

Broad-band temporal and spectral study of TeV blazar TXS 0518+211

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ABSTRACT

We present a long-term broad-band temporal and spectral study of a TeV BL Lac source TXS 0518+211 by analyzing nearly 16 years (MJD 54682 – 60670) of simultaneous optical, UV and X-ray light curves from Swift-XRT/UVOT and gamma-ray light curves from Fermi-LAT. Based on the availability of simultaneous multi-wavelength data and considering flux level as the depiction of AGN-jet activity we identified 11 epochs (named as Epoch-A to Epoch-K) and investigated temporal as well as spectral variability during these epochs to understand the emission properties in this source. The fractional variability analysis reveals that, in all epochs, X-ray light curve exhibits relatively high degree of variability in compared to the optical, UV and gamma-ray light curves. The flux-flux plots among different bands, in general, show weak to moderate correlation with Spearman correlation coefficient ranging from 0.29 to 0.58. Notably, during Epoch-I, we detect a possible orphan flare exhibiting increase in the X-ray flux level (~ 2.4 times of the total average flux) but with no corresponding counterpart seen in the optical, UV bands. In contrast, during Epoch-K, we detect a significant decrease in the X-ray flux but no corresponding decrease in optical, UV and gamma-ray bands. Overall, our study reveals several changes in the flux states and complex nature of jet dominated emission processes. In all the epochs, two-zone leptonic model provides a better description of the broad-band emission in this TeV BL Lac source.

Keywords: Active galactic nuclei (16) — Blazars (164) — Supermassive black holes (1663) — Gamma-rays (637)

1. INTRODUCTION

Blazars are the most luminous and extreme subclass of active galactic nuclei (AGNs). They are accepted to harbor highly collimated relativistic jets aligned closely to the line-of-sight of observers (C. M. Urry & P. Padovani 1995), leading to a Doppler beaming of their emission, thereby enhancing apparent changes in observed spectral and temporal behaviour. Emission in these sources is dominated by non-thermal continuum originating predominantly within the jet and characterized by rapid variability, with time scales ranging from a few minutes to years across the entire accessible electromagnetic (EM) spectrum (R. Blandford et al.

2019). Their continuum emission exhibits a characteristic broad double-hump spectral energy distribution (SED): the “low-energy hump” extends from radio up to X-rays, and the “high-energy hump” extends from X-ray to GeV-TeV gamma-ray. The “low-energy hump” is widely accepted to be predominantly synchrotron emission from relativistic electrons in the jet. This is evident by the polarization fraction variability observed in the radio and optical bands (e.g., F. D. D’arcangelo et al. 2009). Conversely, origin of high-energy hump in blazars SEDs is still a subject of debate within the blazar community and can be explained by leptonic and/or hadronic emission models. In the leptonic scenario, this hump is attributed to the inverse Compton (IC) scattering of photons originated from the synchrotron emission within the jet itself (known as synchrotron self-Compton or SSC), and/or external to the emission region (i.e.,

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external Compton or EC) such as the accretion disk, broad-line region (BLR), dusty torus (DT). On the other hand, the hadronic origin of emission processes involves phenomena such as proton synchrotron emission (A. Mücke & R. J. Protheroe 2001) and/or photo-hadronic interactions (K. Mannheim & P. L. Biermann 1992; W. Bednarek & R. J. Protheroe 1999). The latter can lead to the production of high-energy photons from π^0 decay and synchrotron emission of charged pions/secondary leptons, which can initiate cascades through γ - γ pair productions, i.e., synchrotron-supported pair cascades (M. Böttcher et al. 2013).

Traditionally, depending on the strength of optical emission lines (M. Stickel et al. 1991), blazars have been categorized into two sub-classes: Flat spectrum radio quasars (FSRQs) with broad strong emission lines ($EW > 5\text{\AA}$) and BL Lacertae (BL Lacs) objects with weak or no emission lines ($EW < 5\text{\AA}$). In the extended SED-based classification scheme (refer to A. A. Abdo et al. 2010, for details), all non-thermal radiation domination or jet-dominated AGNs have been categorized into three sub-classes based on the peak frequency (ν_{peak}) of the synchrotron emission: Low-synchrotron-peaked (LSP; $\nu_{peak} \leq 10^{14}$ Hz), Intermediate-synchrotron-peaked (ISP; $10^{14} \leq \nu_{peak} \leq 10^{15}$ Hz), and High-synchrotron-peaked (HSP; $\nu_{peak} \geq 10^{15}$ Hz) sources. Almost all the known FSRQ-type blazars belong to the LSP subclass. On the other hand, BL Lacs can be found in all three sub-classes, also known as LBL, IBL, and HBL. A remarkable property of a particular spectral subclass is the stability of the location of the peaks (i.e., ν_{peak} and high-energy peak) despite significant flux variations, except for a few special cases where shift has been observed for either (e.g., December 2015 - May 2016 activity of OJ 287; P. Kushwaha et al. 2018) or both (e.g., June 2012 outburst of Mrk 501; M. L. Ahnen et al. 2018) of the peaks. Such a shift or change in the broadband SED provides valuable insights about the high-energy emission mechanism. A shift in the location of both peaks may imply that the same particle distribution contributes to the overall emission, whereas a shift only in the high-energy peak can be explained by the external Compton emission (where seed photons originating from the BLR, (P. Kushwaha et al. 2018)), emission from different regions (N. Sahakyan & P. Giommi 2022), or hadronic processes (F. Oikonomou et al. 2019). There is a growing evidence in the literature which suggests that several TeV-detected BL Lac objects are classified as IBLs during low-flux states but as HBLs during high-flux states, e.g., PKS 1424+240 (S. Archambault et al. 2014; J. Aleksić et al. 2014),

S2 0109+22 (MAGIC Collaboration et al. 2018), 1ES 1011+496 (M. L. Ahnen et al. 2016), PKS 0301-243 (H. E. S. S. Collaboration et al. 2013). Correlation studies across multi-wavelength regime are crucial for understanding such emission properties.

In general, the broadband SEDs of IBL- and HBL-type BL Lac objects can be explained by sum of a synchrotron component and an associated SSC component under leptonic scenario. However, there are several sources where occasionally peculiar behaviors have been observed in their multi-wavelength light curves and SEDs such as the observation of orphan flares across different wavebands (B. Rani et al. 2013; R. Chatterjee et al. 2013; M. Hayashida et al. 2015), and/or plateaus in the low-energy gamma-ray SED (S. R. Patel et al. 2018; A. Shukla et al. 2015), which cannot be explained by the simple one-zone leptonic model. In some cases during such exceptional behaviour, a significant shift in the location of the synchrotron peak (ν_{peak}) and/or the high-energy peak has been observed (e.g., M. Liu et al. (2025)). Therefore, to provide a comprehensive explanation, more complex emission models are required. The availability of both multi-wavelength temporal and spectral data are essential for gaining insight into the physical processes occurring in the emission regions.

TXS 0518+211 is an IBL-type blazar located at R.A. = 05h21m45.9658s, Dec. = +21d12m51.451s (M. S. Shaw et al. 2013). The redshift (z) of this source is still uncertain. However, in earlier studies, a lower limit of $z=0.18$ (S. Paiano et al. 2017) and an upper limit of $z=0.34$ (S. Archambault et al. 2013) have been reported. A recent study by MAGIC Collaboration et al. (2025) reported an improved statistical upper limit of $z \leq 0.244$ at the 95% confidence level using simultaneous high-energy and very-high-energy (VHE) observations. This source was first identified as a VHE ($E > 100$ GeV) gamma-ray emitter (also known as VER J0521+211) in October 2009 by the VERITAS collaboration (R. A. Ong 2009). It has also been continuously monitored by Fermi-LAT (Large Area Telescope) since August 2008, and the first gamma-ray outburst ($E > 100$ MeV) was reported on October 14, 2013, with a daily averaged flux of $(1.0 \pm 0.3) \times 10^{-6}$ ph cm $^{-2}$ s $^{-1}$ (S. Buson 2013). Following the report of this gamma-ray outburst, near-infrared (NIR) photometry in the J band was carried out, which revealed correlated flux variability (L. Carasco et al. 2013). However, recently, on February 25, 2020, the VERITAS collaboration (J. Quinn & VERITAS Collaboration 2020) reported an observation of simultaneous flares in the VHE and X-ray (0.3 to 10.0

keV) bands, with no flaring signature in the optical band (R. Bachev 2020). The observations of these exceptional variability signatures in this source motivates us to perform a long-term comprehensive study of both temporal and spectral behavior.

In this paper, we have focused on the study of TeV BL Lac TXS 0518+211 using optical, X-ray, and gamma-ray data collected over a period of ~ 16 years. Analysis methods of optical to high-energy gamma-ray data have been described in section §2. The identification of different epochs using long-term multi-band light curves and temporal study in these epochs are described in section §3. The broad-band spectral properties and SEDs modeling are presented in section §4. The detailed discussions and conclusions are provided in section §5 and section §6, respectively.

2. MULTI-WAVELENGTH OBSERVATION AND DATA ANALYSIS

2.1. Simultaneous optical, UV, and X-ray observations from Swift observatory

We utilized simultaneous optical, UV, and X-ray observations from the Neil Gehrels Swift Observatory⁵ (Swift, hereafter). The Swift, a multi-wavelength space-based observatory, comprises of three primary instruments: UV/Optical telescope (UVOT) with wavelength coverage of 170 - 600 nm, X-ray telescope (XRT) sensitive in 0.3 - 10 keV band, and Burst alert telescope (BAT) operating in hard X-ray energy band of 15 - 150 keV. In this work, we analyzed Swift-UVOT and -XRT data of TXS 0518+211 collected over a period of approximately 15 years (MJD 55131 - 60670) to perform the temporal and spectral study. A total of 131 observations were available during this time period.

2.1.1. The Swift-UVOT data analysis

We analyzed all the image mode Optical-UV data from Swift-UVOT (P. W. A. Roming et al. 2005) available in six filters: *V* (546.8 nm), *B* (439.2 nm), *U* (346.5 nm), *UVW1* (260.0 nm), *UVM2* (224.6 nm), and *UVW2* (192.8 nm). The source and background regions are chosen as circles with radii of 5'' (centered on to the sources) and 10'' (in a nearby source free region), respectively. The 'uvotsource' task is used to compute the magnitudes in all filters. The magnitude is further corrected for galactic extinction using a reddening $E(B-V) = 0.5875$ as reported in E. F. Schlafly & D. P. Finkbeiner 2011. Finally, reddening corrected magnitude is converted into flux using the zero points (A. A. Breeveld

et al. 2011) and appropriate conversion factors (T. S. Poole et al. 2007). The task 'uvotimsum' is used to aggregate multiple observation IDs.

2.1.2. The Swift-XRT data analysis

We used Swift-XRT data taken only in photon counting (PC) and windowed timing (WT) mode. The xrtpipeline (version: 0.13.7) is used to perform the XRT data reduction of each set of observations. The source spectra are extracted from a circular region of 47'' radius centered on to the source, while background spectra are extracted from an annular region with inner and outer radii of 80'' and 180'', respectively, in a source free region. For pile-up correction, we followed recommended steps⁶ that include discarding 2-3 pixels from the central region of the source whenever the source count rate exceeds $0.5 \text{ count sec}^{-1}$ in PC mode or $100 \text{ counts sec}^{-1}$ in WT mode. Subsequently, we employed xrtmkarf and grppha tasks to create the corresponding ancillary response files, and to group the source spectrum with 20 counts per bin, respectively. In a few data sets, we encountered low photon counts and, in such cases, we grouped their spectra with one count per bin and employed the Cash statistic. Finally, these grouped spectra were loaded into XSPEC (version: 12.12.1) to perform the spectral fitting using two models: power law and logparabola. The relatively complex model logparabola is used to achieve the best fit if the F -test probability is ≤ 0.05 . During the spectral fitting we kept all the parameters of the models including N_H as free. However, if the fitted N_H value is found less than or inconsistent with the the Galactic column density value, we fixed it to the Galactic value ($4.38 \times 10^{21} \text{ cm}^{-2}$; P. M. W. Kalberla et al. (2005)) in the direction of source. To add more than one obs-IDs we used addspec task.

2.2. Fermi-Large Area Telescope (LAT)

Fermi-LAT is a gamma-ray (20 MeV to 300 GeV) imaging pair-conversion telescope that scans the entire sky in every two orbits with an orbital period of ~ 96 minutes. It has a peak effective area of nearly 8000 cm^2 . The detailed characteristics and specifications of the LAT are provided on the Fermi-LAT website⁷.

We used the weekly binned light curve of this source (catalog name: 4FGL J0521.7+2112) from the Fermi-LAT Light Curve Repository (LCR)⁸ for the temporal

⁵ https://swift.gsfc.nasa.gov/about_swift/

⁶ <https://www.swift.ac.uk/analysis/xrt/pileup.php>

⁷ <https://fermi.gsfc.nasa.gov/science/instruments/table1-1.html>

⁸ <https://fermi.gsfc.nasa.gov/ssc/data/access/lat/LightCurveRepository/>

study (S. Abdollahi et al. 2023). To analyze the gamma-ray SED for different time durations, we utilized the Fermi Science tools⁹ of version 2.2.0 and followed the standard analysis procedures provided therein. For our analysis we opted the recommended `evclass=128` and `evtype=3`, an energy cut ranging from 0.1 to 300 GeV and a zenith angle cut of 90° . The galactic emission model (`gll_iem_v07.fits`) and isotropic emission model (`iso_P8R3_SOURCE_V3_v1.tx`) are used as diffuse background models. The latest 4FGL DR3 catalog is used to create the model XML file. We used unbinned likelihood analysis method for the analysis of LAT data. We note that two extended sources are detected at $\sim 7^\circ$ (S 147) and $\sim 12^\circ$ (IC 443) away from the center of the region of interest (ROI). During the spectral fitting, we kept free all parameters of the model components within the ROI, as well as those of the two extended and diffuse background sources. We also chose a 10° additional patch around the ROI to account for the contribution of other sources in the analysis but kept all parameters within this region frozen during the spectral fitting procedure.

