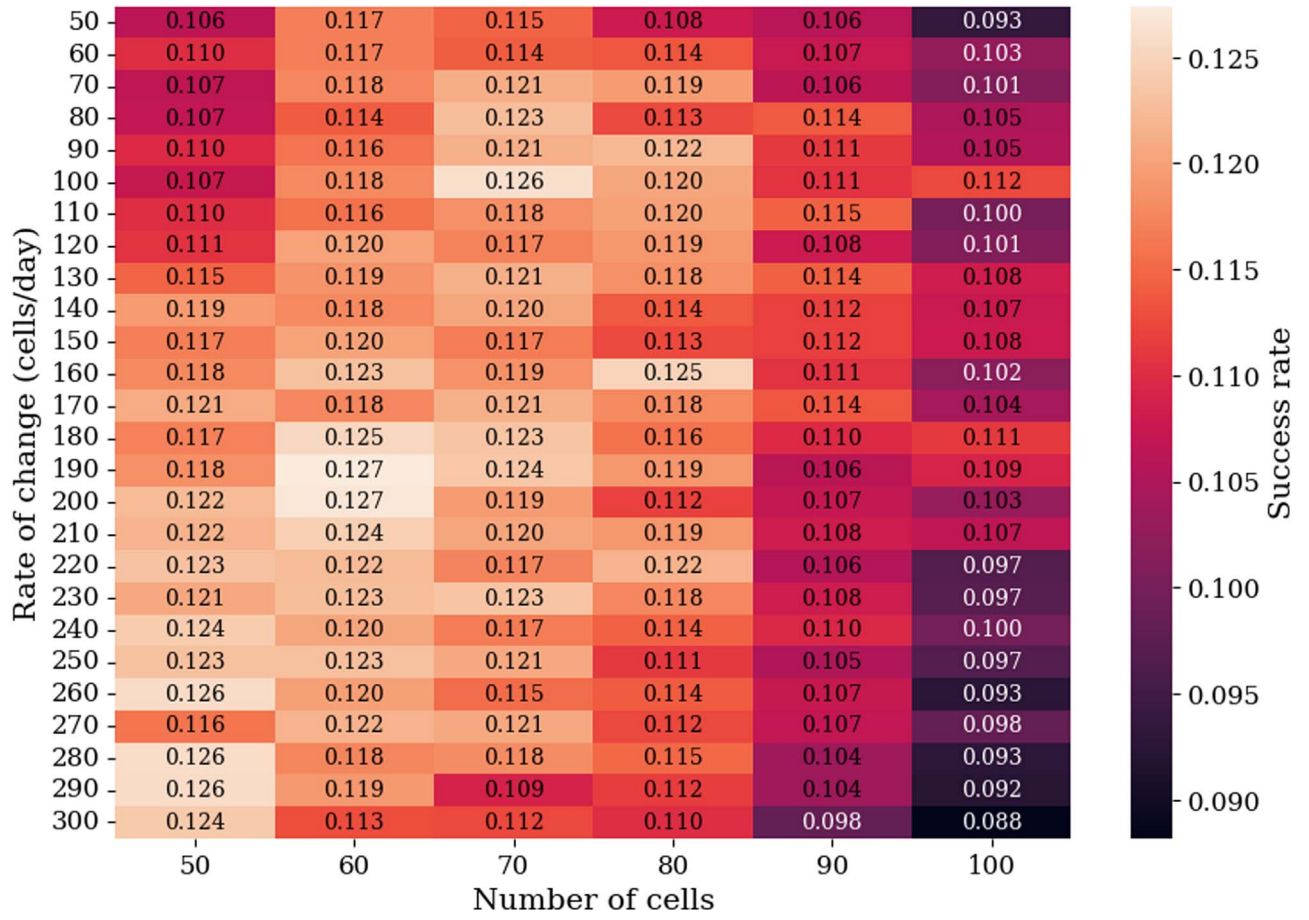


Figure 10. Parameter space of the random-walk simulations. The color bar shows the fraction of successful simulations that reproduce the interquartile range of the polarization degree within 10% of the observed value.

