



Tracking Down the Broadband Polarimetric Properties of PG 1553+113

Riccardo Middei¹ , Svetlana G. Jorstad^{2,3} , Alan P. Marscher² , Ioannis Lioudakis⁴ , Matteo Perri^{1,5} ,
 Alessandro Maselli^{1,5} , Stefano Ciprini^{5,6} , Emanuele Nardini⁷ , Simonetta Puccetti⁵ , Laura Di Gesu⁸ , Iván Agudo⁹ ,
 Dawoon E. Kim¹⁰ , Ioannis Myserlis^{11,12} , A. Trindade Falcão¹³ , D. Ł. Król^{14,15} , Lucio A. Antonelli^{1,5} ,
 Tommaso Aniello¹, Pouya M. Kouch^{16,17} , Kari Nilsson¹⁶ , Elina Lindfors¹⁷ , Tapio Pursimo^{18,19} ,
 Francisco José Aceituno⁹, Víctor Casanova⁹ , Gabriel Emery⁹ , Juan Escudero Pedrosa^{20,14} , Jorge Otero-Santos^{20,21} ,
 Alfredo Sota⁹, Vilppu Piirola²² , George A. Borman²³ , Tatiana S. Grishina³ , Vladimir A. Hagen-Thorn³ ,
 Evgenia N. Kopatskaya³ , Elena G. Larionova³ , Daria A. Morozova³ , Sergey S. Savchenko³ , Ekaterina V. Shishkina³ ,
 Ivan S. Troitskiy³ , Yulia V. Troitskaya³ , Andrey A. Vasilyev³ , Alexey V. Zhovtan²³, Petra Benke^{12,24} ,
 Lena Debbrecht¹² , Julia Eich²⁵, Florian Eppel^{12,25} , Andrea Gokus²⁶ , Steven Hämmerich²⁷, Jonas Hessdörfer^{12,25} ,
 Matthias Kadler²⁵ , Dana Kirchner²⁵, Georgios F. Paraschos^{12,28,29} , Florian Rösch^{12,25}, Wladislaw Schulga²⁵,
 Mark Gurwell¹⁴ , Garrett Keating¹⁴ , Ramprasad Rao¹⁴ , Emmanouil Angelakis³⁰ , Alexander Kraus¹² ,
 Beatriz Agís-González⁴ , Dmitry Blinov^{4,31}, Anastasia Glykopoulou^{4,31}, Sara Capecchiacci^{4,31} , Alberto Floris^{4,31,32} ,
 Panagiotis Fotis^{4,31}, Alkmini Koukoutsis^{4,31}, John A. Kypriotakis⁴, Dimitrios A. Langis^{4,31} , Dimitrios Rompogiannakis^{4,31},
 Aristeidis Polychronakis³¹ , Vasiliki Tsioupli^{4,31}, Stavros Vogiatzis^{4,31}, Orestis Zoumpoulakis^{4,31}, Sumie Tochihara³³,
 Ryo Imazawa³³ , Mahito Sasada³⁴ , Yasushi Fukazawa^{33,35,36} , Koji S. Kawabata^{33,35,36} , Makoto Uemura^{33,35,36} ,
 Tsunefumi Mizuno³⁵ , Tatsuya Nakaoka³⁵, Hiroshi Akitaya³⁷ , and Takahiro Akai³³

¹ INAF Osservatorio Astronomico di Roma, Via Frascati 33, 00078, Monte Porzio Catone (RM), Italy; riccardo.middei@inaf.it

² Institute for Astrophysical Research, Boston University, 725 Commonwealth Avenue, Boston, MA 02215, USA

³ Saint Petersburg State University, 7/9 Universitetskaya Naberezhnaya, St. Petersburg, 199034, Russia

⁴ Institute of Astrophysics, Foundation for Research and Technology-Hellas, GR-71110 Heraklion, Greece

⁵ Space Science Data Center, Agenzia Spaziale Italiana, Via del Politecnico snc, 00133 Roma, Italy

⁶ Istituto Nazionale di Fisica Nucleare, Sezione di Roma “Tor Vergata”, I-00133 Rome, Italy

⁷ INAF—Osservatorio Astrofisico di Arcetri, Largo Enrico Fermi 5, I-50125 Firenze, Italy

⁸ ASI—Agenzia Spaziale Italiana, Via del Politecnico snc, 00133 Roma, Italy

⁹ Instituto de Astrofísica de Andalucía, IAA-CSIC, Glorieta de la Astronomía s/n, 18008 Granada, Spain

¹⁰ INAF Istituto di Astrofisica e Planetologia Spaziali, Via del Fosso del Cavaliere 100, 00133 Roma, Italy

¹¹ Institut de Radioastronomie Millimétrique, Avenida Divina Pastora, 7, Local 20, E-18012 Granada, Spain

¹² Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, D-53121 Bonn, Germany

¹³ NASA Goddard Space Flight Center, Code 662, Greenbelt, MD 20771, USA

¹⁴ Center for Astrophysics | Harvard & Smithsonian, 60 Garden Street, Cambridge, MA 02138, USA

¹⁵ Astronomical Observatory of the Jagiellonian University, Orla 171, 30-244 Kraków, Poland

¹⁶ Finnish Centre for Astronomy with ESO (FINCA), 20014, University of Turku, Finland

¹⁷ Department of Physics and Astronomy, Quantum, Vesilinnantie 5, FI-20014 University of Turku, Finland

¹⁸ Nordic Optical Telescope, Apartado 474, E-38700 Santa Cruz de La Palma, Santa Cruz de Tenerife, Spain

¹⁹ Department of Physics and Astronomy, Aarhus University, Munkegade 120, DK-8000 Aarhus C, Denmark

²⁰ Instituto de Astrofísica de Andalucía, IAA-CSIC, Glorieta de la Astronomía s/n, E-18008 Granada, Spain

²¹ Istituto Nazionale di Fisica Nucleare, Sezione di Padova, 35131 Padova, Italy

²² Department of Physics and Astronomy, 20014, University of Turku, Finland

²³ Crimean Astrophysical Observatory RAS, P/O Nauchny, 298409, Crimea[†]

²⁴ GFZ Helmholtz Centre for Geosciences, Telegrafenberg, 14476, Potsdam, Germany

²⁵ Julius-Maximilians-Universität Würzburg, Institut für Theoretische Physik und Astrophysik, Lehrstuhl für Astronomie, Emil-Fischer-Straße 31, 97074, Würzburg, Germany

²⁶ Physics Department and McDonnell Center for the Space Sciences, Washington University in St. Louis, MO 63130, USA

²⁷ Dr. Karl-Reimis Sternwarte und Erlangen Centre for Astroparticle Physics, Friedrich-Alexander Universität Erlangen-Nürnberg, Sternwartstraße 7, 96049 Bamberg, Germany

²⁸ Finnish Centre for Astronomy with ESO, University of Turku, 20014 Turku, Finland

²⁹ Aalto University Metsähovi Radio Observatory, Metsähovintie 114, 02540, Kylmälahti, Finland

³⁰ Section of Astrophysics, Astronomy & Mechanics, Department of Physics, National and Kapodistrian University of Athens, Panepistimiopolis Zografos 15784, Greece

³¹ Department of Physics, University of Crete, 70013, Heraklion, Greece

³² Istituto Nazionale di Astrofisica (INAF), Osservatorio Astronomico di Padova, IT-35122 Padova, Italy

³³ Department of Physics, Graduate School of Advanced Science and Engineering, Hiroshima University Kagamiyama, 1-3-1 Higashi-Hiroshima, Hiroshima 739-8526, Japan

³⁴ Department of Physics, Tokyo Institute of Technology, 2-12-1 Ookayama, Meguro-ku, Tokyo 152-8551, Japan

³⁵ Hiroshima Astrophysical Science Center, Hiroshima University, 1-3-1 Kagamiyama, Higashi-Hiroshima, Hiroshima 739-8526, Japan

³⁶ Core Research for Energetic Universe (Core-U), Hiroshima University, 1-3-1 Kagamiyama, Higashi-Hiroshima, Hiroshima 739-8526, Japan

³⁷ Planetary Exploration Research Center, Chiba Institute of Technology, 2-17-1 Tsudanuma, Narashino, Chiba 275-0016, Japan

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Abstract

We report on a nine-month monitoring campaign of the blazar PG 1553+113, relying on three observations carried out in 2025 with the Imaging X-ray Polarimetry Explorer (IXPE) and supported by multiwavelength facilities. The source displayed pronounced variability across the electromagnetic spectrum, with X-ray flux changes by up to a factor of ~ 5 and complex evolution of the optical polarization properties, including one of the largest (exceeding 150°) and fastest rotations in the electric vector position angle (EVPA) ever recorded. This swing of the EVPA was also accompanied by a temporary drop of the optical polarization degree to nearly zero. Significant X-ray polarization was observed during the third IXPE pointing, with a polarization degree $\Pi_X = (18.4 \pm 5.8)\%$ and $\Psi_X = 74^\circ \pm 9^\circ$ in the 2–8 keV band, while only upper limits were obtained in the first two epochs. The optical data show that the second IXPE observation occurred shortly after a dramatic optical polarization event characterized by a rapid EVPA swing and strong depolarization. Two possible scenarios may explain the broadband polarimetric behavior: (i) the superposition of two emitting regions with nearly orthogonal magnetic field configurations and variable relative contributions, and (ii) the interaction of a single emitting region with a shock that temporarily reorders the magnetic field. In both cases, the data support a picture in which the X-ray and optical emissions arise from closely related but not strictly cospatial regions within a dynamically evolving, magnetically structured jet.

Unified Astronomy Thesaurus concepts: [Blazars \(164\)](#)

1. Introduction

Blazars are a subclass of active galactic nuclei characterized by relativistic jets of particles oriented almost parallel to our line of sight (e.g., T. Hovatta et al. 2015; R. Blandford et al. 2019). This results in highly variable emission observable at all frequencies of the electromagnetic domain (e.g., C. M. Raiteri 2025). Based on their spectral energy distribution (SED), which is typically double humped, blazars are classified into three categories depending on the frequency (ν_{peak}) of the peak of the low-energy hump: low-synchrotron-peak (LSP), intermediate-synchrotron-peak, and high-synchrotron-peak (HSP) objects. The low frequency peak is ascribed to synchrotron emission, and for these different subclasses it is generally observed in the infrared, optical, and X-ray bands, respectively (G. Fossati et al. 1998; A. A. Abdo et al. 2010).