3. TEMPORAL STUDY

In this section we present long-term (16 years; MJD 54682 – 60670) temporal study of TXS 0518+211 in optical, UV, X-ray and gamma-ray bands.

3.1. Optical, UV, X-ray, Gamma-ray light curves and spectral indices

Based on the availability of simultaneous optical, UV, and X-ray observations, we divided the multi-wavelength light curve into 11 different epochs, labeled alphabetically from Epoch-A to Epoch-K, and displayed as grey shaded regions in Figure-1. We applied the Bayesian block method¹⁰ (J. D. Scargle et al. 2013) to the long-term X-ray light curve (which exhibits higher variability compared to optical/UV and gamma-ray light curves) and verified that the flux level within each epoch was nearly the same. The first four panels (from top to bottom) in Figure-1 represent the optical (V , B , U band fluxes plotted with different colors in the same panel), UV ($UVW1$, $UVM2$, $UVW2$ band fluxes plotted with different colors in the same panel), X-ray ($F_{0.3-10}$ keV), and gamma-ray (F_{20} MeV–300 GeV) bands light curves. The last three panels represent optical-UV (Γ_{UVOT}), X-ray (Γ_X) and gamma-ray (Γ_γ) spec-

tral indices across time. To derive Γ_{UVOT} we fitted a power law to the joint optical-UV spectrum for each observation-ID. We employed this procedure only when there are at least three data points available for a given observation-ID. We also corrected optical UV fluxes for extinction by using $E(V-B) = 0.5875$ following E. F. Schlafly & D. P. Finkbeiner (2011). We notice that D. J. Schlegel et al. (1998) claimed $E(V-B) = 0.703$, a value nearly 16% higher than the recent one. The discrepancy in reddening value can affect the extinction correction and consequently the derived fluxes from the magnitudes, specifically in the $M2$ and $W2$ band of UV filter by $\gtrsim 60\%$. Therefore, we also computed Γ_{UVOT} using the same procedure as before, but excluding $M2$ and $W2$ bands. However, we found that this exclusion did not significantly change the indices as shown (by the open black square symbols) in Figure-1. We derived Γ_X/α_X by fitting the X-ray spectra with a power law/logparabola model (see section 2.1.2). The Γ_γ are obtained from the Fermi-LAT Light Curve Repository (LCR).

The average flux in all the bands during all the epochs is given Table-1. We note that Epoch-K represents the lowest X-ray flux epoch among eleven epochs (Average X-ray flux of 0.43 ± 0.08). The gamma-ray flux in this epoch (average γ -ray flux of 0.10 ± 0.01) is similar to the average flux of the entire light curve. In optical-UV band, flux is low (i.e., below the average flux value of a particular band), but it does not correspond to the lowest flux value. Among all the Epochs, X-ray flux is highest during Epoch-I but optical-UV fluxes are very low i.e., even lower than the optical-UV flux level of Epoch-K, the low flux state. Our analysis of light curves find the detection of a possible orphan X-ray flare during Epoch-I. We note that, during Epoch-I, the average X-ray flux of 7.78 ± 1.13 , approximately two times higher than the overall average flux of 4.74 ± 0.55 . In the optical bands (V , B , U), UV ($W1$, $W2$), and gamma-ray bands, the average fluxes are 1.85 ± 0.12 , 1.85 ± 0.15 , 1.78 ± 0.07 , 1.71 ± 0.18 , 1.52 ± 0.16 , and 0.15 ± 0.02 , respectively. These values are either lower or similar to the overall average flux for their respective bands, and hence Epoch-I can be considered as a unique flux state, i.e., orphan X-ray flare (also reported in MAGIC Collaboration et al. (2025)). In contrast, during Epoch-C, we observe simultaneous activity of the source in all three bands, with flux levels about $\sim 1.5 - 2.0$ times higher than the overall average flux in each band. During Epoch-K, the optical/UV and gamma-ray light curves remained close to the overall average flux level (see Table-1), whereas the X-ray light curve showed a significant decrease. The average X-ray

⁹ https://fermi.gsfc.nasa.gov/ssc/data/analysis/scitools/python_tutorial.html

¹⁰ https://docs.astropy.org/en/stable/api/astropy.stats.bayesian_blocks.html

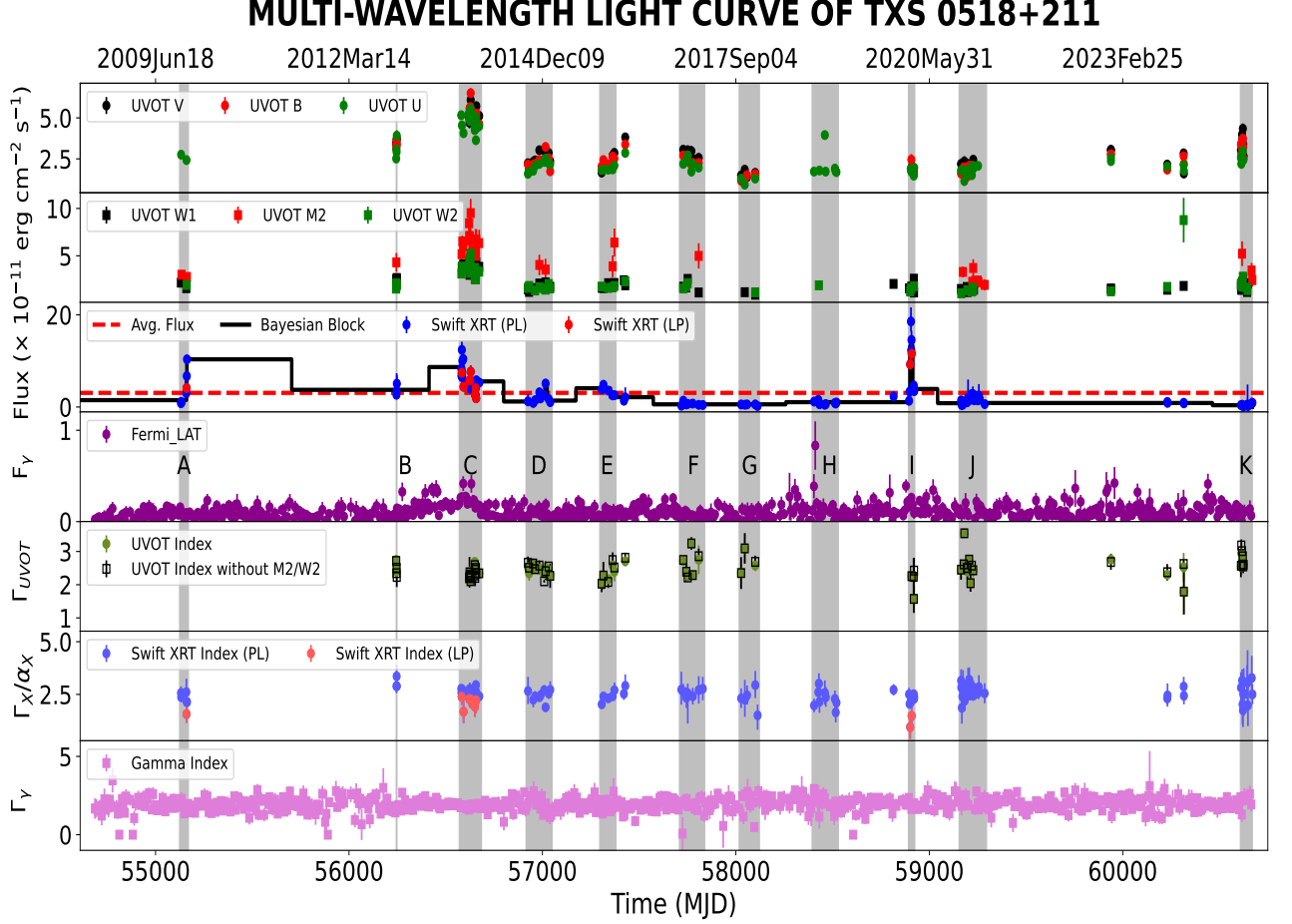


Figure 1. Multi-wavelength light curve of TXS 0518+211 during MJD 54682 – 60148. The eleven different epochs (Epoch-A to Epoch-K) identified based on the availability of simultaneous data across all bands are shown by grey shaded vertical strips. The first four panels from top to bottom represent optical (V , B , U band fluxes plotted with different colours in the same panel), UV ($UVW1$, $UVW2$, $UVW2$ band fluxes plotted with different colours in the same panel), X-ray, and gamma-ray light curves. The last three panels from top to bottom represent optical-UV photon index (Γ_{UVOT}), X-ray photon (Γ_X), and gamma-ray photon index (Γ_γ). The optical/UV, X-ray, and gamma-ray fluxes are in the unit of $10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}$, $10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}$, and $10^{-6} \text{ ph cm}^{-2} \text{ s}^{-1}$, respectively

flux during this time period is 0.43 ± 0.08 (average flux of the entire X-ray light curve is 3.27 ± 0.33). To the best of our knowledge, this is the first time such a flux state in this source is detected.

3.2. Fractional variability

To characterize the long-term variability in the light curve of each band, we used the well-known fractional variability amplitude. It is defined (S. Vaughan et al. 2003) as follows:

$$F_{var} = \sqrt{\frac{S^2 - \sigma_{err}^2}{F^2}} \quad (1)$$

where, S^2 , σ_{err}^2 , and F are the variance, mean square error ($\frac{1}{N} \sum_{i=1}^N \sigma_{err,i}^2$), and mean flux of the light curve segment, respectively. The uncertainty associated with the fractional variability is given by:

$$\Delta F_{var} = \sqrt{\left(\frac{1}{\sqrt{2N}} \frac{\sigma_{err}^2}{F^2 F_{var}} \right)^2 + \left(\frac{\sigma_{err}^2}{N} \frac{1}{F} \right)^2} \quad (2)$$

It is noted that when the signal-to-noise ratio is low or intrinsic variability is weak, then $S^2 \lesssim \sigma_{err}^2$, implying weak detection of variability. The values of fractional variability amplitudes (F_{var}), normalized excess variance (σ_{NXS}^2) estimated for multi-wavelength light curves in different epochs are given in Table-1. To com-

