PROCEEDINGS OF SCIENCE

Flux distribution study of PKS 0208-512 using long-term multi-band observations

Rukaiya Khatoon,[a,*] **Markus Boettcher**[a] **and Raj Prince**[b]

[a] *Center for Space Research, North-West University, Potchefstroom, 2520, South Africa*

[b] *Center for Theoretical Physics, Polish Academy of Sciences, Al.Lotnikow 32/46, PL-02-668 Warsaw, Poland*

E-mail: rukaiyakhatoon12@gmail.com

We conduct a flux distribution study of the blazar PKS 0208-512 through nearly ∼ 9 years (2008 - 2017) of optical, X-ray and γ-ray lightcurves using SMARTS, *Swift*-XRT and *Fermi*-LAT telescopes, respectively. In this study, we use the Anderson-Darling (AD) test and histogram fitting methods to analyze the flux distribution of selected lightcurves. The AD test and histogram fitting reveal that the flux distribution of PKS 0208-512 follows a double lognormal distribution in all energy bands, possibly connected to two flux states of the source. The broadband spectral study of PKS 0208-512 suggested that the optical and γ-ray bands are beyond the break energies of the synchrotron and inverse-Compton components, which in turn suggest that these emissions are caused by the highest-energy electrons. The X-ray band is below the break energy of the inverse-Compton component suggesting that the low-energy electron distribution is responsible for this emission.

High Energy Astrophysics in Southern Africa 2022 - HEASA2022
28 September - 1 October 2022
Brandfort, South Africa

*Speaker

PoS(HEASA2022)002

1. Introduction

Flat Spectrum Radio Quasars (FSRQs) are a class of radio-loud active galactic nuclei (AGN) with relativistic jets oriented close to the observer within a few degrees [1]. The sources emit non-thermal radiation across the entire electromagnetic (EM) spectrum, from radio to very-high-energy γ-rays. They are characterized by strong and stochastic variability, high luminosity and polarization. These characteristics are the result of emissions enhanced by the bulk relativistic motion of plasma along the jet axis. Similar properties are also observed in BL Lac objects, and these two types of AGNs are collectively called blazars.

A key feature of blazars is that their fluxes fluctuate significantly over a broad range of time-scales, from minutes to years across the entire electromagnetic spectrum [16]. Examining the long-term flux variations over time is essential to understanding the physical processes that lead to variability in these systems. Analyses of lightcurves during different flux states and at various wavebands suggest that several blazars show lognormal flux distributions with the variations on the flux being proportional to the average flux [8, 17, 18], implying that lognormal variability is an intrinsic property of these sources.

PKS 0208-512 is an FSRQ located at a redshift of z=1.003. Several studies have been conducted on the multiwavelength properties of PKS 0208-512 [2, 10–12]. In [2], we studied the temporal and spectral properties of PKS 0208-512 during bright flares in γ-rays detected by Fermi-LAT, observed from 2019 November to 2020 May. The simultaneous observations obtained in X-ray, optical/UV using Swift-XRT/UVOT were used to perform a multiband temporal and SED study. The 2-days binned γ-ray lightcurve showed a double lognormal flux distribution, which can be associated with the two flux states, corresponding to high and low flux levels of the source.

In the present work, we used the long-term multi-band observations of PKS 0208-512 from 2008 August to 2017 September using the Fermi-LAT, Swift-XRT/UVOT, SMARTS telescopes. While [13] reported the long-term spectral study of PKS 0208-512 during 2008-2020, we investigate the long-term flux distribution for the source using multi-band observations from 2008 to 2017. Flux distribution studies using multiband observations have been performed previously by other authors [7, 8]. However; a long-term flux distribution study of PKS 0208-512 has not been carried out so far. The paper is constructed as follows: in section 2, we describe the data analysis procedure. In section 3, we present the flux distribution study of the selected lightcurves. Finally, in section 4, we discuss the results.