For decades, the physics of the jets has been studied using multiwavelength data from space observatories, including Fermi Large Area Telescope (LAT; W. B. Atwood et al. 2009), the Neil Gehrels Swift Observatory (hereafter Swift; N. Gehrels et al. 2004), XMM-Newton, and ground-based radio and optical telescopes (e.g., A. R. G. Mead et al. 1990; M. T. Carini et al. 1992; E. Piconcelli & M. Guainazzi 2005; A. P. Marscher et al. 2008; M. Ajello et al. 2009, 2020; P. S. Smith et al. 2009; M. Ackermann et al. 2015; V. A. Acciari et al. 2020). The Imaging X-ray Polarimetry Explorer (IXPE; M. C. Weisskopf et al. 2022) has revolutionized this field, allowing for direct measurements of X-ray polarization. This provides unique constraints on the acceleration mechanisms of the particle population responsible for the observed broadband emission and unprecedented insights on the structure of the magnetic field within the X-ray emitting region of the jet (e.g., L. Di Gesu et al. 2022, 2023; I. Liodakis et al. 2022; R. Middei et al. 2023a; A. L. Peirson et al. 2023; P. M. Kouch et al. 2024; I. Agudo et al. 2025); see A. P. Marscher et al. (2024) for a summary.

The large number of IXPE observations, accompanied by multifrequency polarimetric campaigns, have also enabled ensemble analyses: for LSP objects, the observations (e.g., H. L. Marshall et al. 2024; I. Agudo et al. 2025) suggest that the particle populations giving rise to the KeV emission of these sources are likely of leptonic origin (but see also F. Tavecchio et al. 2025). As noted by S. Capececciacci et al. (2025), while in all the HSP sources observed by IXPE, the

polarization degree in X-rays is systematically higher than at optical and millimeter–radio wavelengths. This finding is compatible with jets being energy stratified, with particles being accelerated in shocks or some other localized regions, from which they propagate while losing energy (e.g., I. Liodakis et al. 2022; A. P. Marscher et al. 2024). IXPE has also performed multiepoch observational campaigns of HSP blazars such as Mrk 501 (C.-T. J. Chen et al. 2024), which maintained fairly constant polarization during 2022 and 2023, and Mrk 421 (D. E. Kim et al. 2024), which on the other hand displayed dramatic changes in the X-ray polarization degree.

Here, we report on novel broadband spectropolarimetric observations of PG 1553+113 (R.A. = $15^{\text{h}} 55^{\text{m}} 43^{\text{s}}.0440$, decl. = $+11^\circ 11' 24''.365$, J2000), a HSP blazar ($\nu_{\text{peak}} \approx 3.9 \times 10^{15}$; M. Ajello et al. 2020). This source, a known TeV emitter (J. Aleksić et al. 2012) likely located at $z = 0.433$ (e.g., F. Nicastro et al. 2018), is one of the few blazars exhibiting quasi-periodic variability patterns (e.g., P. Peñil et al. 2020; S. Abdollahi et al. 2024). Specifically, it displays a compelling ~ 2.2 yr quasi-periodicity in its γ -ray flux and in the optical/UV bands (M. Ackermann et al. 2015; M. Tavani et al. 2018; MAGIC Collaboration et al. 2024). At X-ray energies, the situation is more complex and still debated. While some studies report no statistically significant periodicity (e.g., T. Aniello et al. 2024; MAGIC Collaboration et al. 2024), others have found tentative hints of a similar quasi-periodic pattern (P. Peñil et al. 2026) and interpreted X-ray flares within the framework of jet precession in a binary supermassive black hole (SMBH) system (S. Huang et al. 2021). Therefore, while a long-term modulation may exist across the electromagnetic spectrum, it is most likely masked in X-rays by pronounced stochastic variability. The origin of this quasi-periodic modulation is still poorly understood. The most widely discussed scenario involves a binary SMBH system at subparsec scales (e.g., M. Ackermann et al. 2015; M. Tavani et al. 2018; S. Abdollahi et al. 2024), where the observed ~ 2.2 yr periodicity could arise from jet precession, disk perturbations, or periodic modulation of the accretion rate. In this framework, the reported hints of a longer ~ 22 yr timescale (S. Adhikari et al. 2024) may indicate a more complex, hierarchical variability, possibly associated with large-scale precession of the accretion disk or orbital evolution. However,

alternative interpretations do not necessarily require a binary system. These include geometric effects within a single SMBH scenario, such as jet precession driven by instabilities, or variations in the viewing angle, as well as intrinsic processes within the jet. Supporting a geometric origin, recent analyses have shown that the ~ 2.2 yr quasi-periodicity in γ -rays is nearly achromatic (E. Madero & A. Domínguez 2026). This behavior is naturally explained by periodic changes in the Doppler boosting factor, rather than by intrinsic variations in the particle population, thus favoring scenarios involving jet orientation effects.

Given its unique observational properties, PG 1553+113 is a prime target for X-ray polarization measurements by IXPE. R. Middei et al. (2023b) have already carried out IXPE and multiwavelength observations, reporting on the blazar's broadband polarimetric properties. The X-ray polarization degree was observed to be $\Pi_X = (10 \pm 2)\%$ in the 2–8 keV range, with an electric vector position angle (EVPA) of $\Psi_X = (86^\circ \pm 8^\circ)$. Interestingly, the optical EVPA exhibited a large swing of approximately 125° over a time span of days, at a rate of $\sim 17^\circ$ per day, while no corresponding variation was detected in the X-ray or radio bands. This implies that the X-ray and optical emission regions are not cospatial, since they have distinct magnetic field geometries.

During 2025, we again monitored PG 1553+113 with IXPE and coordinated ground- and space-based facilities. In this work, we report on the broadband polarimetric properties collected within this program. In Section 2, we describe the data reduction procedures and present the data, while Section 3 reports on the spectropolarimetric analyses. In Section 4, we report on the multiwavelength polarimetric data, while in Section 5 we comment the results and draw our conclusions.

2. Data Reduction

PG 1553+113 was the target of an intense monitoring campaign during 2025 involving various polarimeters and CCD detectors. In the X-ray band, we observed PG 1553+113 with IXPE, XMM-Newton (F. Jansen et al. 2001), and Swift. In Table 1, we list the related X-ray observations for IXPE and XMM-Newton, while for Swift a similar table is shown in Table A1.

2.1. IXPE Data Reduction

We processed the IXPE level-1³⁸ event files and made them available for download from the *HEASARC* archive. The Stokes I , Q , and U spectra were derived independently for the available detector units (DUs) through use of the IXPEOBSSIM package (version 31.1.1; M. Pesce-Rollins et al. 2019; L. Baldini et al. 2022), applying the background filtering strategy described in A. Di Marco et al. (2023). In addition, the spectra were generated by utilizing the weighted analysis technique introduced by A. Di Marco et al. (2022), corresponding to the STOKES = NEFF option in XSELECT. Source events were selected from a circular extraction region with a radius of 0.95 centered on the target, whereas the background was estimated from an annular region with inner and outer radii of 1.2 and 3.5, respectively. This selection has been demonstrated to provide optimal polarization sensitivity

³⁸ Detector Unit 2 (DU2) has been operating in an anomalous manner since 2025 April 14; hence, for our observations after 2025 May 10, the DU2 event files were not available in time to include in this study.

Table 1
Log of the IXPE and XMM-Newton Observations of PG 1553+113 Used in this Work

ObsID	Start Date (UTC)	Exposure (ks)
IXPE		
04001701	2025-02-01 14:50:48	119.6
04001801	2025-07-06 11:57:54	117.9
04001901	2025-09-11 07:47:39	115.0
XMM-Newton		
0920901101	2025-02-02 09:15:05	13.6
0920902301	2025-07-28 15:33:14	7.0
0920902501	2025-08-26 18:39:39	15.5

(A. Di Marco et al. 2023). The I -Stokes spectra were rebinned to ensure a minimum signal-to-noise ratio of 7 per energy channel, while a fixed energy bin width of 280 eV was adopted for the Q and U spectra.

2.2. XMM-Newton Data Reduction

PG 1553+113 was also observed three times by XMM-Newton as close in time as possible to the IXPE pointings. Our analysis focused on data collected with the EPIC-pn instrument (L. Strüder et al. 2001), operated in small window mode with the medium optical blocking filter. The data reduction was carried out using the standard XMM-Newton Science Analysis System (SAS version 230412; C. Gabriel et al. 2004). The selection of source extraction regions and identification of time intervals affected by enhanced background were performed iteratively, following the procedure described by E. Piconcelli et al. (2004), with the aim of optimizing the signal-to-noise ratio. The background spectra were extracted from circular regions with a radius of $50''$. The final third-level products were rebinned to include a minimum of 30 counts per channel and to ensure that the instrumental energy resolution was not oversampled by more than a factor of three. The observed net count rate remained well below the threshold above which pile-up effects become significant for EPIC-pn small window observations (e.g., P. Jethwa et al. 2015). A dedicated pile-up assessment was also carried out using the SAS task *epatplot*, confirming that pile-up effects were negligible.

2.3. Swift (XRT and UVOT)

Swift observed PG 1553+113 both prior to and following the IXPE observations and throughout 2025. A total of 48 individual pointings, each with an exposure time of ~ 1 ks, were acquired in either photon counting (PC) or windowed timing (WT) mode, depending on the flux of the source. The data were processed and calibrated using an automated pipeline that relies on the standard *XRTDAS* software package.³⁹ In order to extract the source events, the pipeline handles observations executed in the two observing modes using a circular/annular region centered on the target, depending on the presence of pile-up (see R. Middei et al. 2022, for details). The background contribution was estimated

³⁹ <https://sda2006.ts.infn.it/presentazioni/capalbi.pdf>

from a concentric annular region with inner and outer radii of 120'' and 150'' for observations in PC and with synthetic backgrounds for the WT observations. The resulting spectra were rebinned to ensure at least 25 counts per energy bin, allowing for the application of χ^2 statistics in the subsequent spectral fitting. The Ultraviolet/Optical Telescope (UVOT) data were processed with `uvotimsum` to coadd exposures and with `uvotsource` to extract photometry in all available filters (*V*, *B*, *U*, *UVW1*, *UVM2*, and/or *UVW2*). The observed UVOT fluxes were then used to build broadband SEDs and to monitor optical/UV variability concurrent with X-ray polarimetric measurements. In Table A1 we report the relevant information for the Swift exposures used in this work.