Table 1. The variability parameters

Waveband	Activity Epochs	F_{var}	σ_{NXS}^2	Average flux	χ_{red}^2 (df)	t_{var}
(1)	(2)	(3)	(4)	(5)	(6)	(7)
UVOT-V (Optical)	Epoch-B	-	-0.003	3.55±0.08	0.51(3)	21.72
	Epoch-C	0.04±0.02	0.001±0.001	5.28±0.08	1.47(16)	6.40
	Epoch-D	0.11±0.04	0.012±0.01	2.50±0.12	2.54(8)	38.11
	Epoch-E	0.21±0.05	0.04±0.02	2.24±0.23	6.28(3)	69.89
	Epoch-F	0.05±0.07	0.002±0.006	2.75±0.12	1.34(5)	31.79
	Epoch-G	-	-0.003	1.59±0.10	0.81(3)	38.79
	Epoch-I	-	-0.01	1.85±0.12	0.63(2)	5.44
	Epoch-J	-	-0.002	2.13±0.08	1.04(7)	21.75
	Epoch-K	0.16±0.04	0.02±0.01	3.52±0.25	5.06(5)	8.08
	Full LC	0.41±0.01	0.16±0.01	3.25±0.16	27.13(67)	1.80
UVOT-B (Optical)	Epoch-B	0.013±0.12	0.0002±0.003	3.39±0.11	1.47(3)	9.88
	Epoch-C	0.07±0.01	0.004±0.002	5.24±0.11	2.52(16)	4.74
	Epoch-D	0.16±0.03	0.02±0.01	2.30±0.14	3.66(8)	21.44
	Epoch-E	0.05±0.07	0.03±0.01	2.36±0.11	1.82(3)	51.56
	Epoch-F	0.06±0.06	0.003±0.007	2.46±0.11	1.33(5)	79.72
	Epoch-G	0.03±0.23	0.001±0.01	1.38±0.10	1.05(3)	63.09
	Epoch-I	0.12±0.08	0.01±0.02	1.85±0.15	1.61(4)	3.13
	Epoch-J	0.03±0.12	0.001±0.008	1.85±0.08	1.20(8)	13.09
	Epoch-K	0.10±0.03	0.01±0.001	3.23±0.15	2.96(7)	5.19
	Full LC	0.44±0.01	0.19±0.01	3.05±0.16	32.49(72)	3.13
UVOT-U (Optical)	Epoch-A	0.09±0.02	0.01±0.003	2.59±0.17	8.44(1)	217.45
	Epoch-B	0.17±0.04	0.03±0.01	3.11±0.29	6.39(3)	3.42
	Epoch-C	0.09±0.01	0.01±0.002	4.81±0.11	5.07(19)	5.73
	Epoch-D	0.10±0.05	0.01±0.009	2.06±0.10	1.90(8)	64.00
	Epoch-E	-	-0.01	1.89±0.05	0.34(3)	75.26
	Epoch-F	0.10±0.06	0.01±0.01	2.19±0.14	1.57(5)	29.37
	Epoch-G	0.04±0.34	0.001±0.03	1.17±0.12	1.10(2)	57.83
	Epoch-H	0.04±0.02	0.002±0.002	1.73±0.04	2.05(6)	36.23
	Epoch-I	-	-0.01	1.78±0.07	0.86(5)	3.64
	Epoch-J	0.07±0.05	0.005±0.008	1.76±0.07	2.81(12)	6.63
	Epoch-K	0.04±0.08	0.002±0.007	2.59±0.11	1.12(6)	5.73
	Full LC	0.46±0.01	0.21±0.01	2.71±0.13	38.22(87)	3.42
UVOT-W1 (UV)	Epoch-A	0.20±0.06	0.04±0.03	1.88±0.29	6.54(1)	90.14
	Epoch-B	-	-0.002	2.42±0.16	1.88(3)	3.77
	Epoch-C	0.07±0.03	0.005±0.005	4.09±0.12	1.49(16)	2.56
	Epoch-D	0.08±0.13	0.006±0.02	1.69±0.12	1.23(7)	29.7
	Epoch-E	-	-0.01	1.83±0.12	0.81(3)	28.29
	Epoch-F	0.27±0.11	0.08±0.06	2.97±0.30	2.23(3)	16.42
	Epoch-G	-	-0.06	1.03±0.13	0.38(1)	210.55
	Epoch-I	0.20±0.12	0.04±0.04	1.66±0.21	1.98(5)	1.27
	Epoch-J	-	-0.03	1.47±0.07	0.52(9)	8.04
	Epoch-K	0.14±0.08	0.02±0.02	1.90±0.14	4.05(8)	4.60
	Full LC	0.45±0.02	0.20±0.02	2.29±0.12	10.88(73)	1.27
UVOT-M2 (UV)	Epoch-A	-	-0.02	2.89±0.12	0.14(1)	337.98
	Epoch-C	-	-0.002	6.57±0.30	1.18(15)	2.62
	Epoch-D	-	-0.08	3.79±0.24	0.10(1)	248.51
	Epoch-E	0.23±0.23	0.05±0.11	5.15±1.25	-	18.47
	Epoch-J	0.10±0.21	0.01±0.04	2.64±0.29	1.03(5)	10.26
	Epoch-K	0.28±0.18	0.08±0.10	3.70±0.82	2.52(2)	11.55
	Full LC	0.35±0.04	0.12±0.03	4.90±0.34	7.78(33)	2.62
UVOT-W2 (UV)	Epoch-B	-	-0.02	1.87±0.12	0.89(3)	3.22
	Epoch-C	0.15±0.03	0.02±0.009	3.59±0.16	2.59(18)	2.62
	Epoch-D	-	-0.04	1.63±0.08	0.32(7)	30.13
	Epoch-E	-	-0.06	1.71±0.04	0.07(2)	108.64
	Epoch-F	-	-0.04	1.81±0.16	0.39(2)	42.32
	Epoch-I	-	-0.01	1.52±0.16	0.89(2)	18.17
	Epoch-J	-	-0.03	1.32±0.10	0.79(4)	9.90
	Epoch-K	-	-0.004	1.95±0.17	1.45(6)	4.26
	Full LC	0.50±0.03	0.25±0.03	2.41±0.17	7.34(59)	2.62

Table 1. Continued.

Waveband	Activity Epochs	F_{var}	σ_{NXS}^2	Average flux	χ_{red}^2 (df)	t_{var}
(1)	(2)	(3)	(4)	(5)	(6)	(7)
Swift-XRT (X-ray)	Epoch-A	0.96±0.04	0.92±0.08	4.02±1.58	202.45(5)	2.07
	Epoch-B	0.15±0.67	0.02±0.19	3.86±1.21	0.60(1)	3.21
	Epoch-C	0.37±0.05	0.13±0.03	5.79±0.48	8.34(26)	0.99
	Epoch-D	0.59±0.06	0.35±0.08	2.24±0.49	12.54(7)	10.58
	Epoch-E	0.23±0.07	0.05±0.03	3.46±0.50	3.19(2)	38.60
	Epoch-F	0.36±0.07	0.13±0.05	3.11±0.50	8.39(5)	19.26
	Epoch-G	-	-0.22	0.47±0.07	1.46(4)	13.06
	Epoch-H	0.17±0.19	0.03±0.06	0.88±0.11	1.09(8)	5.44
	Epoch-I	0.71±0.07	0.50±0.09	7.78±1.73	83.75(10)	2.96
	Epoch-J	0.29±0.13	0.08±0.08	1.53±0.18	5.13(18)	1.28
	Epoch-K	-	-0.20	0.43±0.08	0.91(7)	3.21
	Full LC	1.10±0.03	1.02±0.05	3.27±0.33	72.82(109)	0.99
Fermi-LAT (Gamma-ray)	Epoch-A	-	-0.09	0.09±0.01	1.42(6)	7.86
	Epoch-C	0.26±0.07	0.07±0.04	0.23±0.02	3.07(16)	10.30
	Epoch-D	-	-0.02	0.09±0.01	8.63(17)	4.70
	Epoch-E	-	-0.04	0.08±0.01	2.74(9)	5.50
	Epoch-F	-	-0.17	0.08±0.01	3.65(12)	8.70
	Epoch-G	-	-0.03	0.09±0.01	60.52(17)	3.80
	Epoch-H	0.89±0.15	0.79±0.26	0.20±0.06	3.71(12)	5.70
	Epoch-I	0.11±0.31	0.003±0.07	0.18±0.03	1.31(4)	6.69
	Epoch-J	-	-0.09	0.12±0.01	1.17(12)	4.76
	Epoch-K	-	-0.49	0.10±0.01	0.16(3)	3.21
	Full LC	0.45±0.03	0.20±0.02	0.11±0.01	14.77(674)	3.71

Notes. Column 1 : Instrument/filter; Column 2 : Epoch; Column 3 : Fractional variability parameter (F_{var}); Column 4 : Normalized excess variance (σ_{NXS}^2); Column 5 : Average flux in the units of 10^{-11} erg cm $^{-2}$ s $^{-1}$; Column 6 : Reduced chi-square values (χ_{red}^2) of the fit obtained with a constant value and degree of freedom written within brackets; Column 7 : variability time-scale (t_{var}) in days units.

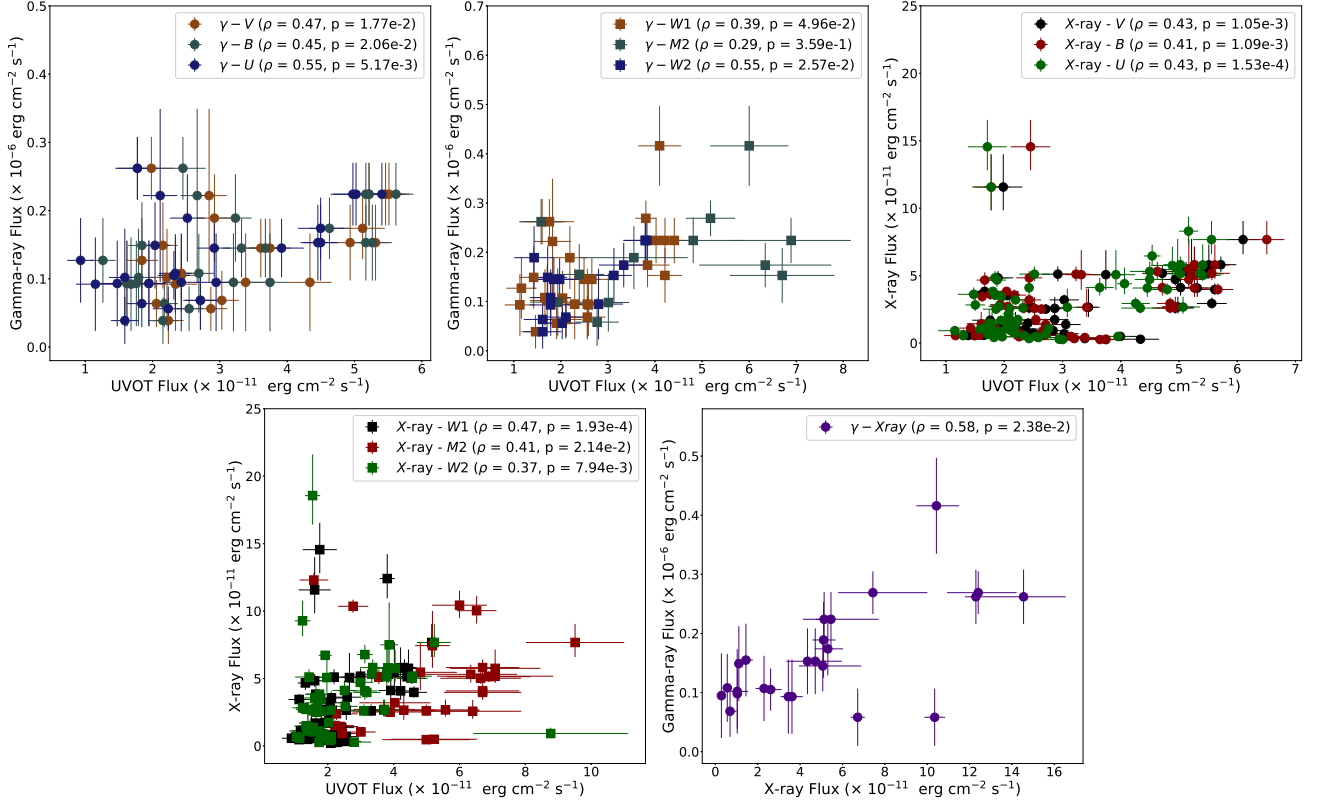


Figure 2. Flux-flux correlation plots.

pute the fractional variability error (ΔF_{var}) in the X-ray band, where uncertainty on the flux is asymmetric, we used larger error value for each data point. Also, during a few epochs we lack some data points. For instance *V* band optical data are missing in Epoch-A.

We found that the X-ray flux variability across different epochs is relatively higher compared to that of the optical and gamma-ray bands, as indicated by the fractional variability analysis (see Table 1). More detailed results of the fractional variability study are discussed in Section 5.1.

3.3. Variability timescales

To characterize the fastest timescale of variability, we computed the ‘doubling time’ using the procedure given in Y. H. Zhang et al. (1999). It is defined by:

$$\tau_{ij} = \left| \frac{F \Delta t_{ij}}{\Delta F_{ij}} \right| \quad (3)$$

where, $\Delta t_{ij} = t_j - t_i$, $\Delta F_{ij} = F_j - F_i$, and $F = \frac{F_j + F_i}{2}$. F_i and F_j are the flux values at time t_i and t_j , respectively. Using equation 3, the timescales for all pairs of two data points in a given light curve segment are computed, and the minimum value of timescale corresponds to the shortest variability time scale (t_{var}). This timescale is useful for constraining the size of the emis-

sion regions. We note that t_{var} depends on the various quantities such as bin size, length, signal-to-noise ratio of the time series.

For the entire light curve, the shortest t_{var} is found in the X-ray band ($t_{var} \sim 1$ day), followed by the UV ($t_{var} \sim 2.2$ days, averaged over W1, M2, and W2 bands), optical ($t_{var} \sim 2.8$ days, averaged over V, B, and U bands), and gamma-ray ($t_{var} \sim 3.5$ days) bands. We list the variability timescales (t_{var}) for each light curve in different epochs in Table 1.

3.4. The correlation between fluxes in different bands

The flux–flux correlations between different bands are useful to understand the location of the emission regions. We examined correlations between fluxes in optical-UV bands (*U*, *B*, *V*, *W1*, *W2* and *M1*), X-ray and gamma-ray bands. The correlation plots are shown in Figure-2. For gamma – optical/UV and gamma – X-ray correlations where cadence of data is widely different in the two bands, we ensured simultaneity by considering only those data points in the two bands which lie within a 1-day window. To evaluate the strength of correlations we computed Spearman correlation coefficients (ρ) and *p*-values for each correlations. We find that, in general, there is a moderate trend of increase in flux in one band with the increase in flux in other band. The correla-

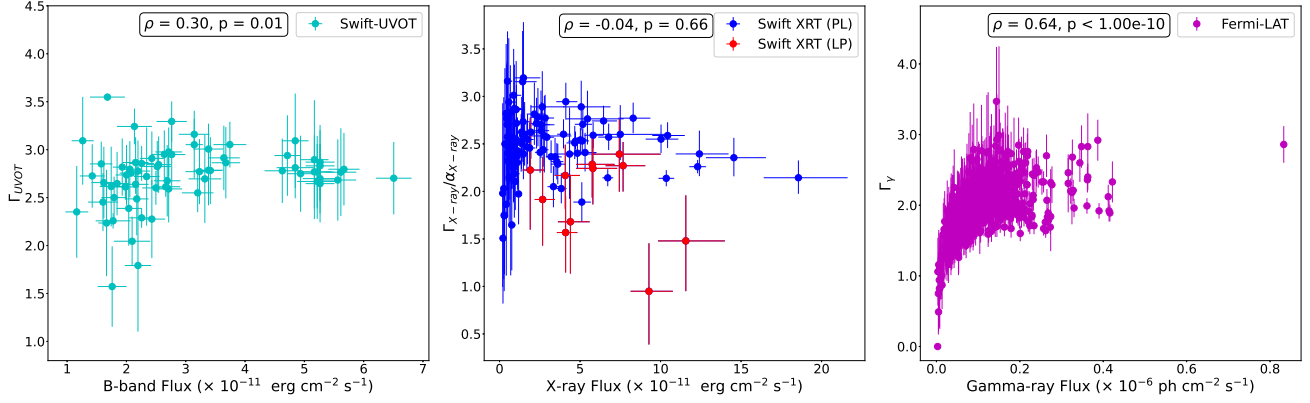


Figure 3. Photon index/spectral index versus flux plots.

tion coefficient (ρ) in flux-flux correlations among various bands are found to be on the range of 0.29 to 0.58 ($> 95\%$ significance level in all cases except one, gamma-ray vs. M2 band). X-ray and γ -ray, the two high energy bands, show relatively strong correlation with correlation coefficient (ρ) 0.58 and p -value = 0.024. From X-ray versus optical/UV correlation plot, a possible X-ray flare with no optical-UV counterpart is also evident, which is consistent from the result obtained from multi-wavelength light curves analysis i.e, an X-ray flare detected in Epoch-I but with no optical/UV counterpart (see Section 3.1).