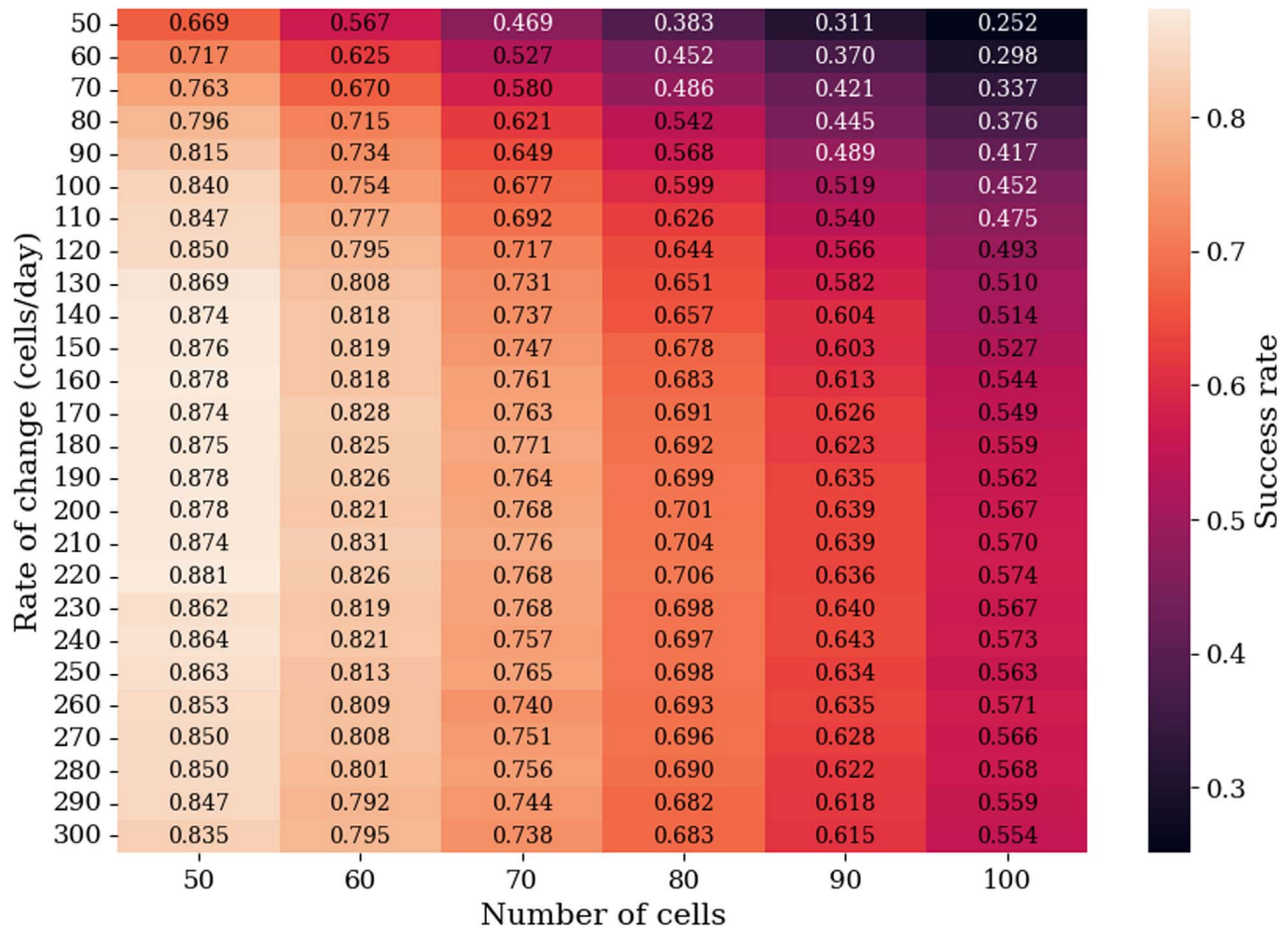


Figure 11. Parameter space of the random-walk simulations. The color bar shows the fraction of successful simulations that reproduce an equal or larger amplitude rotation of the polarization angle compared with the observed value.