2. Observations and data analysis

2.1 *Fermi*-LAT

The LAT (Large Area Telescope) [14] is an electron-positron pair conversion γ-ray instrument on board the Fermi satellite launched by NASA in 2008. The instrument is sensitive in energy range between 20 MeV – 300 GeV. The LAT instrument has a large field of view (FoV) of 2.4 sr covers the entire sky every 3 hours. The source PKS 0208-512 has been continuously monitored by Fermi-LAT since August 2008.

We used data collected over $\sim$ 9 years, spanning from August 2008 to September 2017 (MJD 54698-58000) in our analysis. To analyze the γ-ray data, we followed the standard procedure based on the likelihood optimization method described in the Fermi science tools documentation.[1] The analysis was performed in the energy range from 100 MeV to 300 GeV, with a region of interest (ROI) of 10 degrees centred on the source position. The model xml file was generated using the "gll_iem_v07" galactic diffuse emission model and "$iso\_P8R3\_SOURCE\_V2$" isotropic background model, available at the Fermi Science Support Center. Spectral models and parameters for ROI sources are defined in the first version of 4FGL catalog [19]. Spectral parameters were optimized using the maximum Likelihood method, and sources with TS < 9 were excluded (corresponding to $\sim 3\sigma$). The analysis used the "unbinned likelihood analysis with python" by the Fermi collaboration.

The default spectral model for PKS 0208-512 is log-parabola, and the model parameters were optimized by the likelihood analysis. Consequently, we fit the source spectrum integrated over the entire energy range 0.1-300 GeV during the period MJD 54698-58000 with a log-parabola function. While producing the lightcurve, only the parameters for PKS 0208-512 were adjusted, while the parameters for others were frozen.

2.2 Swift-XRT/UVOT

Swift is a multi-waveband telescope specifically designed to detect the transient events in both the Galactic and extra-galactic sky. Both the X-ray Telescope (XRT, 0.3-10 keV) and the Ultraviolet-Optical Telescope (UVOT, 170-650 nm) with optical filters (U, B, V) and UV filters (W1, M2, W2), respectively, on board Swift are used in our study. Some of the brightest sources detected by *Fermi* are also continuously monitored by Swift[2] through the telescope's monitoring program.

The source PKS 0208-512 is regularly observed through the monitoring program and as part of a Target-of-Opportunity (ToO) program. We select the *Swift* observations during the period MJD 54698-58000, similar to the period used for the Fermi-LAT analysis. We used the online *Swift*-XRT products generation tool[3] [4], which utilizes HEASOFT software version 6.22. The tool generates X-ray lightcurves, spectra, and images of any point source within the field of view of the Swift-XRT and accounts for instrumental artifacts such as pile-up and bad column CCD corrections. The XRT online tool provides 0.3–10 keV X-ray spectra for each observation. Using XSPEC (Arnaud 1996), we fit the X-ray spectrum of each observation with an absorbed power-law model to estimate the flux. A Swift-XRT lightcurve is then created, with each point representing the results from a single observation.

Swift UVOT ([5]) covers a wide range of optical-UV wavelengths. To extract the magnitudes from each of the images, the task `UVOTSOURCE` has been used with source and background regions of 5 arcsecs and 10 arcsecs, respectively. A detailed analysis is discussed in [2].

2.3 SMARTS

We collected data of PKS 0208-512 from the SMARTS 1.3m telescope during the period MJD 54698 - 58000, with observations available in optical (B, V, R) and near-IR (J, K) bands. The details of data access, calibration and reduction are described in [6].

[1]https://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/
[2]https://www.swift.psu.edu/monitoring/
[3]https://www.swift.ac.uk/user_objects/

3. Flux distribution study

We selected reliable flux measurements for each time bin, i.e. at least a detection at 2-sigma level (flux > 2× error in flux) for each band. The multi-band flux lightcurves are presented in Figure 1. The selected lightcurves are then investigated with the Anderson-Darling (AD) test statistics and histogram fitting in order to characterize their flux distributions.