Figure 3 shows correlation plots of spectral indices versus fluxes i.e., F_{optical} Vs Γ_{UVOT} , $F_{\text{X-ray}}$ Vs $\Gamma_{\text{X-ray}}$ and $F_{\gamma\text{-ray}}$ Vs $\Gamma_{\gamma\text{-ray}}$. In γ -ray band, we find a clear ‘softer-when-brighter’ trend with a high significance (Spearman rank correlation coefficient (ρ) = 0.64 and p -value $< 1.00 \times 10^{-10}$). In optical (B-band) too we observe a similar trend between flux and spectral index but with smaller correlation coefficient and lower significance level ($\rho = 0.30$ and $p = 0.01$). We note that the long-term observations do not show any clear correlation between X-ray flux and photon index with $\rho = -0.04$ and p -value = 0.66. However, considering only index values with relatively lower error bars (corresponding to X-ray flux levels $\gtrsim 1.0 \times 10^{-11}$), we observe a very weak harder-when-brighter trend ($\rho = -0.32$, $p = 3.98 \times 10^{-3}$). A similar trend was reported in C. B. Adams et al. (2022), but with a higher correlation coefficient (Pearson’s correlation coefficient, $r = 0.74$). Their broadband study covered a time span of ~ 1 year (MJD $\sim 56244 - 56673$).

3.5. Intra-Night Optical Variability (INOV)

In addition to long-term variability study we also examined intra-night optical variability (INOV) in this

source using R -band photometric monitoring observations from a $11\text{K} \times 8.0\text{K}$ front illuminated CMOS imager installed on 1.2m telescope at the Mount Abu observatory¹¹. Our observations include monitoring on three sessions, each lasting ≥ 3.0 hours, on three different nights. The imager is equipped with Johnson filter system (U , B , V , R , I filters) and we chose to perform monitoring in R filter owing to the fact that imager sensitivity is maximum in this filter. The CMOS imager having $3.76 \mu\text{m}$ pixel size provides $9'.0 \times 8'.0$ field-of-view (FoV). It has readout noise of approximately 1e^- at 0°C and gives a dark current of $0.003 \text{e}^- \text{pixel}^{-1} \text{sec}^{-1}$. During observations we set exposure time of each frame 3.0 to 5.0 minutes depending upon sky conditions and achieved signal-to-noise ratio (SNR) of 20–25. To perform flat fielding and bias subtraction we also acquired five flat frames taken at the dusk or dawn and 10 bias frames in each observing session.

We reduced data using standard tasks in AstroImageJ¹² software. We extracted instrumental magnitudes of both the target and comparison stars using standard aperture photometry K. A. Collins et al. 2017. The comparison stars are chosen such that they are non-varying or least varying among a set chosen potential comparison stars, have counts/magnitudes similar to the target source. We note that aperture size is a crucial parameter while deducing the instrumental magnitude. To determine optimum aperture size we followed a method based on the stabilization of flux/magnitude with gradual increase in the aperture size (see V. Ojha et al. 2021). We find optimum aperture size equal to $2 \times \text{FWHM}$. Further, to examine INOV in each monitoring session we plot Differential Light Curves (DLCs) of target source

¹¹ <https://www.prl.res.in/~miro/>

¹² <https://www.astro.louisville.edu/software/astroimagej/>

(say ‘T’) *w.r.t* two comparison stars named as ‘C1’ and ‘C2’.

The presence or absence of INOV is determined by performing two different versions of F -test: (i) standard F -test (hereafter F^η test; J. A. de Diego 2010; A. Goyal et al. 2012), and (ii) power-enhanced F -test (hereafter F^{p-en} test; J. A. de Diego 2014). In case of F^η test, we compute the F -statistic of each DLCs in a monitoring session using the following equation:

$$F_1^\eta = \frac{Var(T - C1)}{\eta^2 \sigma_{err}^2(T - C1)}, F_2^\eta = \frac{Var(T - C2)}{\eta^2 \sigma_{err}^2(T - C2)},$$

$$F_3^\eta = \frac{Var(C1 - C2)}{\eta^2 \sigma_{err}^2(C1 - C2)} \quad (4)$$

where, $Var(T - C1)$, $Var(T - C2)$, $Var(C1 - C2)$ are the observed variances in the data and $\sigma_{err}^2(T - C1)$, $\sigma_{err}^2(T - C2)$, $\sigma_{err}^2(C1 - C2)$ are the expected variance (i.e., mean square rms errors of each DLCs, defined by $\frac{\sum_{i=1}^N \sigma_{err,i}^2}{N}$). The value of η is set to 1.54, as described in V. Singh et al. (2025). To assess the INOV we compared F_1^η and F_2^η values with the critical value (F_{crit}), which corresponds to 95% and 99% confidence levels. A DLC is designated to be variable (V) if F^η is higher than $F_{crit}(0.99)$ (i.e., 99% significant), else non-variable (NV; $F^\eta < F_{crit}(0.95)$) or probably variable (PV) if $F_{crit}(0.95) \leq F^\eta \leq F_{crit}(0.99)$. The target is considered variable if both DLCs i.e., T-C1 and T-C2 exhibit variability.

The power enhanced F -test (F^{p-en}) is more robust than the standard one as it includes more than two comparison stars to compute the combined variance and hence enhance the power of the F -test (see J. A. de Diego 2014 for more discussion). We used three steady stars (one Reference (R1) star and two comparison stars (C1, C2) for this test. The F^{p-en} is defined as follows:

$$F^{p-en} = \frac{Var(T - R1)}{\sigma_{comb}^2} \quad (5)$$

where, $Var(T - R1)$ is the observed variance of the ‘T-R1’ DLC and σ_{comb}^2 is the combined variance of ‘Companion - R1’ DLCs.

$$\sigma_{comb}^2 = \frac{1}{(\sum_{j=1}^p N_j) - p} \sum_{j=1}^p \sum_{i=1}^N s_{ji}^2, s_{ji}^2 = \omega_j (m_{ji} - \bar{m}_j)^2 \quad (6)$$

N_j is the number of data points in j th ‘Companion-R1’ DLC. In our case, j runs from 1 to 2. $\bar{m}_j$ represents the mean magnitude of the j th ‘Companion-R1’ DLC. ω_j is

the scaling factor used to scale the variance of the j th ‘Companion-R1’ DLC to the level of the ‘T-R1’ DLC, and its value is taken as described in R. Joshi et al. 2011. The INOV status of the target is derived by the same criteria as discussed in case of F^η test.

The INOV status of our target sources TXS 0518+022 resulting from the two different versions of F -tests is listed in Table-2. The DLCs of all three monitoring sessions are shown in Figure-3. Among three intra-night optical monitoring sessions carried out during January and March, 2025, none of the sessions showed strong INOV. During MJD 60755, DLC is identified as ‘variable’; however, after correcting for false discovery (i.e., the Bonferroni correction), it changes to ‘probable variable’ case. It should be noted that the INOV results mentioned here are not absolute, and the source may have been in an INOV-quiescent phase during the total time period of observation (G. E. Romero et al. 1999).

4. BROADBAND SPECTRAL STUDY

To understand change in flux state and emission mechanisms across various epochs we analyse broad-band SEDs in all epochs. In Figure-5 we have plotted broad-band SEDs where each epoch is depicted by a different color. We note the exclusion of *UVM2* and *UVW2* bands data in each epoch due to issues in extinction correction (see Section 3). In Epochs B, G, and K, gamma-ray fluxes are only upper limits, and hence, these epochs are not considered for SED modeling. As discussed earlier, the redshift of this source is still uncertain, $0.18 \leq z \leq 0.34$. We assume $z = 0.25$ for the SED modeling. Also, we include X-ray fluxes only above 1 keV, as our source TXS 0518+211 is located near the Galactic plane and high absorption X-ray photons is expected at ≤ 1.0 keV.

4.1. Broad-band SED modeling

To model the broad-band SED we used the publicly available code ‘GAMERA’¹³ (J. Hahn 2016) that solves time-dependent continuity equation for an input injected particle (only leptons are considered in our case) spectrum and compute the photon spectrum for different radiative losses of electrons (e.g., synchrotron, SSC) at different time stamps. This code also incorporates the Klein-Nishina cross section to compute the IC/SSC spectrum. To model the SED we have tried both one-zone and two-zone SSC models. More details on these models are given in the following sub-sections.

¹³ http://libgamera.github.io/GAMERA/docs/main_page.html

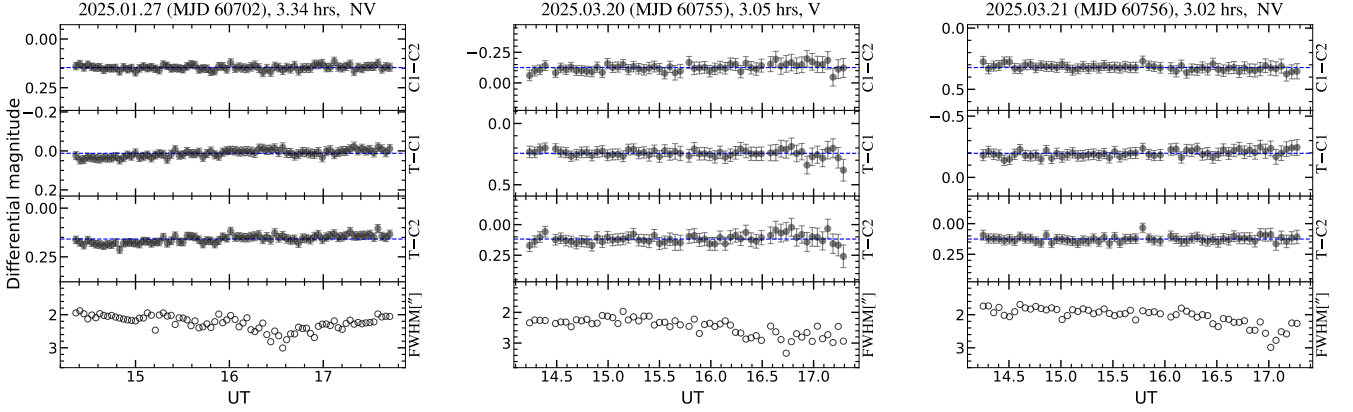


Figure 4. The differential light curves (DLCs) of TXS 0518+211 in R -band for three intra-night monitoring sessions. The date, time duration, and variability status are mentioned in the top of each DLC plot. In each plot, the uppermost panel represents the DLC of two comparison sources (C1 and C2), while the other panels show DLCs of target *w.r.t.* to two comparison sources (T-C1, T-C2). The lowermost panel shows seeing (PSF) variations across the monitoring session.

Table 2. INOV status based on the F^η and F^{p-en} statistical tests.

Observation Date (yyyy.mm.dd)	N	Time Duration (Hours)	Mean FWHM (arcseconds)	F_1^η, F_2^η	INOV status	F_3^η	INOV status	F^{p-en}	INOV status
2025.01.27	80	3.34	2.24	0.28, 0.41	NV, NV	0.15	NV	0.96	NV
2025.03.20	59	3.05	2.48	0.26, 0.25	NV, NV	0.13	NV	1.87	V
2025.03.21	59	3.00	2.05	0.13, 0.18	NV, NV	0.18	NV	1.02	NV

Notes - NV : non-variable, V : variable. N represents the number of data points in a DLC.