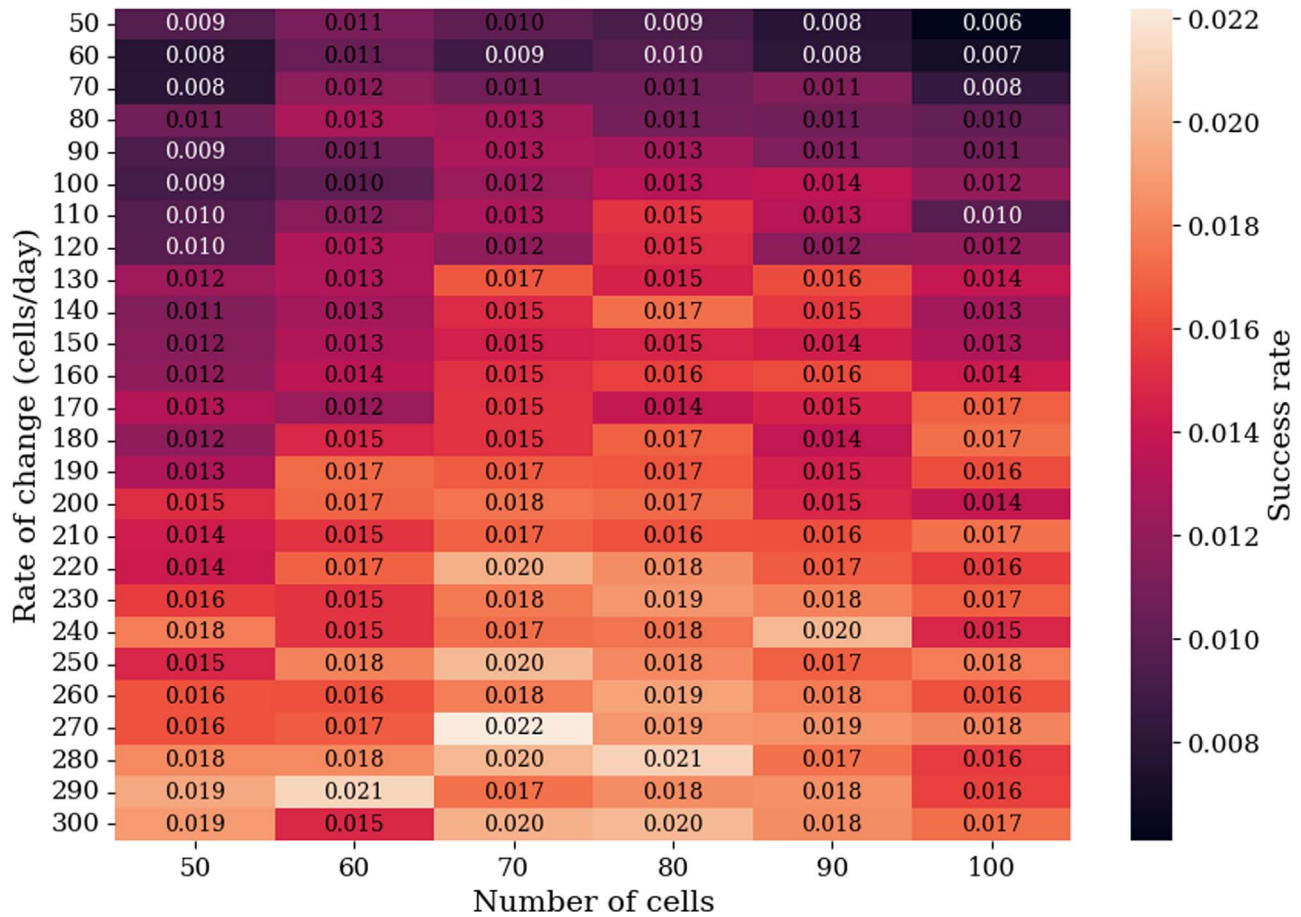


Figure 12. Parameter space of the random-walk simulations. The color bar shows the fraction of successful simulations that reproduce the observed median and interquartile range of the polarization degree (within 10%) and show an equal or larger amplitude rotation of the polarization angle relative to the observed value.

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