3.1 AD Test

Generally, the flux distribution of blazar lightcurves shows an asymmetric/tailed pattern. The Anderson-Darling (AD) test is a useful method for determining if the data follows a normal distribution [15]. The p-value, or probability of the null hypothesis, can be used to determine if the distribution of the data sample is drawn from a particular distribution (such as a normal distribution in our case). The AD test computes this p-value, with a value below 0.01 suggesting a deviation from normality in the data sample. The analysis of the γ-ray lightcurve, X-ray lightcurve and optical lightcurve using the AD test shows that the fluxes follow neither a Gaussian nor a lognormal distribution. The AD statistic and the p-value results of PKS 0208-512 are summarized in Table 1.

3.2 Flux Histogram

In addition to the AD test analysis, we construct the histograms of the log of flux of PKS 0208-512 for the selected lightcurves. The flux histograms in the γ-ray, X-ray and optical bands exhibit a double peak and are fitted with a double lognormal probability density function (PDF) (see Equation 3. of [7]). The histogram plots are shown in Figure 2. These results are consistent with the AD test results. Similar results have been found before for the 2-day binned γ-ray lightcurve of PKS 0208-512 [2].

4. Discussion and Conclusions

In this work, we report for the first time a long-term flux distribution study of the blazar PKS 0208-512, using *Fermi*-LAT, *Swift*-XRT/UVOT and SMARTS observations from 2008 August to 2017 September. The flux distributions of the selected lightcurves are characterized by the AD test and histogram fitting methods. The AD test statistic suggests that the flux distributions of the lightcurves in all the energy bands do not conform to either a Gaussian or a lognormal distribution. Moreover, the flux histograms display two distinct peaks and are successfully modeled using double lognormal probability density functions (PDFs). In [2], the double lognormal flux distribution is evident in the 2-days binned γ-ray lightcurve of PKS 0208-512, for the duration from 2017 September to 2020 July. In this study, we discovered the double lognormal flux distribution in the γ-ray, X-ray, and optical bands in the duration 2008-2017. In the case of FSRQ sources like PKS 0208-512, the optical and γ-ray are beyond the break energy of the synchrotron and Compton components, which implies that they are mainly produced by the highest-energy electrons. On the other hand, the X-ray band is below the peak frequency of the Compton component and is primarily a result of the lower energy portion of the electron distribution. The obtained double lognormal flux distribution results suggest that the emission in the γ-ray, X-ray, and optical bands are produced in the same emission region and may be related to the two flux states of the source.

PoS(HEASA2022)002

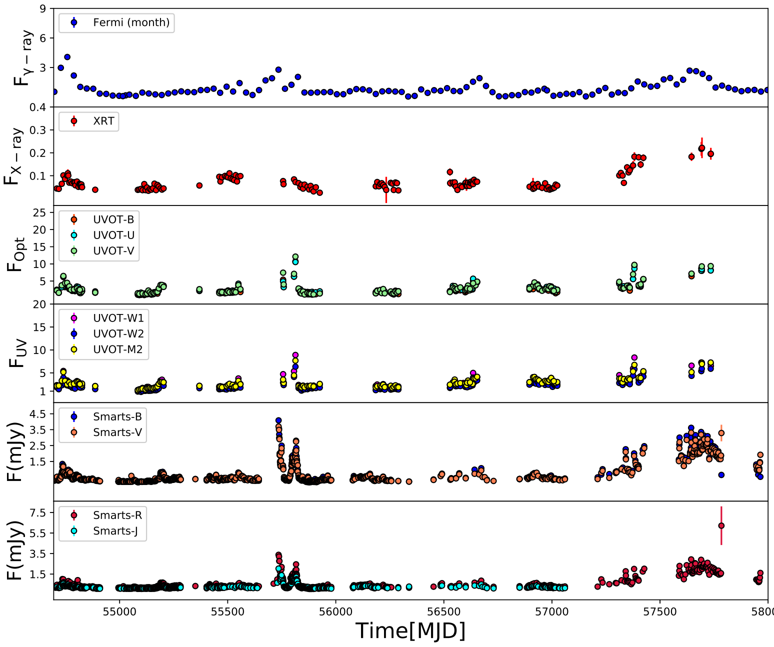

Figure 1: Multiwaveband flux lightcurves of PKS0208-512 from 2008(August)-2017(September) (MJD 54698-58000) showing in panel 1: *Fermi*-LAT flux in 10^{-7} ph cm^{-2} s^{-1}, panel 2: *Swift*-XRT flux in 10^{-12} erg cm^{-2} s^{-1}, panels 3 & 4: Optical and UV flux in 10^{-12} erg cm^{-2} s^{-1} (in the Swift-UVOT B, U and V bands, and Swift-UVOT W1, W2, M2 bands); panels 5 & 6 : Optical and near-IR flux in mJy (in the SMARTS B, V bands, and SMARTS R, J bands).