3. Data Analysis

Joint X-ray spectral and polarimetric modeling was carried out with the XSPEC package (K. A. Arnaud 1996), adopting the weighted analysis approach described by A. Di Marco et al. (2022). The effects of Galactic photoelectric absorption were included in the fits through the `TBabs` model, with the hydrogen column density fixed to $N_H = 3.62 \times 10^{20} \text{ cm}^{-2}$, as derived from the HI4PI survey (HI4PI Collaboration et al. 2016). Whenever a distance-dependent quantity for PG 1553+113 was required, we assumed a standard cosmological model characterized by $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and $\Lambda_0 = 0.73$. Finally, all the errors quoted in the tables correspond to 68% uncertainties, except for upper/lower limits, which are at the 99.7% confidence level.

3.1. Broadband Properties of PG 1553+113 during 2025

As described in Section 2.3, PG 1553+113 was observed 48 times with Swift between 2025 early January and late September. Each spectrum was fitted with a phenomenological model, a logarithmic parabola (e.g., E. Massaro et al. 2004), absorbed by gas in the Milky Way. The fits provide the spectral shape (α), curvature parameter (β), and flux normalization for a selected pivot energy of 1 keV (e.g., P. Giommi et al. 2021). This model adequately accounts for all spectra; the best-fit parameters are reported in Table A1.

During the analyzed period, PG 1553+113 shows significant flux variability, by up to a factor of ~ 5 in the 2–8 keV band. The spectral shape and curvature also vary substantially on both daily and monthly timescales. From Figure 1, we find that IXPE observed PG 1553+113 at three different flux levels within the range $F \sim (0.5\text{--}2) \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}$. The XRT spectra and UVOT data can be used to build the broadband SED of PG 1553+113, which we show in Figure 2. In this figure, we present the temporal evolution of the source SEDs and compare them with the corresponding γ -ray flux measured by Fermi-LAT (S. Abdollahi et al. 2023). Significant variability is observed in both amplitude and spectral shape across the optical/UV and X-ray bands, on timescales ranging from weeks to months.

To further investigate the multiwavelength variability and search for correlations between different energy bands, we have constructed monthly averaged SEDs. For the X-ray band, we estimated the monochromatic flux at a reference energy of 2 keV (νF_ν at 2 keV). This flux was derived for each observation through a log-log linear interpolation between the two nearest energy bins. For the UV band, we adopted the UVW1 filter ($\lambda_{\text{eff}} \approx 2486 \text{ \AA}$, A. A. Breeveld et al. 2011) as a

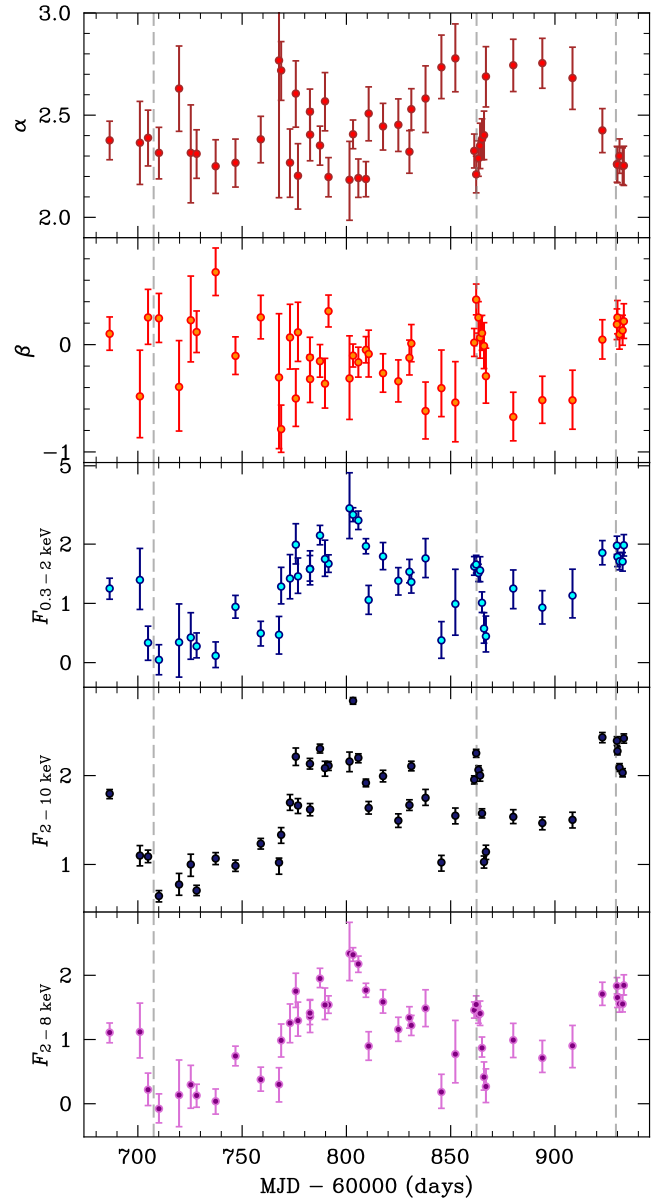


Figure 1. Temporal evolution of the spectral properties (α and β panels) and the flux in multiple bands of PG 1553+113. Vertical dashed lines identify the epochs of the IXPE exposures. Fluxes are in units of $10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}$.

proxy for the UV emission. The monthly mean fluxes ($\langle F \rangle$) were computed by averaging observations within each calendar month. The associated uncertainties were estimated as the standard deviations of the corresponding fluxes. When only a single observation was available, the corresponding instrumental uncertainty was adopted. We then performed correlations between the γ -ray integrated Fermi-LAT flux and the X-ray and UV fluxes, finding strong correlations with Pearson coefficients of $R = 0.890$ ($p = 1.3 \times 10^{-3}$) for the X-ray versus γ -ray flux and $R = 0.887$ ($p = 1.4 \times 10^{-3}$) for the UV versus γ -ray flux.

3.2. XMM-Newton Spectral Analysis

Although the XMM-Newton observations are not fully simultaneous with the IXPE pointings, the large effective area in the soft band can help constrain the overall spectral shape of the source. For this reason, we have modeled the three

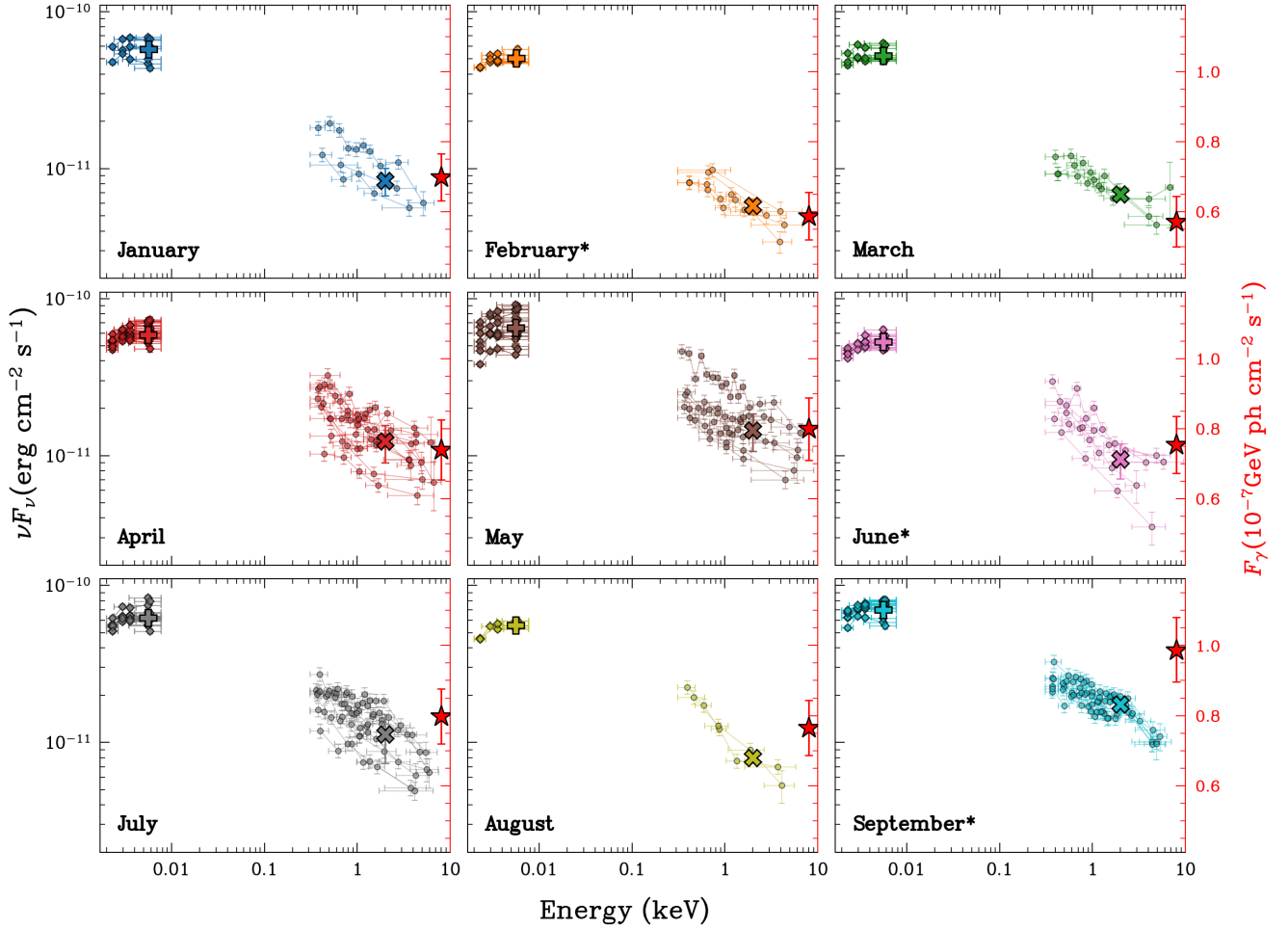


Figure 2. Monthly SEDs of PG 1553+113 during 2025 January–September, covering the optical/UV and X-ray bands. Each panel shows the collected Swift UVOT and XRT data. Both the UV and X-ray emissions exhibit significant variability in amplitude and spectral shape. The black asterisks near the name of months in the bottom of panels mark the months during which IXPE observed the source. The corresponding monthly Fermi-LAT photon flux level (S. Abdollahi et al. 2023) is shown as a red star in each subpanel. The right y-axis provides the scale for the γ -ray flux.