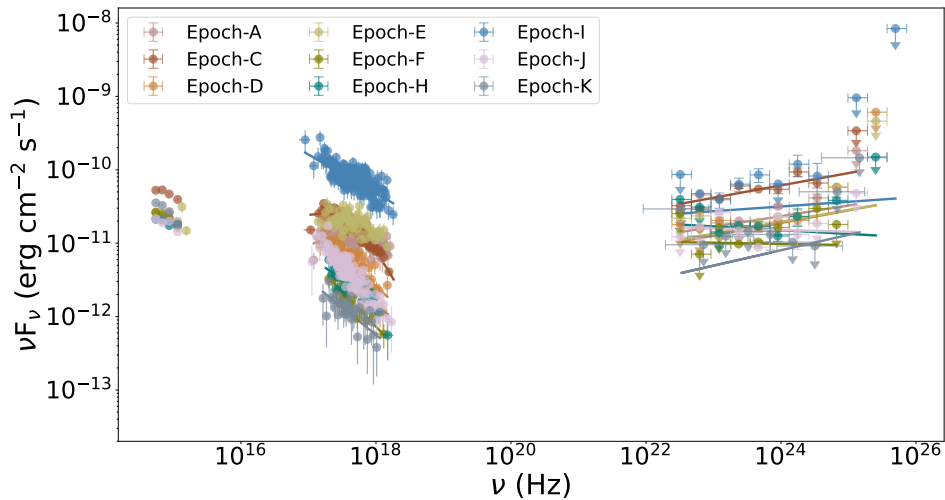


Figure 5. Multi-wavelength SED for nine different epochs (including Epoch-K).

4.1.1. One-zone SSC model:

In one-zone SSC model, the low-energy hump (radio to X-ray) of SED is described by synchrotron emission of relativistic electrons present in the jet, whereas the high-energy hump (gamma-ray to VHE gamma-ray) is described by SSC emission of the same electron population. This model has been extensively used in the literature for the SED modeling of BL Lac sources and in many cases, it successfully explained the emission spectra (e.g., [N. Sahakyan 2020](#); [S. K. Mondal et al. 2021](#); [R. Prince et al. 2022](#), and reference therein). We assumed particle injection spectra governed by broken power-law given as:

$$N(\gamma') = \begin{cases} N_0 \times \gamma'^{-\alpha_1}, & \gamma'_{min} \leq \gamma' \leq \gamma'_{br} \\ N_0 \times \gamma'_{br}^{-(\alpha_1-\alpha_2)} \times \gamma'^{-\alpha_2}, & \gamma'_{br} \leq \gamma' \leq \gamma'_{max} \end{cases} \quad (7)$$

where, primed quantities represent parameters in the co-moving frame. To fit the broadband SED of each epoch we varied several parameters e.g., spectral index of the injection spectrum (α_1), minimum and maximum energy of electrons (γ'_{min} and γ'_{max}), break energy (γ'_{br}), magnetic field (B), and radius (R) of the emission region. We assume the Doppler factor (δ) to be 26 for all epochs, with $\Gamma \sim \delta$ ([C. B. Adams et al. 2022](#)). It should be noted that the jet opening angle is not measured for this source ([MAGIC Collaboration et al. 2020](#)), therefore δ is not well constrained. The energy density of the electrons/positrons is given as :

$$U'_e = \frac{3}{4\pi R^3} \int_{\gamma'_{min}}^{\gamma'_{max}} EQ(E)dE \quad (8)$$

and the energy density in the magnetic field is expressed as:

$$U'_{B'} = \frac{B'^2}{8\pi} \quad (9)$$

The total absolute jet power required to model broadband SED is given by:

$$P_{tot} = P_e + P_B + P_p = \pi R'^2 \Gamma^2 c (U'_e + U'_{B'} + U'_p) \quad (10)$$

We assumed charge neutrality scenario and ratio of electron-positron pairs to cold protons of 10:1 in the emission region to calculate the energy density of cold protons (U_p) and, subsequently, the cold proton power in the jet. We also incorporated the correction due to extra-galactic background light (EBL) absorption using the model described in [R. C. Gilmore et al. \(2012\)](#). The one-zone leptonic model fits for all epochs (except Epoch-B, Epoch-G, and Epoch-K) are shown in Figure 6. The values of all the model parameters required

for SED modeling are listed in Table 3.

In case of TXS 0518+211, we found that the one-zone model cannot fully explain the broad-band SED. It is unable to account for the observed optical-UV slope and gamma-ray fluxes. Therefore, we also attempt to fit the SEDs using two-zone SSC model.

4.1.2. Two-zone SSC model:

In the literature it has been shown that the simple one-zone SSC models are often insufficient to explain the broad-band emissions from VHE detected BL Lac type blazars ([M. L. Ahnen et al. 2017](#); [MAGIC Collaboration et al. 2020](#)). In two-zone model we consider two emission regions, namely inner-zone and outer-zone, which are spatially separated from each other in the jet (see [A. K. Das et al. 2021](#)). Both the zones emit radiation via synchrotron and SSC processes. The light curves in the X-ray and VHE wavebands are strongly correlated in VHE-detected blazars ([MAGIC Collaboration et al. 2020](#)). The inner zone, located closer to the central engine, primarily explains the X-ray and VHE components of the SED, whereas the outer-zone explains the optical-UV and partially the high-energy gamma-ray components. We assume that the shape of the injected spectrum is the same for both zones (described by Equation-7).

Two-zone model requires more number of parameters than simple one-zone model. To use two-zone model we placed constraints in some parameters that include Doppler factor of the two emission regions assumed to be equal and same (i.e., $\delta = 26$ and $\delta \sim \Gamma$) as for the one-zone emission model. The radius (R) of the two emission regions estimated from the variability timescales given by X-ray ($t_{var} \sim 1$ day) and optical/UV ($t_{var} \sim 2.5$ days) light curves. Using causality condition ($R' \leq \frac{c\delta t_{var}}{1+z}$), we obtain inner and outer-zone's radii to be $\sim 5.4 \times 10^{16}$ cm and $\sim 1.4 \times 10^{17}$ cm, respectively. However, we note that these values are only approximate and several effects can introduce large uncertainties (see [R. J. Protheroe \(2002\)](#)). For our work, we set R' value to be the order of $\sim 10^{16}$ cm and $\sim 10^{17}$ cm for the two emission zones. The magnetic field strength (B) is typically assumed to decrease with distance from the central engine (Z), i.e., $B \propto Z^{-1}$ ([S. P. O'Sullivan & D. C. Gabuzda 2009](#)). The Z value can be estimated from the variability timescale ($Z = \frac{2\Gamma^2 ct_{var}}{1+z}$), assuming the conical jet approximation. This implies $\frac{B'_{outer}}{B'_{inner}} = \frac{t_{var,inner}}{t_{var,outer}}$ or $B'_{outer} \sim \frac{B'_{inner}}{3}$ G. We assumed high-energy electron index for each emission zone as $\alpha_2 = \alpha_1 + 1$, which is expected for the canonical cooling break in a homogeneous model. Further, to compute power carried by the cold protons, we assumed the charge neutrality condition and

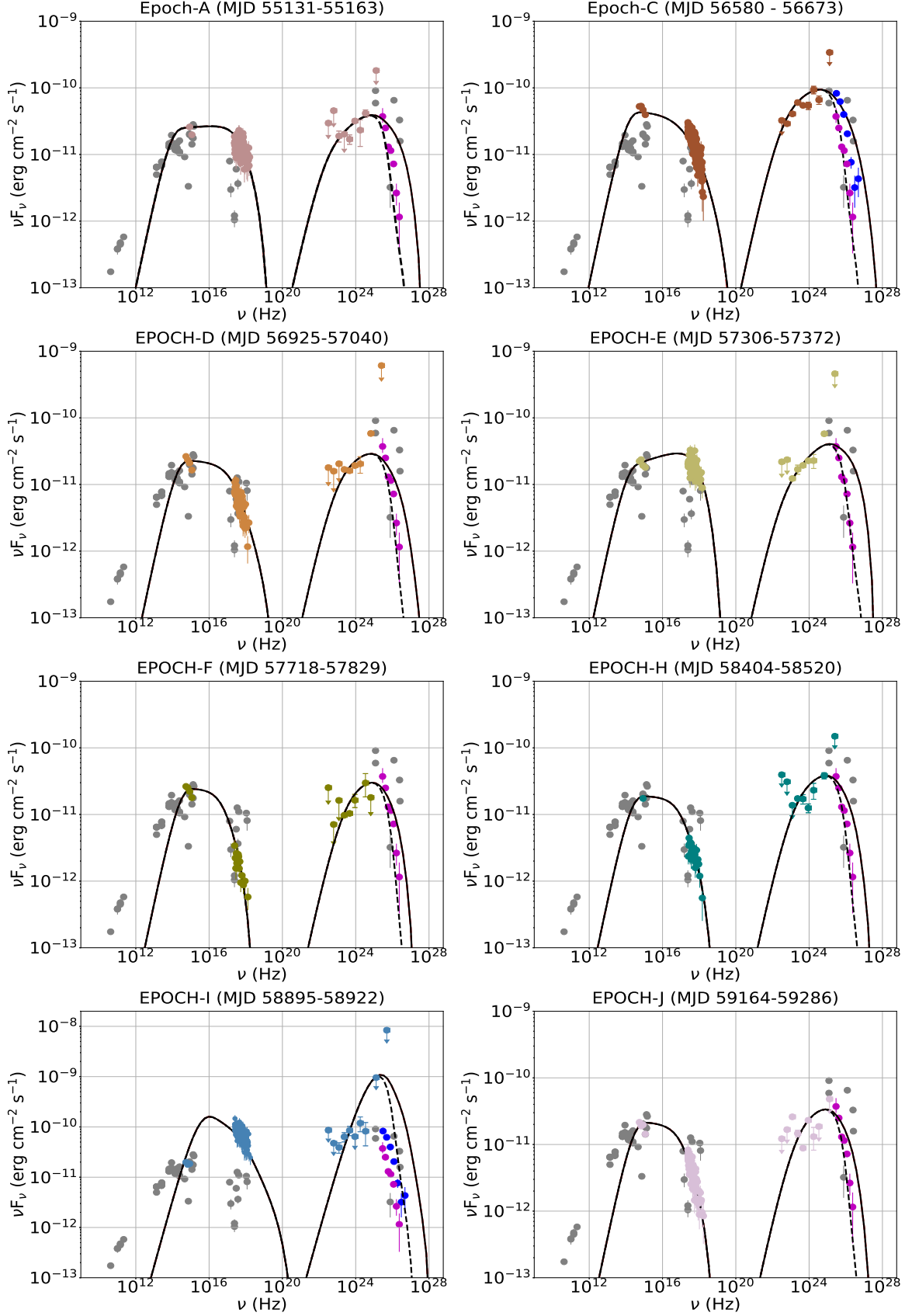


Figure 6. One-zone leptonic model fits of the broad-band (optical to high-energy gamma-ray) SEDs for different epochs. Non-simultaneous archival data are depicted by grey colored points in each plot. Non-simultaneous VHE data taken from C. B. Adams et al. (2022) are shown by pink and blue colored points corresponding to low flux state (MJD 56632.5-56689.0) and high flux state (MJD 56628.5-56632.5), respectively. Dashed curve represents the EBL corrected model.

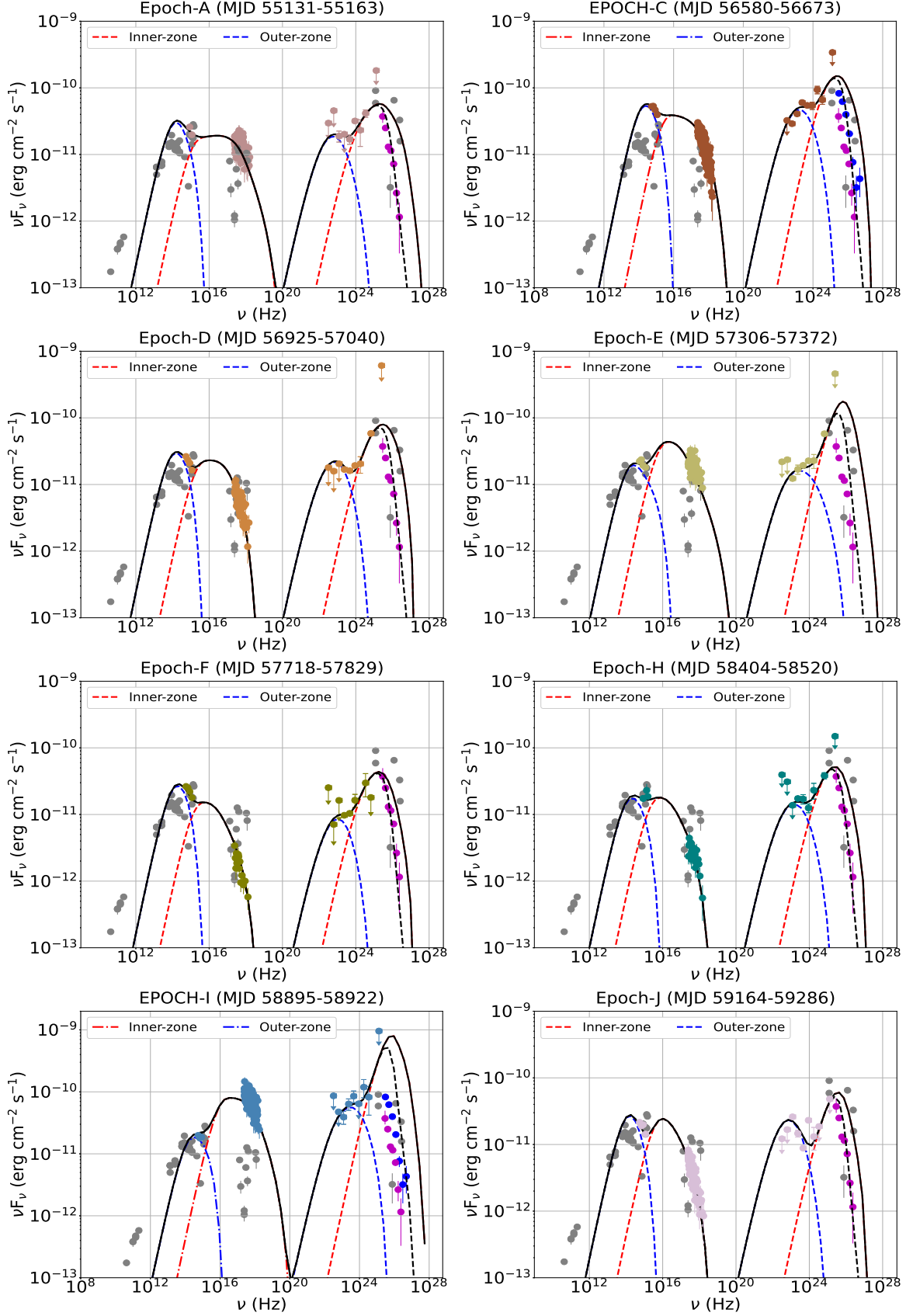


Figure 7. Two-zone leptonic model fits of the broadband SEDs (optical to high-energy gamma-ray) for different epochs. Non-simultaneous archival are represented by grey colored data points in each figure. Non-simultaneous VHE data taken from [C. B. Adams et al. \(2022\)](#) are shown by pink and blue colored points corresponding to low flux state (MJD 56632.5-56689.0) and high flux state (MJD 56628.5-56632.5), respectively. Dashed curve represents the EBL corrected model.