5. Acknowledgements

R. K. and M. B. acknowledge support from the South African Research Chairs Initiative (SARChI, grant no. 64789) of the Department of Science and Innovation. R. P. acknowledges the support of the Polish Funding Agency National Science Centre, project 2017/26/A/ST9/-00756(MAESTRO 9) and the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation program (grant agreement No. 951549).

References

[1] Urry C. M., Padovani P., 1995, PASP, 107, 803

[2] Khatoon, R.; Prince, R.; Shah, Z.; Sahayanathan, S.; Gogoi, R. Temporal and spectral study of PKS 0208-512 during the 2019-2020 flare. MNRAS 2022, 513, 611–623.

[3] Mattox J. R., et al., 1996, ApJ, 461, 396

[4] Evans P. A. et al., 2009, MNRAS , 397, 1177

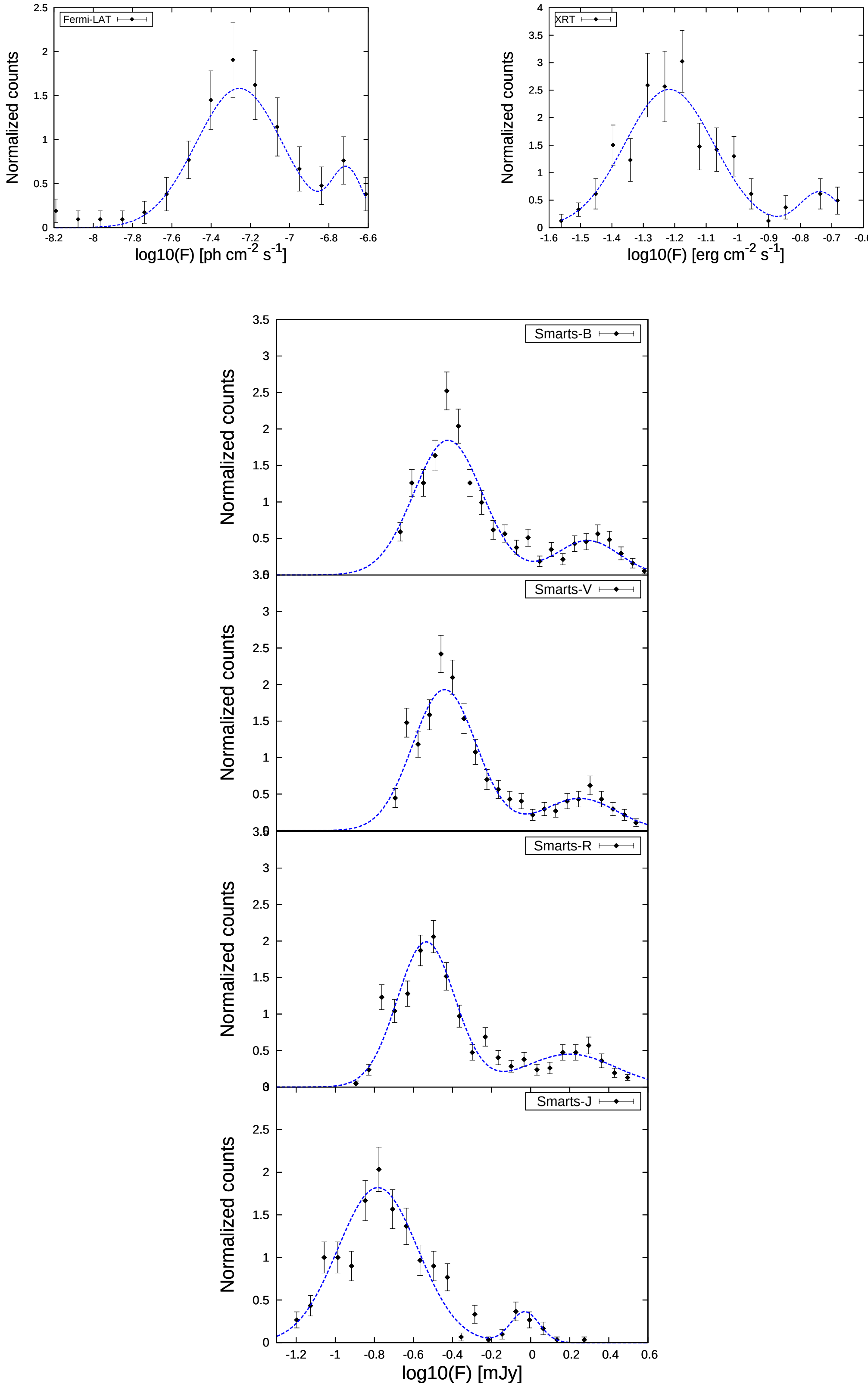

Figure 2: Multi-wavelength flux histograms of PKS 0208-512 from IR to γ-ray energies.

Table 1: AD test results for the normal and lognormal fluxes of the γ-ray, X-ray, optical and near-IR lightcurves for the source PKS 0208-512.

Facility	Normal (Flux) AD(p–value)	Lognormal (Flux) AD(p–value)
Fermi	$6.4(8.1 \times 10^{-16})$	$1.2(5.7 \times 10^{-4})$
Swift-XRT	$9.2(1.8 \times 10^{-22})$	$1.7(1.8 \times 10^{-4})$
SMARTS-B	$76.1(3.7 \times 10^{-24})$	$26.3(3.7 \times 10^{-24})$
SMARTS-V	$77.9(3.7 \times 10^{-24})$	$27.5(3.7 \times 10^{-24})$
SMARTS-R	$76.5(3.7 \times 10^{-24})$	$23.4(3.7 \times 10^{-24})$