EPIC-pn spectra with the simple phenomenological model applied above for the XRT snapshots. The fitting procedure is the same, and we report the corresponding results in Table 2. The XMM-Newton spectra are compatible with a softening of the spectrum when the source becomes brighter (softer when brighter). During these epochs, no strong curvature is observed in the spectra.

3.3. IXPE Spectropolarimetric Analysis

The strong short-term variability displayed by PG 1553+113 prevents us from performing joint IXPE–XMM spectral fits. Thus, we fit the three sets of IXPE Stokes-parameter spectra, adopting the TBabs*constant*polconst*logpar model for each distinct exposure in XSPEC. The constant parameter takes into account the cross calibration among the different DUs, logpar models the nonthermal continuum of the source (in this case we set the pivot energy to 3 keV, within the IXPE operating band), while polconst, operating on the Q and U spectra, returns the degree Π_X and position angle (PA) Ψ_X of the 2–8 keV polarization. The fit to the data is straightforward (see Figure 3) and the corresponding results are listed in Table 3. Only for IXPE observation 3 are the polarization properties of PG 1553+113 constrained, and for this measurement we obtain values of $\Pi_X = (18.4 \pm 5.8)\%$ and $\Psi_X = 74^\circ \pm 9^\circ$. Only upper

Table 2 Best-fit Parameters of the Spectral Fits to the XMM-Newton Data			
Comp. and Param.	Obs 1	Obs 2	Obs 3
logpar α	2.61 ± 0.01	2.67 ± 0.01	2.68 ± 0.01
logpar β	0.04 ± 0.03	-0.02 ± 0.03	0.03 ± 0.02
norm ($\times 10^{-3}$)	5.87 ± 0.03	6.81 ± 0.05	8.59 ± 0.03
$F_{0.3-2 \text{ keV}} (\times 10^{-11})$	1.65 ± 0.01	1.97 ± 0.01	2.48 ± 0.01
$F_{2-10 \text{ keV}} (\times 10^{-12})$	6.03 ± 0.12	6.85 ± 0.20	8.09 ± 0.11
χ^2/dof	149/136	130/114	186/152

limits are found for observations 1 and 2, thus in Table 3 we report their corresponding values at the 3σ confidence level. Interestingly, if we considered only 1σ uncertainties, for Obs. 1 we would obtain $\Pi_X = (18.4 \pm 8.1)\%$ and $\Psi_X = 150^\circ \pm 13^\circ$, while for Obs. 2 we would obtain $\Pi_X < 12\%$. In Figure 3, we show the best fit to the I -Stokes spectra for both XMM-Newton and IXPE data, as well as the best-fit to the Q and U Stokes spectra, while the corresponding contours for the polarization properties are displayed in Figure 4.

To further search for the presence of any polarimetric signal in the IXPE data, we also fit the three exposures jointly. This

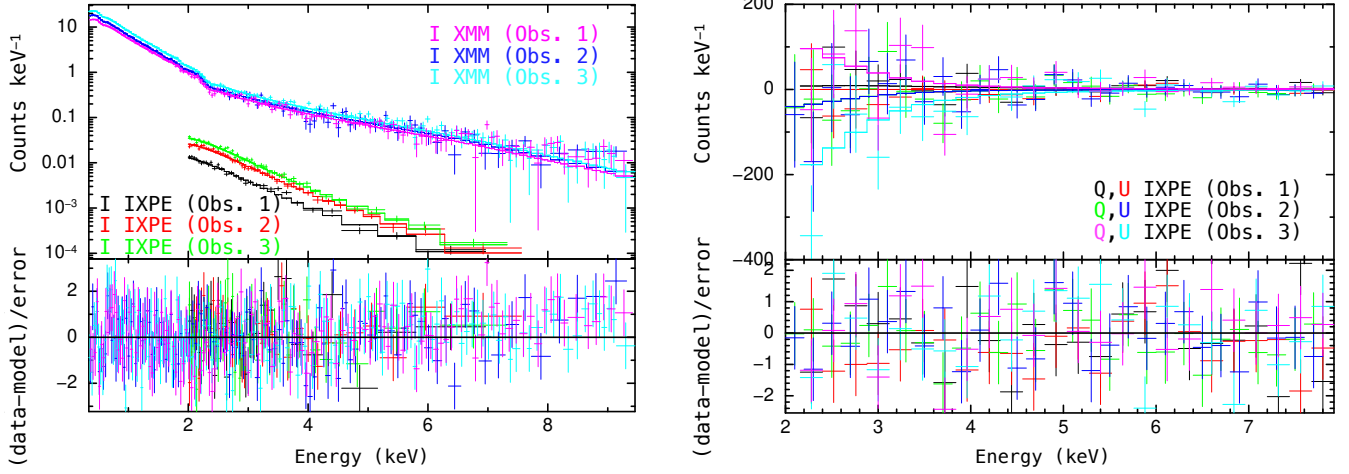


Figure 3. Left panel: Best fit to the I -Stokes (i.e., total flux density) spectra derived for the IXPE and XMM-Newton observations reported in Table 1. Right panel: The corresponding best fit to the Q and U Stokes spectra.

Table 3
Best-fit Model for the Three IXPE Observations

Comp. and Param.	Obs 1	Obs 2	Obs 3
$\log \alpha$	2.59 ± 0.07	2.84 ± 0.24	2.70 ± 0.05
$\log \beta$	-0.77 ± 0.56	1.01 ± 0.90	0.18 ± 0.40
$\text{norm} (\times 10^{-4})$	2.27 ± 0.08	4.92 ± 0.16	6.54 ± 0.15
$\text{polconst } \Pi_X$	$<39\%$	$<24\%$	18.4 ± 5.8
$\text{polconst } \Psi_X$	...	...	$74^\circ \pm 9^\circ$
DU2/DU1	0.97 ± 0.04	...	...
DU3/DU1	0.96 ± 0.03	0.89 ± 0.02	0.89 ± 0.02
$F_{2-8 \text{ keV}} (\times 10^{-12})$	4.2 ± 0.3	7.5 ± 0.6	10.8 ± 0.2
$\chi^2/\text{d.o.f.}$	205/236	157/186	226/192

only returns an upper limit to the polarization degree $\Pi_X < 13\%$, this fit being slightly worse than that quoted in Table 3. As an additional check, we assume the polarization degree to be constant across the observations and allow the polarization angle to vary. This leads to a fit with a statistic compatible with our best fit and a “constant” $\Pi_X = (14.6 \pm 3.9)\%$, with polarization angles of $\Psi_X > 110^\circ$ and $\Psi_X = 74^\circ \pm 10^\circ$ for Obs. 1 and Obs. 3, respectively, while this quantity is unconstrained by the data in Obs. 2.

4. Multiwavelength Polarimetric Data

As supplements to the IXPE multiepoch observations, different ground-based observatories monitored PG 1553+113 at both radio and optical wavelengths: Calar Alto Observatory (CAFOS; J. Escudero Pedrosa et al. 2024a, 2024b), Effelsberg 100 m telescope (QUIVER and TELAMON programs; A. Kraus et al. 2003; I. Myserlis et al. 2018, 2025; F. Eppel et al. 2024), the Higashi-Hiroshima Observatory (Kanata telescope—HONIR; K. S. Kawabata et al. 1999; H. Akitaya et al. 2014), the Nordic Optical Telescope (ALFOSC; MAGIC Collaboration et al. 2018; K. Nilsson et al. 2018), the LX-200 telescope (St. Petersburg University, Russia; V. M. Larionov et al. 2008), Boston University’s Perkins Telescope (PRISM camera; S. G. Jorstad et al. 2010), Skinakas observatory (RoboPol; A. N. Ramaprakash et al. 2019; D. Blinov et al. 2021) and the Submillimeter Array (SMAPOL program; I. Myserlis et al. 2025). Details of the data analysis of the

individual observatories and monitoring programs can be found in, e.g., I. Liodakis et al. (2022, 2025), L. Di Gesu et al. (2023), and A. L. Peirson et al. (2023). The emission from PG 1553+113 does not contain significant host-galaxy contamination, hence no correction has been performed to the optical flux or polarization degree. In Figures 5 and 6, we show how the optical magnitudes, as well as the optical polarization degree and angle, of this blazar vary as a function of time.

Until MJD 60849, the optical R -band polarization fluctuated about an average value of $\langle \Pi_{R \text{ band}} \rangle \sim 4\%$ and a roughly stable polarization angle of $\langle \Psi_{R \text{ band}} \rangle \sim 15^\circ$. Following this “stable” phase, the polarization properties of PG 1553+113 began to vary systematically, with the polarization degree reaching a maximum of $\Pi_{R \text{ band}} \sim 8.7\%$ in June 23 (MJD ~ 60849). Within approximately two weeks, the polarization degree decreased to $\Pi_{R \text{ band}} \sim 0\%$, accompanied by a large swing in the polarization angle ($\Delta \Psi_{R \text{ band}} > 100^\circ$) starting from a polarization angle $\sim 45^\circ$ down to $\sim -180^\circ$ with low amplitude variability. After the R -band polarization degree reached nadir roughly half-way through the rotation, it exhibited a steady, essentially linear increase over the ensuing two months, reaching a prerotation level of approximately 8%.

In 2025 September, around the time of the third IXPE pointing (MJD ~ 60930), the optical polarization degree exhibited further strong variations; however, these changes were no longer accompanied by polarization angle swings as pronounced as those observed between June and July (i.e., between MJD ~ 60845 and MJD ~ 60864).

In the bottom panel of Figure 5, we present the contemporaneous Fermi-LAT light curve (S. Abdollahi et al. 2023). Around mid 2025 December, between MJD 60657 and 60666, PG 1553+113 displayed enhanced γ -ray emission, after which the flux decreased significantly. The optical emission seems to have followed this trend (see the top panel in Figure 5), such that the first IXPE observation in 2025 occurred while the source was in a low flux state.