Table 3. Results of multi-wavelength SED modeling (One-zone). The time duration of different phases is given in the last column. The second to eleventh columns represent the value of various parameters used in the one-zone modeling. Here, α_1, α_2 = Spectral indices of injected electron spectrum; $\gamma_{min}, \gamma_{max}, \gamma_{br}$ = Minimum, maximum and break Lorentz factor of injected electron spectrum; R = Size of the emission region; P_e = Power in the injected spectrum; P_B = Power in the magnetic field; P_{tot} = Total required jet power. Several parameters are kept fixed at a specific value during modeling/fitting including $\delta = 26$, $\Gamma = 25$ (see text for more details).

Activity Epochs	α_1	α_2	γ'_{min}	γ'_{max}	γ'_{br}	B' (G)	R' (cm.)	P_e (erg/sec)	P_B (erg/sec)	P_{tot} (erg/sec)	Time duration (days)
Epoch-A	2.95	3.95	8.50×10^3	2.30×10^6	5.00×10^5	0.01	1.40×10^{17}	2.44×10^{45}	4.59×10^{42}	2.45×10^{45}	32
Epoch-C	2.98	3.98	9.00×10^3	4.00×10^6	9.00×10^5	0.017	1.60×10^{17}	2.53×10^{45}	1.18×10^{43}	2.55×10^{45}	93
Epoch-D	2.98	3.98	1.20×10^4	3.60×10^6	5.00×10^5	0.012	1.80×10^{17}	1.36×10^{45}	1.00×10^{43}	1.38×10^{45}	115
Epoch-E	2.80	3.80	9.30×10^3	2.00×10^6	9.00×10^5	0.012	1.10×10^{17}	2.26×10^{45}	4.08×10^{42}	2.27×10^{45}	66
Epoch-F	2.98	3.98	1.55×10^4	8.50×10^5	2.00×10^5	0.011	1.90×10^{17}	1.16×10^{45}	9.32×10^{42}	1.17×10^{45}	111
Epoch-H	2.98	3.98	1.45×10^4	1.50×10^6	3.00×10^5	0.009	1.60×10^{17}	1.80×10^{45}	4.86×10^{42}	1.81×10^{45}	116
Epoch-I	2.98	3.98	3.70×10^4	5.50×10^6	4.50×10^5	0.038	4.00×10^{16}	3.11×10^{45}	5.41×10^{42}	3.12×10^{45}	27
Epoch-J	2.98	3.98	1.45×10^4	1.30×10^6	3.00×10^5	0.012	1.40×10^{17}	1.41×10^{45}	6.61×10^{42}	1.42×10^{45}	107

Table 4. Results of two-zone multi-wavelength SED modeling. The third to thirteenth columns represent the value of various parameters used in the one-zone modeling (see text for more details).

Activity Epochs	Emission region	α_1	α_2	γ'_{min}	γ'_{max}	γ'_{br}	B' (G)	R' (cm.)	P_e (erg/sec)	P_B (erg/sec)	P_{tot} (erg/sec)	Time duration (days)
Epoch-A	Inner-zone	2.84	3.84	1.70×10^4	3.00×10^6	4.00×10^5	0.03	2.50×10^{16}	1.32×10^{45}	1.32×10^{42}	1.33×10^{45}	32
	Outer-zone	2.85	3.85	7.90×10^3	3.20×10^4	1.00×10^4	0.011	1.30×10^{17}	2.52×10^{45}	4.84×10^{42}	2.54×10^{45}	
Epoch-C	Inner-zone	2.95	3.95	2.50×10^4	1.20×10^6	4.00×10^5	0.03	3.30×10^{16}	3.29×10^{45}	2.30×10^{42}	3.30×10^{45}	93
	Outer-zone	2.86	3.86	9.50×10^3	4.30×10^4	2.00×10^4	0.01	1.90×10^{17}	4.21×10^{45}	7.79×10^{42}	4.25×10^{45}	
Epoch-D	Inner-zone	2.84	3.84	2.80×10^4	7.70×10^5	2.00×10^5	0.02	4.20×10^{16}	3.00×10^{45}	1.49×10^{42}	3.01×10^{45}	115
	Outer-zone	2.84	3.84	8.00×10^3	3.05×10^4	2.00×10^4	0.008	1.80×10^{17}	4.21×10^{45}	5.48×10^{42}	4.24×10^{45}	
Epoch-E	Inner-zone	2.75	3.75	4.80×10^4	3.50×10^6	2.00×10^5	0.02	4.30×10^{16}	3.13×10^{45}	1.73×10^{42}	3.13×10^{45}	66
	Outer-zone	2.84	3.84	1.00×10^4	9.50×10^4	2.00×10^4	0.008	1.80×10^{17}	3.23×10^{45}	5.35×10^{42}	3.25×10^{45}	
Epoch-F	Inner-zone	2.84	3.84	2.35×10^4	8.00×10^5	1.00×10^5	0.02	3.80×10^{16}	2.50×10^{45}	1.35×10^{42}	2.50×10^{45}	111
	Outer-zone	2.84	3.84	9.50×10^3	3.30×10^4	2.00×10^4	0.008	2.50×10^{17}	2.14×10^{45}	9.75×10^{42}	2.16×10^{45}	
Epoch-H	Inner-zone	2.80	3.80	2.90×10^4	7.80×10^5	1.00×10^5	0.02	3.80×10^{16}	2.52×10^{45}	1.35×10^{42}	2.53×10^{45}	116
	Outer-zone	2.84	3.84	9.00×10^3	4.50×10^4	2.00×10^4	0.008	1.50×10^{17}	3.56×10^{45}	3.37×10^{42}	3.58×10^{45}	
Epoch-I	Inner-zone	2.88	3.88	4.40×10^4	3.00×10^6	5.00×10^5	0.035	1.50×10^{16}	3.98×10^{45}	6.46×10^{41}	3.99×10^{45}	27
	Outer-zone	2.87	3.87	9.50×10^3	5.50×10^4	2.80×10^4	0.01	6.00×10^{16}	4.05×10^{45}	8.29×10^{41}	4.07×10^{45}	
Epoch-J	Inner-zone	2.80	3.80	3.80×10^4	7.50×10^5	1.00×10^5	0.02	4.20×10^{16}	2.32×10^{45}	1.65×10^{42}	2.32×10^{45}	122
	Outer-zone	2.84	3.84	9.50×10^3	3.50×10^4	1.00×10^4	0.008	1.70×10^{17}	4.56×10^{45}	4.33×10^{42}	4.60×10^{45}	

the ratio of electron-positron pairs to cold protons same as in the one-zone model.

After constraining the above parameters, we performed the two-zone model fit. The total jet power is computed by summing the contributions from each emission zone:

$$P_{tot} = \sum_{i=1}^2 P_{e,i} + P_{B,i} + P_{p,i} = \sum_{i=1}^2 \pi R'^2 \Gamma^2 c (U'_{e,i} + U'_{B,i} + U'_{p,i}) \quad (11)$$

The two-zone leptonic model fit for all epochs (except Epoch-B, Epoch-G, and Epoch-K) are shown in Figure-7. In our two-zone model fit, we found that the spectral index (α_1) lies in the range 2.75–2.95 for both emission zones. The magnetic field (B') of the inner emission zone lies in the range 0.02–0.035 G. For the high-flux

state, a relatively stronger magnetic field is required to model the broadband SEDs. We found that the minimum (γ'_{min}) and maximum (γ'_{max}) Lorentz factors of electrons in the inner zone are relatively higher than those in the outer emission zone. All the model parameters values required for two-zone model fit are listed in Table-4.

5. DISCUSSIONS

Since the beginning of the Fermi-LAT monitoring program (August 2008), TXS 0518+211 has been found to be in active-state on several occasions in optical to high-energy gamma-ray bands. This source was first reported and studied in the TeV band by [S. Archambault et al. \(2013\)](#). They explored the observational properties (i.e., spectral indices, optical polarization, Compton

dominance, etc.) in radio, optical, X-ray, and TeV bands and revealed that the source resembles with IBL-type BL Lac during low flux phase. However, during high flux state on 27 November 2009, the source exhibited elevated X-ray level by a factor of ~ 15 with significant spectral hardening behavior ($\Gamma_X = 2.00 \pm 0.10$) and the synchrotron component showed HBL-like properties. Later, C. B. Adams et al. (2022) studied this source (using simultaneous optical to TeV data) from October 2013 to February 2014 during both low and high flux states. They did not observe any significant spectral hardening with increasing X-ray flux levels, as reported during the previous November 2009 high flux state, and the broadband SED in this time span exhibited similar properties to IBLs in all flux states.

5.1. Low and high flux states characteristics from the multi-wavelength data

In this study, we have divided the entire multi-wavelength light curve into 11 different Epochs (Epoch-A to Epoch-K). We computed the fractional variability (F_{var}) and reduced chi-square value (χ_{red}^2) for each epoch and the entire light curve to characterize the long-term variability across optical, UV, X-ray, and gamma-ray wavebands. The value of F_{var} and χ_{red}^2 (ref Table-1) reveal that the light curve in X-ray band shows more prominent variability than optical and gamma-ray light curves. However, we caution that for low number of data points, χ_{red}^2 values are not reliable as the standard deviation of this quantity follows $\sqrt{\frac{2}{df}}$ (where, df = degrees of freedom). In the X-ray band, the largest F_{var} is observed for the entire light curve, with a value of 1.10 ± 0.03 , followed by Epoch-A (0.96 ± 0.04) and Epoch-I (0.71 ± 0.07). A similar result was also reported by C. B. Adams et al. (2022), based on ~ 1 year (2013 - 2014) of near-simultaneous optical to VHE data. Similarly, in the optical-UV bands, the largest F_{var} is for the entire light curve, but with comparatively lower values ranging from 0.35 to 0.50. Whereas, in the case of gamma-ray, it is observed for the Epoch-H with a value of 0.89 ± 0.15 . During Epoch-H, flaring behavior was observed over a short duration (MJD 58402 to 58417) in the gamma-ray band with an average flux of 0.47 ± 0.10 , resulting in a higher fractional variability. Corresponding optical U-band and X-ray light curves showed comparatively low flux values (1.73 ± 0.08 and $1.04^{+0.20}_{-0.17}$, respectively during MJD 58402 - 58417), which are similar to the average flux of Epoch-H. However, the lack of high-cadence data in these bands (i.e., optical and X-ray) during this short period makes it difficult to draw

any decisive conclusion about the flux state (i.e., possibility of orphan gamma-ray flare). During the total observing period, the source remains in either a low- or intermediate-activity phase in the X-ray band for most of the time. As the source evolves from the low- to the high-flux phase, we observe a decrease in the X-ray spectral index (i.e., spectral hardening trend), with the highest value of Γ_X in Epoch-K ($2.74^{+0.23}_{-0.23}$) and the lowest in Epoch-I ($2.18^{+0.04}_{-0.04}$). A similar trend is also observed in the optical-UV band, although the variation of spectral indices (Γ_{UVOT}) between the low- and high-flux phases is relatively smaller and within the error bars. This result is consistent with the index-flux correlation study discussed in section 3.4 (see Figure 3).

The INOV study of this source reveals that none of the sessions exhibit strong variability on minute-to-hour timescales. It is worth pointing out that V. Negi et al. (2023) conducted INOV study on six TeV-detected HBLs, and detected variability in only one out of 24 intra-night sessions. The low INOV duty cycle is comparable to IBL sub-class but much less compared to LBL sub-class (V. S. Paliya et al. 2017). Despite both sub-classes exhibit fairly high degree of optical polarization. HBLs/TeV-HBLs generally exhibit a parsec-scale jet with either subluminal or mildly superluminal radio knots. It has been argued that the presence of superluminal/fast-moving radio knots could be a key diagnostic for INOV detection (V. Negi et al. 2023). According to M. L. Lister et al. (2019), TeV-detected TXS 0518+211 showed a combination of quasi-stationary and mildly super-luminal radio knots. Hence, our INOV results suggest that the source is consistent with either belonging to IBL or HBL subclass. The INOV study alone can not identify its specific subclass. A detailed comparable INOV study between TeV-detected IBL and HBL sources could be helpful in the future to resolve this issue.