SMARTS-J	$47.3(3.7 \times 10^{-24})$	$5.1(1.2 \times 10^{-12})$

[5] Roming P. W. A., et al., 2005, Space Sci. Rev., 120, 95

[6] Bonning E., et al., 2012, ApJ, 756, 13

[7] Khatoon R., Shah Z., Misra R., Gogoi R., 2020, MNRAS, 491, 1934

[8] Shah, Z., Mankuzhiyil, N., Sinha, A., et al.: Log-normal flux distribution of bright Fermi blazars. Research in Astronomy and Astrophysics, 18, 141 (2018)

[9] Tosti G., 2008, The Astronomer's Telegram, 1759, 1

[10] Zhang S., Collmar W., Torres D. F., Wang J. M., Lang M., Zhang S. N., 2010, A&A, 514, A69

[11] Chatterjee R., et al., 2013a, ApJ, 763, L11

[12] Chatterjee R., Nalewajko K., Myers A. D., 2013b, ApJ, 771, L25

[13] Ammenadka K. M., Bhattacharya D., Bhattacharyya S., Bhatt N., Stalin C. S., 2022, *Universe*, 8,534

[14] Atwood W. B., et al., 2009, ApJ, 697, 1071

[15] Press W. H., Teukolsky S. A., Vetterling W. T., Flannery B. P., 1992, Numerical Recipes in FORTRAN: The Art of Scientific Computing. Cambridge Univ. Press, Cambridge

[16] Shukla A., Mannheim K., 2020, Nature Communications , 11, 4176

[17] Kushwaha P., Chandra S., Misra R., Sahayanathan S., Singh K. P., Baliyan K. S., 2016, ApJ, 822, L13

PoS(HEASA2022)002

[18] Sinha A., Khatoon R., Misra R., Sahayanathan S., Mandal S., Gogoi R., Bhatt N., 2018, MNRAS, 480, L116

[19] S. Abdollahi and F. Acero and M. Ackermann et al., 2020, The American Astronomical Society, 247, 33