In the radio, observations at 14, 17, and 225 GHz show a comparable polarization degree at $\sim 2\% - 3\%$ throughout the IXPE observations, although much less-sampled compared to the optical observations. Our campaign also included observations at 36 GHz; however, the analysis yielded only upper limits. Close in time to the second IXPE observation, there is a significant drop of the polarization degree to $\sim 1.5\%$ at 17 GHz

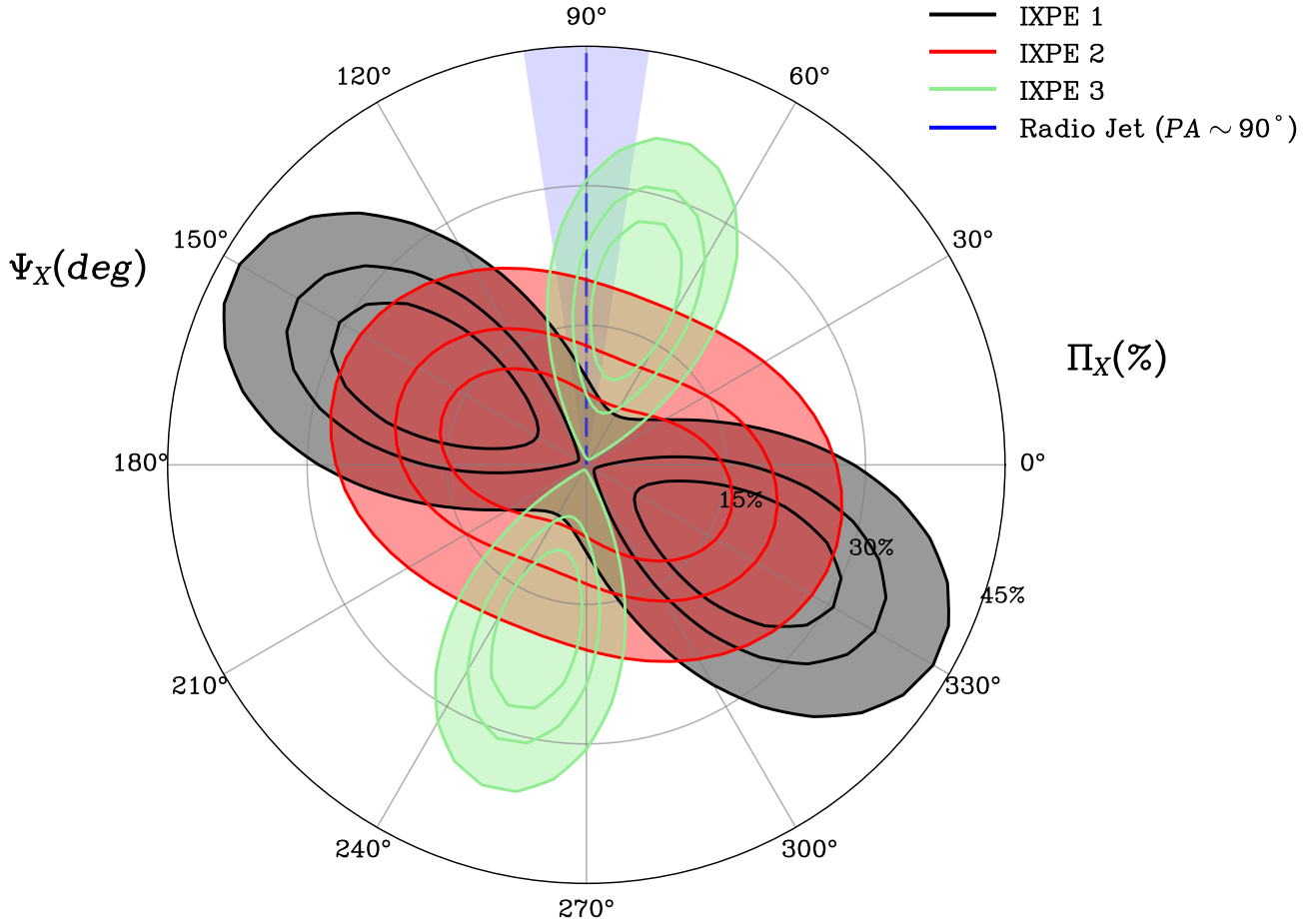


Figure 4. Confidence regions for the polarization properties of PG 1553+113 at 68%, 90%, and 99% confidence level. Only Obs. 3 enables us to determine both the X-ray polarization degree and angle. The jet’s projection is taken from S. Capecchiacci et al. (2025).

and 0.85% at 225 GHz. This is in agreement with the optical observations, which show their lowest polarization degree values at around the same time, i.e., while the rotation of the optical polarization angle was taking place. The radio polarization angle remains consistent across all frequencies and roughly perpendicular to the jet axis, except during the second IXPE observation. During the optical rotation, the 225 GHz polarization angle becomes near parallel to the jet axis.

5. Discussion and Conclusions

We have presented the results of a multiwavelength polarimetric campaign on the blazar PG 1553+113, centered on three IXPE observations performed at distinct flux and polarization states. The source exhibited substantial variability across all wavelengths, characterized by X-ray flux changes by up to a factor of ~ 5 and a complex optical polarimetric behavior, including a large EVPA rotation ($\Delta\Psi_{\text{opt}} \gtrsim 150^\circ$) and a transient drop in the polarization degree to nearly zero.

5.1. X-Ray Polarization and Jet Geometry

This behavior highlights the peculiar nature of PG 1553+113 compared to the broader class of HSP blazars. In the standard scenario for HSPs, the magnetic field is typically compressed by shocks oriented transverse to the jet axis, resulting in a mean field perpendicular to the axis and, consequently, an EVPA aligned with the jet direction

(R. A. Laing 1980; T. V. Cawthorne & W. K. Cobb 1990; A. P. Marscher et al. 2008). This paradigm has been largely confirmed by IXPE observations of sources such as Mrk 501 (e.g., I. Liodakis et al. 2022; C.-T. J. Chen et al. 2024).

However, PG 1553+113 deviates significantly from this trend. As imaged by the MOJAVE program at 15 GHz, the source is extremely core dominated, exhibiting only faint extended structure at a projected PA between 30° and 50° (R. Lico et al. 2014). Our measured $\Psi_X \sim 74^\circ \pm 9^\circ$ in Obs. 3 is thus oblique to this parsec-scale jet direction, with an offset of $\sim 30^\circ$ – 45° . This configuration is reminiscent of the “oblique” polarization seen in Mrk 421 during its first IXPE epoch (L. Di Gesu et al. 2023), suggesting that the emission might originate in regions where the magnetic field is either helical or influenced by oblique shocks.

Crucially, the jet geometry in PG 1553+113 is known to be nonstationary. R. Lico et al. (2020) reported that the jet’s PA varies over time, and S. Capecchiacci et al. (2025) quoted a jet direction of $\sim 90^\circ$, potentially resulting from a precessing jet nozzle or a complex helical motion of the emitting plasma. If we adopt this more recent estimate, our measured $\Psi_X = 74^\circ \pm 9^\circ$ would appear much closer to alignment with the jet’s axis, shifting the interpretation back toward a shock-compressed field scenario. This would possibly suggest that the previously observed “obliquity” of the X-ray polarization may be a transient effect tied to some structural evolution (e.g., precession) of the jet itself, rather than a static property of the source.

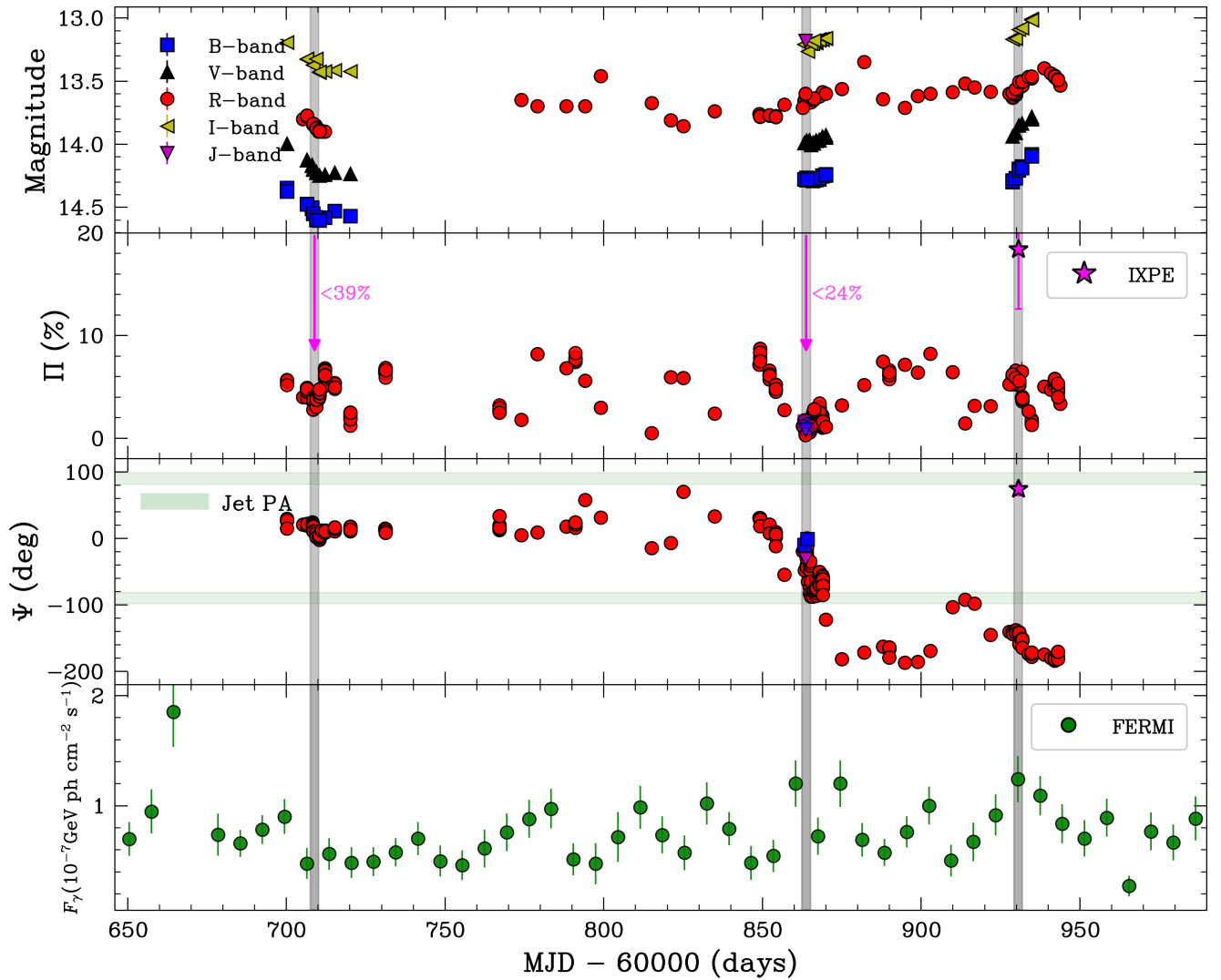


Figure 5. Temporal evolution of the flux (optical and γ -ray) and the optical polarization properties of PG 1553+113. From top to bottom, the panels show the source brightness expressed in magnitudes; the optical polarization degree; the polarization angle; and the γ -ray light curve in the 0.1–100 GeV energy range, with the weekly photon flux measured by the Fermi-LAT during the IXPE monitoring campaign. The time intervals corresponding to the IXPE observations are highlighted by gray shaded regions. Error bars indicate 1σ uncertainties. IXPE upper limits (arrows) and measurements (stars) are shown in magenta. Finally, the horizontal green bars show the direction of the jet.