As discussed earlier, the redshift of this source is still uncertain, and only lower and upper limits are available in the literature. To estimate the redshift and flux state, we conducted spectroscopic observations of this source with an exposure time of ~ 50 minutes using the low-resolution spectrograph LISA ($R \sim 850$) mounted on the PRL 1.2 m telescope, Mount Abu, India. The data analysis was performed using standard PYTHON scripts and the IRAF package¹⁴. The details of the instrument and the standard reduction procedures, including bias subtraction, flat-fielding, cosmic-ray correction, one-dimensional spectrum extraction, and wavelength

¹⁴ <https://iraf-community.github.io/install.html>

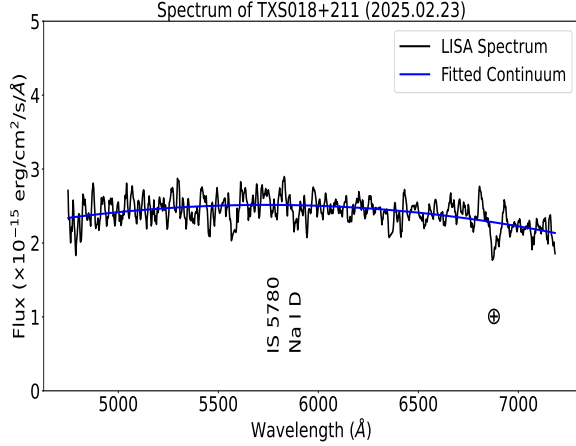


Figure 8. Spectroscopic result (de-reddened) of TXS 0518+211, observed on 23rd February, 2025. The spectrum is de-reddened (corrected for interstellar reddening) using $R = 3.1$ and $E(B-V) = 0.5875$ (E. F. Schlafly & D. P. Finkbeiner 2011). The telluric line is indicated by $\oplus$ sign. Absorption lines due to the interstellar medium of our Galaxy are visible but not prominent.

and flux calibrations, are presented in K. Venkataramani et al. (2016) and G. Ahuja et al. (2025). Due to the limited sensitivity of the instrument and average weather condition, we obtained a low signal-to-noise ratio ($S/N < 6$). The optical spectrum is shown in Figure-8. It is evident that no clear emission lines are seen in the spectrum. The continuum emission (shown by the solid blue line) during this period is relatively bluer than that observed in earlier spectra taken in October and December 2009 by S. Archambault et al. (2013).

5.2. Emission mechanisms during low and high flux states

The broadband temporal as well as spectral studies (specifically during Epoch-I, Epoch-C, and Epoch-K discussed in Section 3.4), suggest that the source exhibits complex emission mechanisms. We used simple one-zone and two-zone (non-interacting) leptonic models to investigate the emission processes across different epochs. In the one-zone scenario, we found that the emission region is particle-dominated for all epochs, with a maximum total required jet power (P_{tot}) of 3.11×10^{45} erg/sec during Epoch-I. The values of various model parameters, including the magnetic field (B) and minimum, maximum, break Lorentz factors (γ'_{min} , γ'_{max} and γ'_{br}) of the injected electron spectrum, and radius of the emission region (R'), determined in this work (for one-zone scenario) are comparable to those reported in C. B. Adams et al. (2022). However, we noticed that

none of the optical–UV slopes can be reproduced with the simple one-zone scenario. Furthermore, we notice a clear plateau in the low-energy gamma-ray range ($\lesssim 3.0$ GeV) during several epochs, such as Epoch-C, Epoch-D, Epoch-E, and Epoch-H. Such a trend has previously been observed in other BL Lac-type objects (e.g., 1ES 1959+650; S. R. Patel et al. 2018) and could indicate that emission from two or more zones contributes to the observed SED.

In the two-zone scenario, we considered two emission region sites with similar Doppler factor ($\delta = 26$) that are non-interacting and spatially separated from each other. The inner-zone predominantly explains the X-ray and high-energy to VHE gamma-ray ($\gtrsim 3$ GeV) emission component, while the outer emission-zone explains the optical-UV and low-energy gamma-ray (0.1 to ~ 3 GeV) emission component of the broadband SED. According to the flux levels of different epochs in the X-ray band, Epoch-F and Epoch-H can be considered as quiescent states. From the SED modeling, we found that the change in total electron number density (greater than 80%) in both emission zones was greater than the change in the magnetic field during the high-flux states of the source (e.g. Epoch-C and Epoch-I). The injection of fresh electrons and/or the re-acceleration of particles could increase the electron energy density in the emission region, which might be responsible for the enhanced or high-state activities of this source. In our two-zone modeling, we require a relatively smaller emission region radius ($R'_{outer} = 6.0 \times 10^{16}$ cm, which implies a denser seed photon field) for Epoch-I to explain the stronger SSC component from the outer zone. According to our SED modeling, during Epoch-E and Epoch-I, the source exhibits an HBL-like property ($\nu_{peak} > 10^{15}$ Hz). In both cases, we noticed a spectral hardening trend in the X-ray band ($\Gamma_X = 2.32^{+0.09}_{-0.09}$ for Epoch-E and $\Gamma_X = 2.18^{+0.04}_{-0.05}$ for Epoch-I). The intrinsic bolometric synchrotron emission (and the corresponding SSC emission) from the inner zone dominates the emission from the outer zone (~ 3 times higher for Epoch-E and ~ 6 times higher for Epoch-I) for these two epochs, whereas in all other epochs it is nearly comparable (0.8–1.3 times higher) to the outer zone emission. The maximum total required jet power (computed using Equation 11) in the two-zone scenario is found to be 8.06×10^{45} erg/s for Epoch-I, followed by Epoch-C. We observed a significant dip between the low-energy (synchrotron) hump and high-energy (SSC) hump in our two-zone model fit for all epochs (see Figure-7). The depth of this dip decreases as the source evolves from a quiescent state to a high-flux state. Hence, observations in wavebands that cover the frequency range between X-rays and gamma-

rays (e.g., NuSTAR observations) would help better constrain the model parameters in future, especially the minimum Lorentz factor ($\gamma'_{\min}$) of the outer zone and maximum Lorentz factor ($\gamma'_{\max}$) of the inner-zone. Recently, [MAGIC Collaboration et al. \(2025\)](#) studied this source during the activity period of Epoch-I over a short timescale duration and found that, with a one-zone lepto-hadronic model fit, the dip between the two emission humps almost disappears. Therefore, panchromatic simultaneous observations, along with NuSTAR data, could also be helpful in understanding the emission mechanisms in more detail.

6. CONCLUSIONS

In this work, we have performed a broad-band temporal and spectral study of TeV-detected BL Lac TXS 0518+211 using long-term (MJD 54682 - 60670; 16 years) near-simultaneous optical, UV, X-ray (from *Swift* UVOT/XRT) and gamma-ray (from *Fermi*-LAT) data. Based on the availability of simultaneous multi-wavelength data we identified 11 different epochs (Epoch-A to Epoch-K) and investigated the emission properties of the source in all the epochs. In the following, we highlight some important findings of our work:

- Fractional variability reveals that, in all the epochs, the source exhibits higher variability in the X-ray band compared to the optical/UV and gamma-ray bands. This is also evident from the average fractional variability parameter of long-term light curves spanning across full 16 years, wherein fractional variability in X-ray band is 1.10 ± 0.03 , while it ranges between 0.35 to 0.45 in the other bands.
- We also probed variability on short timescales by conducting three intra-night photometric monitoring sessions in optical *R*-band during January and March 2025. Notably, none of DLCs show any strong variability signature. The INOV behavior of TXS 0518+211 is consistent with a typical INOV trend seen among IBL/HBL-type sources.
- Correlation study shows a weak to moderate correlation across different wavebands, with the Spearman correlation coefficient ranging from 0.29 to 0.58 in the long-term light curve.
- We identified two high-flux states in the long-term X-ray light curve using a Bayesian block representation, namely Epoch-C (MJD 56580 - 56673) and Epoch-I (MJD 58895 - 58922). During Epoch-C, the source showed simultaneous variability across all three wavebands, whereas during Epoch-I, a significant increase in the X-ray

flux level was observed without a corresponding counterpart in the optical/UV bands. Another recent flux state, during Epoch-K (MJD 60611 - 60670), we noticed a significant decrease in X-ray flux, but the optical/UV and gamma-ray flux levels remained nearly steady. These behaviors in the multi-wavelength light curve suggest complex emission region structure in the jet.

- We used both one-zone and two-zone (non-interacting) leptonic models to explain the broad-band SED of all epochs. The two-zone model provides a better explanation of the optical to high-energy gamma-ray SED. The maximum total jet power required in the two-zone model is found to be 8.06×10^{45} erg/s for Epoch-I. The high X-ray flux observed during this epoch could be explained by the increased activity in the inner emission region.

DATA AVAILABILITY

This work has made use of publicly available *Fermi*-LAT data obtained from FSSC's website data server and provided by NASA Goddard Space Flight Center. This work has also made use of data, software/tools obtained from NASA High Energy Astrophysics Science Archive Research Center (HEASARC), developed by the Smithsonian Astrophysical Observatory (SAO), and the XRT Data Analysis Software (XRTDAS) developed by ASI Science Data Center, Italy. We acknowledge the use of data collected from the CMOS imager on the 1.2 m telescope at Mt. Abu Observatory.

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Facilities: *Fermi*-LAT, *Swift* (XRT and UVOT), Mt Abu observatory: 1.2m

Software: Fermitools (Fermi Science Support Development Team 2019), HEASARC (Nasa High Energy Astrophysics Science Archive Research Center (Heasarc)

2014), XSPEC (K. A. Arnaud 1996), IRAF (D. Tody 1986), AstroimageJ (K. A. Collins et al. 2017), GAMERA (J. Hahn 2016), astropy (Astropy Collaboration et al. 2013, 2018, 2022)