5.2. Possible Decoupling between Flux and Polarization

Our results suggest a complex relationship between X-ray flux and polarization that may challenge the trends typically observed in HSP blazars (see, e.g., Figure 6). To date, IXPE observations of bright HSPs, such as Mrk 421 and Mrk 501, have generally shown that higher X-ray flux states are accompanied by well-defined, significant polarization signals. In PG 1553+113, however, the degree of magnetic field ordering appears to be independent of the total energetic output of the jet. While one should remain cautious given the 1σ uncertainties, a comparison between Obs. 1 and Obs. 2 is particularly interesting. Despite an increase in the X-ray flux by a factor of approximately two during Obs. 2, the polarization signal becomes undetectable, failing to reach even a 1σ threshold. In contrast, the lower-flux state of Obs. 1 tentatively suggests a polarized signal with $\Pi_X \sim 18\%$, being detected up to $\sim 2.3\sigma$. This may indicate that the physical conditions responsible for increasing the flux (e.g., a higher

efficiency of particle injection or stronger Doppler boosting) do not necessarily enhance, and may even disrupt (e.g., via turbulence), the magnetic field order.

Furthermore, the nondetection in Obs. 2 coincides with a period of nearly zero optical polarization (see Figure 6). This synchronized depolarization across all radio, optical, and X-ray bands is a remarkable feature, suggesting a high degree of cospatiality between the electron populations responsible for the synchrotron emission at the various energy scales. Contrary to other HSPs, where the optical emission often originates from a more extended and turbulent region compared to the compact X-ray site, in PG 1553+113 the X-ray and lower-energy emitting zones appear to “communicate” more directly. In this framework, the global depolarization observed during Obs. 2 may reflect a large-scale stochastic reconfiguration or a surge of turbulence that simultaneously affects the entire synchrotron emitting volume, regardless of the electron energy.

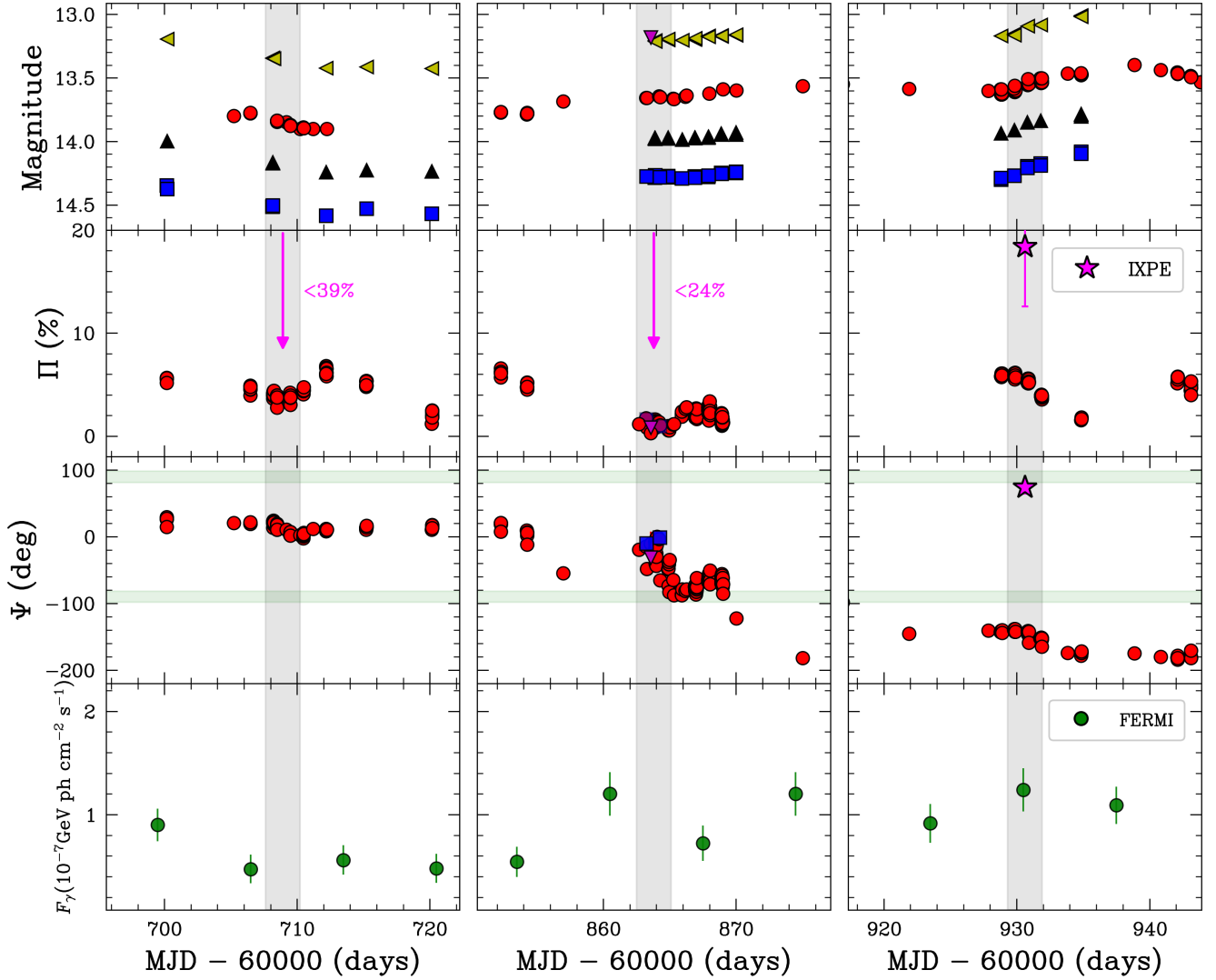


Figure 6. Zooms extracted from Figure 5. The different panels focus on the multiwavelength behavior of PG 1553+113 before and after the IXPE pointings. The quantities in the different subplots are the same as for Figure 5.

5.3. The Extraordinary Optical Polarization Swing of PG 1553+113

The dramatic optical polarization event observed between 2025 June and July, characterized by a rapid EVPA rotation exceeding 180° and a simultaneous drop in Π_{opt} , represents one of the most extreme polarimetric variations ever sampled for this source. While EVPA rotations are well documented in blazars (e.g., A. A. Abdo et al. 2010; D. Blinov et al. 2015, 2016), the rotation reported here, along with the historical swings discussed by C. M. Raiteri et al. (2017), identifies PG 1553+113 as a source capable of some of the largest EVPA rotations ever recorded in the literature. These swings in the EVPA can be seen as the signature of a complex magnetic field structure within the jet. In particular, such rotations favor a scenario in which an ordered component, most plausibly a helical magnetic field, is combined with a stochastic component arising from shocks, plasmoid formation, and turbulence.

A similar large-scale rotation was observed in 2023 (R. Middei et al. 2023b), although in that instance the degree of X-ray polarization remained remarkably constant throughout

the optical EVPA swing, and the swing seemed to also be connected to observed γ -ray brightening. The authors explained this behavior in light of various scenarios, such as kink-driven magnetic reconnection (G. Bodo et al. 2021) and the merging of reconnection plasmoids (D. N. Hosking & L. Sironi 2020). However, the former scenario typically predicts similar polarization degrees across bands, failing to explain the observed chromaticity, while the latter involves timescales much shorter than the ~ 7 days observed for the swing. Alternatively, the rotation was also interpreted within the Turbulent Extreme Multi-Zone (TEMZ) framework (A. Marscher et al. 2017) as a stochastic random walk, where the lower optical Π stems from a more extended and turbulent emission region compared to a more ordered and compact X-ray core.

The 2025 multiwavelength campaign reveals a spectropolarimetric behavior that significantly differs from previous epochs. The lack of a significant X-ray polarization detection in Obs. 2, contrasted with the recovery in Obs. 3 and the tentative signal in Obs. 1, may hint at a highly variable emitting environment. In the following, we discuss two possible frameworks to explain the observed multiwavelength spectropolarimetric properties of the 2025 campaign.

Two-component model and vector cancellation. We consider two spatially distinct emitting regions (or substructures) within the jet, each characterized by a relatively ordered magnetic field but with EVPAs differing by somewhat less than 90° . In this framework, the observed rotation and deep depolarization would not be caused by a physical rotation of the field, but rather by the temporal variation in the relative flux contributions of these two components. As one component fades and the other rises, their competing electric vectors increasingly cancel each other, naturally leading to the observed $\Pi_{\text{opt}} \sim 0\%$ state. The X-ray polarization behavior would then depend on which component dominates the high-energy synchrotron emission at a given epoch. The nearly orthogonal EVPAs suggested by the data between Obs. 1 and Obs. 3 are qualitatively consistent with this “vector cancellation” picture and point to a dynamically evolving magnetic topology within the inner jet.

Shock-turbulence interaction in a helical field. Alternatively, the observed behavior could be explained by the interaction between a transverse moving shock and a stationary (standing) shock within the jet. The collision between these two structures would trigger a simultaneous increase in the radio, optical, and X-ray fluxes. However, the interaction likely develops strong localized turbulence, which causes significant depolarization and the observed EVPA rotation during IXPE Obs. 2, as supported by the optical data (see Figure 6, top middle panel) and the lack of a significant X-ray polarization detection. This turbulent phase appears to be short-lived, as suggested by the optical polarization degree dropping close to zero. By the time of IXPE Obs. 3, the moving shock has likely passed the standing shock and becomes more prominent. This leads to the recovery of the characteristic polarization behavior observed in HSP blazars (e.g., I. Liodakis et al. 2022), where the polarization degree follows the hierarchy $\Pi_X > \Pi_{\text{opt}} > \Pi_{\text{rad}}$ and the X-ray EVPA aligns closely with the jet’s direction. In both scenarios, the data support an energy-stratified jet structure in which different electron populations, possibly located in partially overlapping regions, contribute to the optical and X-ray synchrotron emission. These interpretations remain tentative because the rapid variability and the 1σ nature of some X-ray constraints do not yet allow us to uniquely identify the underlying engine of the observed rotation.