REFERENCES

- Abdo, A. A., Ackermann, M., Agudo, I., et al. 2010, *Astrophys. J.*, 716, 30, doi: [10.1088/0004-637X/716/1/30](https://doi.org/10.1088/0004-637X/716/1/30)
- Abdollahi, S., Ajello, M., Baldini, L., et al. 2023, *Astrophys. J. Suppl. Ser.*, 265, 31, doi: [10.3847/1538-4365/acbb6a](https://doi.org/10.3847/1538-4365/acbb6a)
- Adams, C. B., Batista, P., Benbow, W., et al. 2022, *Astrophys. J.*, 932, 129, doi: [10.3847/1538-4357/ac6dd9](https://doi.org/10.3847/1538-4357/ac6dd9)
- Ahnen, M. L., Ansoldi, S., Antonelli, L. A., et al. 2016, *MNRAS*, 459, 2286, doi: [10.1093/mnras/stw710](https://doi.org/10.1093/mnras/stw710)
- Ahnen, M. L., Ansoldi, S., Antonelli, L. A., et al. 2017, *A&A*, 603, A31, doi: [10.1051/0004-6361/201629540](https://doi.org/10.1051/0004-6361/201629540)
- Ahnen, M. L., Ansoldi, S., Antonelli, L. A., et al. 2018, *Astron. Astrophys.*, 620, A181, doi: [10.1051/0004-6361/201833704](https://doi.org/10.1051/0004-6361/201833704)
- Ahuja, G., Aravind, K., Ganesh, S., et al. 2025, *Monthly Notices of the Royal Astronomical Society*, 543, 1178, doi: [10.1093/mnras/staf1528](https://doi.org/10.1093/mnras/staf1528)
- Aleksić, J., Ansoldi, S., Antonelli, L. A., et al. 2014, *A&A*, 567, A135, doi: [10.1051/0004-6361/201423364](https://doi.org/10.1051/0004-6361/201423364)
- Archambault, S., Arlen, T., Aune, T., et al. 2013, *Astrophys. J.*, 776, 69, doi: [10.1088/0004-637X/776/2/69](https://doi.org/10.1088/0004-637X/776/2/69)
- Archambault, S., Aune, T., Behera, B., et al. 2014, *ApJL*, 785, L16, doi: [10.1088/2041-8205/785/1/L16](https://doi.org/10.1088/2041-8205/785/1/L16)
- Arnaud, K. A. 1996, in *Astronomical Society of the Pacific Conference Series*, Vol. 101, *Astronomical Data Analysis Software and Systems V*, ed. G. H. Jacoby & J. Barnes, 17
- Astropy Collaboration, Robitaille, T. P., Tollerud, E. J., et al. 2013, *A&A*, 558, A33, doi: [10.1051/0004-6361/201322068](https://doi.org/10.1051/0004-6361/201322068)
- Astropy Collaboration, Price-Whelan, A. M., Sipőcz, B. M., et al. 2018, *AJ*, 156, 123, doi: [10.3847/1538-3881/aabc4f](https://doi.org/10.3847/1538-3881/aabc4f)
- Astropy Collaboration, Price-Whelan, A. M., Lim, P. L., et al. 2022, *ApJ*, 935, 167, doi: [10.3847/1538-4357/ac7c74](https://doi.org/10.3847/1538-4357/ac7c74)
- Bachev, R. 2020, *Astronomer's Telegram*, 13523, 1. <https://ui.adsabs.harvard.edu/abs/2020ATel13523....1B/abstract>
- Bednarek, W., & Protheroe, R. J. 1999, *MNRAS*, 302, 373, doi: [10.1046/j.1365-8711.1999.02132.x](https://doi.org/10.1046/j.1365-8711.1999.02132.x)
- Blandford, R., Meier, D., & Readhead, A. 2019, *Annu. Rev. Astron. Astrophys.*, 57, 467, doi: [10.1146/annurev-astro-081817-051948](https://doi.org/10.1146/annurev-astro-081817-051948)
- Böttcher, M., Reimer, A., Sweeney, K., & Prakash, A. 2013, *Astrophys. J.*, 768, 54, doi: [10.1088/0004-637X/768/1/54](https://doi.org/10.1088/0004-637X/768/1/54)
- Breeveld, A. A., Landsman, W., Holland, S. T., et al. 2011, *AIP Conf. Proc.*, 1358, 373, doi: [10.1063/1.3621807](https://doi.org/10.1063/1.3621807)
- Buson, S. 2013, *Astronomer's Telegram*, 5472, 1. <https://ui.adsabs.harvard.edu/abs/2013ATel.5472....1B/abstract>
- Carrasco, L., Recillas, E., Porras, A., & Carraminana, A. 2013, *Astronomer's Telegram*, 5520, 1. <https://ui.adsabs.harvard.edu/abs/2013ATel.5520....1C/abstract>
- Chatterjee, R., Fossati, G., Urry, C. M., et al. 2013, *ApJL*, 763, L11, doi: [10.1088/2041-8205/763/1/L11](https://doi.org/10.1088/2041-8205/763/1/L11)
- Collins, K. A., Kielkopf, J. F., Stassun, K. G., & Hessman, F. V. 2017, *Astron. J.*, 153, 77, doi: [10.3847/1538-3881/153/2/77](https://doi.org/10.3847/1538-3881/153/2/77)
- Collins, K. A., Kielkopf, J. F., Stassun, K. G., & Hessman, F. V. 2017, *AJ*, 153, 77, doi: [10.3847/1538-3881/153/2/77](https://doi.org/10.3847/1538-3881/153/2/77)
- D'arcangelo, F. D., Marscher, A. P., Jorstad, S. G., et al. 2009, *Astrophys. J.*, 697, 985, doi: [10.1088/0004-637X/697/2/985](https://doi.org/10.1088/0004-637X/697/2/985)
- Das, A. K., Prince, R., & Gupta, N. 2021, *ApJ*, 920, 117, doi: [10.3847/1538-4357/ac178c](https://doi.org/10.3847/1538-4357/ac178c)
- de Diego, J. A. 2010, *Astron. J.*, 139, 1269, doi: [10.1088/0004-6256/139/3/1269](https://doi.org/10.1088/0004-6256/139/3/1269)
- de Diego, J. A. 2014, *Astron. J.*, 148, 93, doi: [10.1088/0004-6256/148/5/93](https://doi.org/10.1088/0004-6256/148/5/93)
- Fermi Science Support Development Team. 2019, *Fermitools: Fermi Science Tools*, *Astrophysics Source Code Library*, record ascl:1905.011 <http://ascl.net/1905.011>
- Gilmore, R. C., Somerville, R. S., Primack, J. R., & Domínguez, A. 2012, *MNRAS*, 422, 3189, doi: [10.1111/j.1365-2966.2012.20841.x](https://doi.org/10.1111/j.1365-2966.2012.20841.x)
- Goyal, A., Wiita, P. J., Anupama, G. C., et al. 2012, *Astron. Astrophys.*, 544, A37, doi: [10.1051/0004-6361/201218888](https://doi.org/10.1051/0004-6361/201218888)
- H. E. S. S. Collaboration, Abramowski, A., Acero, F., et al. 2013, *A&A*, 559, A136, doi: [10.1051/0004-6361/201321639](https://doi.org/10.1051/0004-6361/201321639)
- Hahn, J. 2016, *PoS, ICRC2015*, 917, doi: [10.22323/1.236.0917](https://doi.org/10.22323/1.236.0917)
- Hayashida, M., Nalewajko, K., Madejski, G. M., et al. 2015, *ApJ*, 807, 79, doi: [10.1088/0004-637X/807/1/79](https://doi.org/10.1088/0004-637X/807/1/79)
- Joshi, R., Chand, H., Gupta, A. C., & Wiita, P. J. 2011, *Mon. Not. R. Astron. Soc.*, 412, 2717, doi: [10.1111/j.1365-2966.2010.18099.x](https://doi.org/10.1111/j.1365-2966.2010.18099.x)

- Kalberla, P. M. W., Burton, W. B., Hartmann, D., et al. 2005, *Astron. Astrophys.*, 440, 775, doi: [10.1051/0004-6361:20041864](https://doi.org/10.1051/0004-6361:20041864)
- Kushwaha, P., Gupta, A. C., Wiita, P. J., et al. 2018, *MNRAS*, 473, 1145, doi: [10.1093/mnras/stx2394](https://doi.org/10.1093/mnras/stx2394)
- Lister, M. L., Homan, D. C., Hovatta, T., et al. 2019, *ApJ*, 874, 43, doi: [10.3847/1538-4357/ab08ee](https://doi.org/10.3847/1538-4357/ab08ee)
- Liu, M., Zhang, Y., Wang, Y., et al. 2025, *ApJ*, 984, 5, doi: [10.3847/1538-4357/adc301](https://doi.org/10.3847/1538-4357/adc301)
- MAGIC Collaboration, Ansoldi, S., Antonelli, L. A., et al. 2018, *MNRAS*, 480, 879, doi: [10.1093/mnras/sty1753](https://doi.org/10.1093/mnras/sty1753)
- MAGIC Collaboration, Acciari, V. A., Ansoldi, S., et al. 2020, *A&A*, 640, A132, doi: [10.1051/0004-6361/202037811](https://doi.org/10.1051/0004-6361/202037811)
- MAGIC Collaboration, Abe, S., Abhir, J., et al. 2025, *A&A*, 694, A308, doi: [10.1051/0004-6361/202451378](https://doi.org/10.1051/0004-6361/202451378)
- Mannheim, K., & Biermann, P. L. 1992, *A&A*, 253, L21
- Mondal, S. K., Prince, R., Gupta, N., & Das, A. K. 2021, *Astrophys. J.*, 922, 160, doi: [10.3847/1538-4357/ac11fa](https://doi.org/10.3847/1538-4357/ac11fa)
- Mücke, A., & Protheroe, R. J. 2001, *Astroparticle Physics*, 15, 121, doi: [10.1016/S0927-6505\(00\)00141-9](https://doi.org/10.1016/S0927-6505(00)00141-9)
- Nasa High Energy Astrophysics Science Archive Research Center (Heasarc). 2014, HEASoft: Unified Release of FTOOLS and XANADU., *Astrophysics Source Code Library*, record ascl:1408.004 <http://ascl.net/1408.004>
- Negi, V., Gopal-Krishna, Chand, H., & Britzen, S. 2023, *MNRAS*, 524, L66, doi: [10.1093/mnrasl/slاد077](https://doi.org/10.1093/mnrasl/slاد077)
- Oikonomou, F., Murase, K., Padovani, P., Resconi, E., & Mészáros, P. 2019, *MNRAS*, 489, 4347, doi: [10.1093/mnras/stz2246](https://doi.org/10.1093/mnras/stz2246)
- Ojha, V., Chand, H., & Gopal-Krishna. 2021, *Mon. Not. R. Astron. Soc.*, 501, 4110, doi: [10.1093/mnras/staa3937](https://doi.org/10.1093/mnras/staa3937)
- Ong, R. A. 2009, *Astronomer's Telegram*, 2260, 1. <https://ui.adsabs.harvard.edu/abs/2009ATel.2260....1O/abstract>
- O'Sullivan, S. P., & Gabuzda, D. C. 2009, *MNRAS*, 400, 26, doi: [10.1111/j.1365-2966.2009.15428.x](https://doi.org/10.1111/j.1365-2966.2009.15428.x)
- Paiano, S., Landoni, M., Falomo, R., et al. 2017, *ApJ*, 837, 144, doi: [10.3847/1538-4357/837/2/144](https://doi.org/10.3847/1538-4357/837/2/144)
- Paliya, V. S., Stalin, C. S., Ajello, M., & Kaur, A. 2017, *ApJ*, 844, 32, doi: [10.3847/1538-4357/aa77f5](https://doi.org/10.3847/1538-4357/aa77f5)
- Patel, S. R., Shukla, A., Chitnis, V. R., et al. 2018, *A&A*, 611, A44, doi: [10.1051/0004-6361/201731987](https://doi.org/10.1051/0004-6361/201731987)
- Poole, T. S., Breeveld, A. A., Page, M. J., et al. 2007, *Mon. Not. R. Astron. Soc.*, 383, 627, doi: [10.1111/j.1365-2966.2007.12563.x](https://doi.org/10.1111/j.1365-2966.2007.12563.x)
- Prince, R., Khatoon, R., Majumdar, P., Czerny, B., & Gupta, N. 2022, *Mon. Not. R. Astron. Soc.*, 515, 2633, doi: [10.1093/mnras/stac1866](https://doi.org/10.1093/mnras/stac1866)
- Protheroe, R. J. 2002, *PASA*, 19, 486, doi: [10.1071/AS02008](https://doi.org/10.1071/AS02008)
- Quinn, J., & VERITAS Collaboration. 2020, *Astronomer's Telegram*, 13522, 1. <https://ui.adsabs.harvard.edu/abs/2020ATel13522....1Q/abstract>
- Rani, B., Krichbaum, T. P., Fuhrmann, L., et al. 2013, *A&A*, 552, A11, doi: [10.1051/0004-6361/201321058](https://doi.org/10.1051/0004-6361/201321058)
- Romero, G. E., Cellone, S. A., & Combi, J. A. 1999, *A&AS*, 135, 477, doi: [10.1051/aas:1999184](https://doi.org/10.1051/aas:1999184)
- Roming, P. W. A., Kennedy, T. E., Mason, K. O., et al. 2005, *Space Sci. Rev.*, 120, 95, doi: [10.1007/s11214-005-5095-4](https://doi.org/10.1007/s11214-005-5095-4)
- Sahakyan, N. 2020, *Mon. Not. R. Astron. Soc.*, 496, 5518, doi: [10.1093/mnras/staa1893](https://doi.org/10.1093/mnras/staa1893)
- Sahakyan, N., & Giommi, P. 2022, *Mon. Not. R. Astron. Soc.*, 513, 4645, doi: [10.1093/mnras/stac1011](https://doi.org/10.1093/mnras/stac1011)
- Scargle, J. D., Norris, J. P., Jackson, B., & Chiang, J. 2013, *ApJ*, 764, 167, doi: [10.1088/0004-637X/764/2/167](https://doi.org/10.1088/0004-637X/764/2/167)
- Schlafly, E. F., & Finkbeiner, D. P. 2011, *Astrophys. J.*, 737, 103, doi: [10.1088/0004-637X/737/2/103](https://doi.org/10.1088/0004-637X/737/2/103)
- Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, *Astrophys. J.*, 500, 525, doi: [10.1086/305772](https://doi.org/10.1086/305772)
- Shaw, M. S., Romani, R. W., Cotter, G., et al. 2013, *Astrophys. J.*, 764, 135, doi: [10.1088/0004-637X/764/2/135](https://doi.org/10.1088/0004-637X/764/2/135)
- Shukla, A., Chitnis, V. R., Singh, B. B., et al. 2015, *ApJ*, 798, 2, doi: [10.1088/0004-637X/798/1/2](https://doi.org/10.1088/0004-637X/798/1/2)
- Singh, V., Kumar, P., Das, A. K., & Ojha, V. 2025, *ApJ*, 990, 79, doi: [10.3847/1538-4357/adf210](https://doi.org/10.3847/1538-4357/adf210)
- Stickel, M., Padovani, P., Urry, C. M., Fried, J. W., & Kuehr, H. 1991, *ApJ*, 374, 431, doi: [10.1086/170133](https://doi.org/10.1086/170133)
- Tody, D. 1986, in *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, Vol. 627, *Instrumentation in astronomy VI*, ed. D. L. Crawford, 733, doi: [10.1117/12.968154](https://doi.org/10.1117/12.968154)
- Urry, C. M., & Padovani, P. 1995, *Publ. Astron. Soc. Pac.*, 107, 803, doi: [10.1086/133630](https://doi.org/10.1086/133630)
- Vaughan, S., Edelson, R., Warwick, R. S., & Uttley, P. 2003, *Mon. Not. R. Astron. Soc.*, 345, 1271, doi: [10.1046/j.1365-2966.2003.07042.x](https://doi.org/10.1046/j.1365-2966.2003.07042.x)
- Venkataramani, K., Ghetiya, S., Ganesh, S., et al. 2016, *MNRAS*, 463, 2137, doi: [10.1093/mnras/stw1820](https://doi.org/10.1093/mnras/stw1820)
- Zhang, Y. H., Celotti, A., Treves, A., et al. 1999, *Astrophys. J.*, 527, 719, doi: [10.1086/308116](https://doi.org/10.1086/308116)