Finally, we note a key difference when comparing our data with the historical events reported by C. M. Raiteri et al. (2017), who also measured a long optical polarization swing of $\sim 350^\circ$. Interestingly, their sampled optical EVPA swings were not accompanied by a clear or dramatic depolarization in the same band (see their Figure 4), contrary to our 2025 event, which exhibited a near-total drop of Π_{opt} to zero during the rotation.

5.4. Long-term Stability versus Short-term Variability

Despite the short-term variations observed in the optical band, the X-ray polarization measured in 2025 remains statistically consistent with the values reported by R. Middei et al. (2023b). Specifically, both the polarization degree (Π_X) and the polarization angle (Ψ_X) are compatible between the two epochs. This consistency, also observed in Mrk 501 (C.-T. J. Chen et al. 2024), suggesting that the X-ray emission originates from a persistent acceleration zone, likely associated with the most internal and ordered regions of the jet (e.g.,

F. Tavecchio et al. 2022). While the optical emission is susceptible to local, stochastic fluctuations, often attributed to smaller turbulent cells or transient shocks (A. P. Marscher et al. 2008; A. P. Marscher 2014), the X-ray emitting particles probe a “magnetic backbone” that may represent a large-scale, ordered magnetic field structure defining the core geometry of the inner jet.

Future monitoring with higher cadence and improved sensitivity will be crucial to disentangle the physical origin of the observed polarization variability. In particular, distinguishing between stochastic processes, such as those described within the TEMZ framework, and more deterministic scenarios involving shocks propagating through an ordered magnetic field will require the detailed temporal evolution of both the polarization degree and angle to be resolved. These scenarios are expected to produce qualitatively different signatures, such as random-walk behavior versus smooth coherent rotations.

5.5. X-Ray and Optical Polarization Properties as a Function of γ -Ray Activity

In Figure 7, we show two intervals of the Fermi-LAT light curve of PG 1553+113, with vertical lines marking the epochs of X-ray observations performed with IXPE (R. Middei et al. 2023b), including those presented in this work. Previous studies (e.g., M. Ackermann et al. 2015) have reported hints of nearly zero-lag correlations among the γ -ray, X-ray, and optical bands, together with a possible delay of ~ 200 days with respect to the radio emission, suggesting a rather coherent multiwavelength variability pattern. Although the current dataset does not allow us to establish a clear correlation between the X-ray polarization degree or EVPA swings and the long-term variability pattern, we note that all IXPE observations with a significant polarization detection (i.e., at $\geq 3\sigma$ confidence level) occurred approximately simultaneously with episodes of enhanced γ -ray activity (see Figure 7). The 2023 observation and the one in 2025 September display a comparable enhanced γ -ray flux level and strikingly similar X-ray polarization properties. On the other hand, only tentative polarization was observed during IXPE observation 1 (corresponding to a relatively low γ -ray flux state), while no clear polarization was detected in X-rays during periods of intermediate-to-high γ -ray flux (IXPE observation 2). This temporal behavior may suggest that the conditions leading to detectable X-ray polarization, such as an increased ordering of the magnetic field or enhanced particle acceleration, are more likely to be met during high γ -ray flux states.

A comparison between the γ -ray light curve and the epochs of large optical EVPA rotations (Figure 7) does not reveal a clear and unique connection between polarization swings and high-energy activity. However, this comparison has small statistics, being limited to the EVPA rotations reported in C. M. Raiteri et al. (2017), R. Middei et al. (2023b), and those identified in this work.

The observed behavior of PG 1553+113 changes with epoch. During the 2014–2015 flaring event, a large-amplitude EVPA rotation occurred, followed by enhanced γ -ray activity. Subsequently, in 2015, a smaller variation ($\Delta\Psi_{\text{opt}} \sim 60^\circ$) was detected after the main flare. Similarly, in 2023 the EVPA rotation appears to precede the increase in γ -ray flux, suggesting a possible causal link in which the physical conditions leading to the rotation may also trigger enhanced high-energy emission (see, e.g., D. Blinov et al. 2016). In

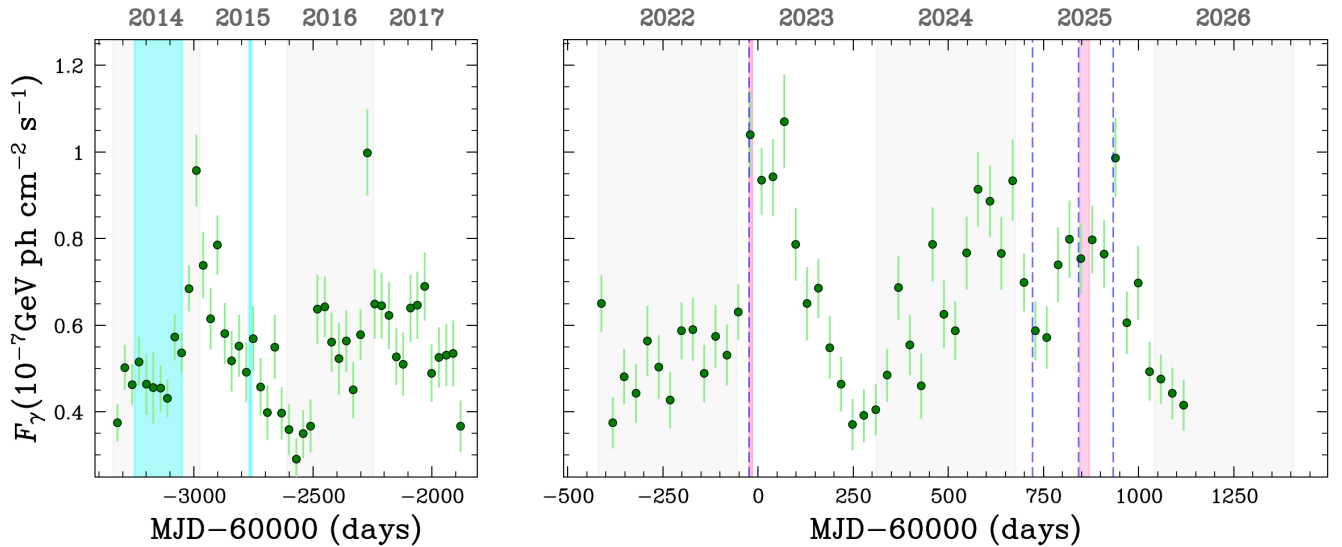


Figure 7. Selected intervals of the monthly Fermi-LAT light curve for PG 1553+113. Vertical blue dashed lines indicate the epochs of the IXPE observations, while shaded colored areas in cyan and pink highlight the EVPA swings reported in C. M. Raiteri et al. (2017) and R. Middei et al. (2023b), respectively. Light gray bands are used to mark the alternation of different years.

contrast, the 2025 rotation occurs during a relatively low γ -ray state, characterized by a possibly declining flux trend rather than a contemporaneous major flare. This is consistent with recent results on a large number of EVPA rotations in a γ -ray complete sample of blazars suggesting no correlation between rotation amplitude and γ -ray brightness (A. Glykopolou et al. 2026, in preparation). Alternatively, as discussed in S. Kiehlmann et al. (2017) and D. Blinov et al. (2018), while not all EVPA rotations can be due to random walks of the magnetic field, some of them could. In this case, the TEMZ framework (A. P. Marscher 2014) would be more consistent with our observations.

These results emphasize the need for sustained polarimetric monitoring of PG 1553+113 with IXPE, which represents a unique tool to probe the dynamical evolution of the jet magnetic field and to unveil the physical conditions underlying the connection (or lack thereof) between EVPA rotations and γ -ray activity, as well as understanding the multiwavelength quasi-periodic variations of the source brightness.

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Appendix

Swift-XRT Observations and Spectral Results

In this appendix, we report the Swift-XRT spectral fitting results (Table A1).

Table A1
Spectral Parameters and Fluxes Inferred for all the Swift-XRT Observations Analyzed in the Present Work

ObsID	Date	α	β	F_{ixpe}	F_{soft}	F_{hard}
00015387019	2025-01-11	2.38 ± 0.09	0.10 ± 0.16	1.08 ± 0.11	1.74 ± 0.06	1.19 ± 0.15
00015387020	2025-01-26	2.37 ± 0.20	-0.48 ± 0.41	1.09 ± 0.33	1.07 ± 0.08	1.32 ± 0.48
00015387021	2025-01-29	2.39 ± 0.14	0.25 ± 0.26	0.58 ± 0.10	1.06 ± 0.05	0.63 ± 0.13
00015387022	2025-02-04	2.32 ± 0.13	0.25 ± 0.23	0.47 ± 0.07	0.78 ± 0.03	0.52 ± 0.09
00015387023	2025-02-13	2.63 ± 0.21	-0.39 ± 0.42	0.55 ± 0.21	0.86 ± 0.07	0.63 ± 0.29
00015387024	2025-02-19	2.32 ± 0.24	0.23 ± 0.40	0.61 ± 0.14	1.00 ± 0.09	0.67 ± 0.19
00015387025	2025-02-22	2.31 ± 0.12	0.12 ± 0.19	0.55 ± 0.07	0.82 ± 0.03	0.61 ± 0.09
00015387026	2025-03-03	2.25 ± 0.13	0.68 ± 0.22	0.51 ± 0.07	1.05 ± 0.05	0.54 ± 0.08
00015387027	2025-03-12	2.27 ± 0.12	-0.10 ± 0.17	0.84 ± 0.09	0.99 ± 0.03	0.96 ± 0.14
00015387028	2025-03-24	2.38 ± 0.11	0.25 ± 0.20	0.65 ± 0.08	1.18 ± 0.05	0.70 ± 0.10
00015387030	2025-04-02	2.77 ± 0.80	-0.31 ± 0.63	0.62 ± 0.14	1.02 ± 0.06	0.69 ± 0.15
00098116001	2025-04-03	2.72 ± 0.14	-0.79 ± 0.22	0.99 ± 0.18	1.26 ± 0.08	1.22 ± 0.27
00015387031	2025-04-08	2.27 ± 0.17	0.07 ± 0.30	1.19 ± 0.25	1.62 ± 0.10	1.34 ± 0.36
00098116002	2025-04-10	2.61 ± 0.16	-0.50 ± 0.27	1.68 ± 0.32	2.32 ± 0.16	1.99 ± 0.48
00015387032	2025-04-11	2.20 ± 0.16	0.11 ± 0.28	1.23 ± 0.23	1.58 ± 0.09	1.37 ± 0.29
00015387033	2025-04-17	2.40 ± 0.13	-0.32 ± 0.22	1.28 ± 0.23	1.54 ± 0.07	1.50 ± 0.30
00098116003	2025-04-17	2.52 ± 0.11	-0.12 ± 0.19	1.33 ± 0.18	2.19 ± 0.09	1.49 ± 0.23
00015387034	2025-04-22	2.35 ± 0.10	-0.15 ± 0.15	1.93 ± 0.20	2.47 ± 0.09	2.21 ± 0.25
00098116004	2025-04-24	2.57 ± 0.14	-0.36 ± 0.23	1.45 ± 0.25	2.12 ± 0.12	1.68 ± 0.36
00015387035	2025-04-26	2.20 ± 0.10	0.31 ± 0.15	1.45 ± 0.14	2.16 ± 0.08	1.59 ± 0.16
00015387036	2025-05-06	2.18 ± 0.19	-0.31 ± 0.39	2.53 ± 0.83	2.23 ± 0.17	3.04 ± 1.24
00098116006	2025-05-08	2.41 ± 0.07	-0.10 ± 0.11	2.50 ± 0.18	3.58 ± 0.09	2.82 ± 0.23
00015387037	2025-05-10	2.19 ± 0.09	-0.16 ± 0.14	2.26 ± 0.20	2.30 ± 0.08	2.64 ± 0.29
00015387038	2025-05-14	2.19 ± 0.09	-0.05 ± 0.12	1.70 ± 0.13	1.89 ± 0.06	1.95 ± 0.17
00098116007	2025-05-15	2.51 ± 0.13	-0.09 ± 0.22	0.93 ± 0.14	1.55 ± 0.08	1.04 ± 0.18
00098116008	2025-05-22	2.44 ± 0.11	-0.27 ± 0.18	1.50 ± 0.19	1.99 ± 0.09	1.73 ± 0.28
00098116009	2025-05-29	2.45 ± 0.13	-0.34 ± 0.20	1.12 ± 0.15	1.41 ± 0.07	1.30 ± 0.21
00015387041	2025-06-04	2.32 ± 0.10	-0.12 ± 0.16	1.26 ± 0.15	1.59 ± 0.07	1.45 ± 0.20
00098116010	2025-06-05	2.53 ± 0.10	0.01 ± 0.17	1.16 ± 0.13	2.15 ± 0.08	1.28 ± 0.15
00098116011	2025-06-12	2.58 ± 0.16	-0.62 ± 0.27	1.40 ± 0.28	1.68 ± 0.10	1.69 ± 0.39
00098116012	2025-06-19	2.73 ± 0.16	-0.41 ± 0.31	0.57 ± 0.11	1.02 ± 0.06	0.65 ± 0.14
00098116013	2025-06-26	2.78 ± 0.17	-0.54 ± 0.37	0.85 ± 0.48	1.46 ± 0.09	0.99 ± 0.40
00019035001	2025-07-05	2.33 ± 0.08	0.02 ± 0.13	1.37 ± 0.12	1.94 ± 0.06	1.54 ± 0.17
00019035005	2025-07-06	2.21 ± 0.09	0.42 ± 0.14	1.46 ± 0.13	2.38 ± 0.07	1.58 ± 0.16
00019035006	2025-07-07	2.29 ± 0.09	0.25 ± 0.15	1.30 ± 0.12	2.09 ± 0.07	1.43 ± 0.14
00019035007	2025-07-08	2.35 ± 0.11	0.06 ± 0.19	1.32 ± 0.18	2.00 ± 0.08	1.47 ± 0.22
00019035008	2025-07-09	2.38 ± 0.10	0.11 ± 0.16	0.91 ± 0.10	1.49 ± 0.05	1.01 ± 0.12
00019035009	2025-07-10	2.40 ± 0.12	-0.01 ± 0.21	0.67 ± 0.10	1.02 ± 0.05	0.75 ± 0.13
00098116014	2025-07-10	2.69 ± 0.15	-0.29 ± 0.26	0.60 ± 0.11	1.10 ± 0.06	0.68 ± 0.15
00098116015	2025-07-24	2.74 ± 0.13	-0.67 ± 0.23	0.99 ± 0.18	1.45 ± 0.08	1.19 ± 0.27
00098116016	2025-08-07	2.75 ± 0.12	-0.52 ± 0.22	0.82 ± 0.14	1.38 ± 0.07	0.95 ± 0.17
00098116017	2025-08-21	2.68 ± 0.15	-0.52 ± 0.28	0.93 ± 0.21	1.42 ± 0.09	1.10 ± 0.32
00098116018	2025-09-04	2.43 ± 0.11	0.05 ± 0.18	1.63 ± 0.20	2.69 ± 0.11	1.81 ± 0.26
00019035010	2025-09-11	2.26 ± 0.09	0.19 ± 0.14	1.78 ± 0.16	2.62 ± 0.09	1.97 ± 0.21
00019035011	2025-09-12	2.26 ± 0.07	0.25 ± 0.16	1.57 ± 0.16	2.42 ± 0.08	1.72 ± 0.21
00019035012	2025-09-13	2.30 ± 0.08	0.10 ± 0.14	1.47 ± 0.14	2.13 ± 0.07	1.64 ± 0.17
00019035013	2025-09-14	2.25 ± 0.09	0.13 ± 0.14	1.47 ± 0.14	2.05 ± 0.07	1.63 ± 0.18
00019035014	2025-09-15	2.25 ± 0.10	0.22 ± 0.16	1.79 ± 0.20	2.67 ± 0.10	1.97 ± 0.25

Note. Fluxes are reported in units of $10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}$.

ORCID iDs

Riccardo Middei  <https://orcid.org/0000-0001-9815-9092>
 Svetlana G. Jorstad  <https://orcid.org/0000-0001-6158-1708>
 Alan P. Marscher  <https://orcid.org/0000-0001-7396-3332>
 Ioannis Liodakis  <https://orcid.org/0000-0001-9200-4006>
 Matteo Perri  <https://orcid.org/0000-0003-3613-4409>
 Alessandro Maselli  <https://orcid.org/0000-0003-3760-1910>
 Stefano Ciprini  <https://orcid.org/0000-0002-0712-2479>
 Emanuele Nardini  <https://orcid.org/0000-0001-9226-8992>
 Simonetta Puccetti  <https://orcid.org/0000-0002-2734-7835>
 Laura Di Gesu  <https://orcid.org/0000-0002-5614-5028>
 Iván Agudo  <https://orcid.org/0000-0002-3777-6182>

Dawoon E. Kim  <https://orcid.org/0000-0001-5717-3736>
 Ioannis Myserlis  <https://orcid.org/0000-0003-3025-9497>
 A. Trindade Falcão  <https://orcid.org/0000-0001-8112-3464>
 D. Ł. Król  <https://orcid.org/0000-0002-3626-5831>
 Lucio A. Antonelli  <https://orcid.org/0000-0002-5037-9034>
 Pouya M. Kouch  <https://orcid.org/0000-0002-9328-2750>
 Kari Nilsson  <https://orcid.org/0000-0002-1445-8683>
 Elina Lindfors  <https://orcid.org/0000-0002-9155-6199>
 Tapio Pursimo  <https://orcid.org/0000-0002-5578-9219>
 Víctor Casanova  <https://orcid.org/0000-0003-2036-8999>
 Gabriel Emery  <https://orcid.org/0000-0001-6155-4742>

Juan Escudero Pedrosa  <https://orcid.org/0000-0002-4131-655X>
 Jorge Otero-Santos  <https://orcid.org/0000-0002-4241-5875>
 Vilppu Piirola  <https://orcid.org/0000-0003-0186-206X>
 George A. Borman  <https://orcid.org/0000-0002-7262-6710>
 Tatiana S. Grishina  <https://orcid.org/0000-0002-3953-6676>
 Vladimir A. Hagen-Thorn  <https://orcid.org/0000-0002-6431-8590>
 Evgenia N. Kopatskaya  <https://orcid.org/0000-0001-9518-337X>
 Elena G. Larionova  <https://orcid.org/0000-0002-2471-6500>
 Daria A. Morozova  <https://orcid.org/0000-0002-9407-7804>
 Sergey S. Savchenko  <https://orcid.org/0000-0003-4147-3851>
 Ekaterina V. Shishkina  <https://orcid.org/0009-0002-2440-2947>
 Ivan S. Troitskiy  <https://orcid.org/0000-0002-4218-0148>
 Yulia V. Troitskaya  <https://orcid.org/0000-0002-9907-9876>
 Andrey A. Vasilyev  <https://orcid.org/0000-0002-8293-0214>
 Lena Debbrecht  <https://orcid.org/0009-0003-8342-4561>
 Florian Eppel  <https://orcid.org/0000-0001-7112-9942>
 Andrea Gokus  <https://orcid.org/0000-0002-5726-5216>
 Jonas Hessdörfer  <https://orcid.org/0009-0009-7841-1065>
 Matthias Kadler  <https://orcid.org/0000-0001-5606-6154>
 Georgios F. Paraschos  <https://orcid.org/0000-0001-6757-3098>
 Mark Gurwell  <https://orcid.org/0000-0003-0685-3621>
 Garrett Keating  <https://orcid.org/0000-0002-3490-146X>
 Ramprasad Rao  <https://orcid.org/0000-0002-1407-7944>
 Emmanouil Angelakis  <https://orcid.org/0000-0001-7327-5441>
 Alexander Kraus  <https://orcid.org/0000-0002-4184-9372>
 Beatriz Agís-González  <https://orcid.org/0000-0001-7702-8931>
 Sara Capecchiacci  <https://orcid.org/0009-0007-1918-577X>
 Alberto Floris  <https://orcid.org/0009-0004-1671-5454>
 Dimitrios A. Langis  <https://orcid.org/0009-0003-9365-9073>
 Aristeidis Polychronakis  <https://orcid.org/0009-0005-7962-6296>
 Ryo Imazawa  <https://orcid.org/0000-0002-0643-7946>
 Mahito Sasada  <https://orcid.org/0000-0001-5946-9960>
 Yasushi Fukazawa  <https://orcid.org/0000-0002-0921-8837>
 Koji S. Kawabata  <https://orcid.org/0000-0001-6099-9539>
 Makoto Uemura  <https://orcid.org/0000-0002-7375-7405>
 Tsunefumi Mizuno  <https://orcid.org/0000-0001-7263-0296>
 Hiroshi Akitaya  <https://orcid.org/0000-0001-6156-238X>

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