

Detection of quasiperiodic oscillations in the blazar PKS 0735+178 with *TESS*

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ABSTRACT

We report here the detection of signatures of a quasiperiodic oscillation (QPO) and a short flare in the optical light curve of the blazar PKS 0735+178, observed in two sectors, 71 and 72, spanning around 49 d with the *Transiting Exoplanet Survey Satellite*. The modest flare in sector 71 lasted ~ 4.3 d and appears as a combination of two sub-flares. In sector 72, a transient QPO with a period ~ 11.2 h is detected at local and global significance levels of 4.11σ and 3.06σ , respectively. We used weighted wavelet z transform, Lomb–Scargle periodogram, and phase dispersion minimization analysis techniques to look for and confirm the QPO feature. We also performed a segment-wise statistical inspection of these light curves and discuss here possible mechanisms that could explain the observed flux behaviour.

Key words: radiation mechanisms: non-thermal – galaxies: active – BL Lacertae objects: individual: PKS 0735 + 178 – gamma-rays: galaxies.

1 INTRODUCTION

A subclass of radio-loud (RL) active galactic nuclei (AGNs), blazars emit radiation in all electromagnetic (EM) bands, from radio to γ -rays. Blazars contain relativistic charged particle jets that are nearly aligned with the observer's line of sight (C. M. Urry & P. Padovani 1995). The jet emission dominates the total observed fluxes from blazars in almost all EM bands due to relativistic effects, which produce significantly magnified observed emissions due to the extremely small viewing angle. Blazars exhibit notable flux, spectral, and polarization variation across the whole EM spectrum, with non-thermal processes dominating their emission (e.g. C. M. Urry et al. 1997; M. Böttcher et al. 2007; F. Aharonian et al. 2009; A. A. Abdo et al. 2010a, b; M. Hayashida et al. 2015; A. C. Gupta et al. 2017, 2023; C. M. Raiteri et al. 2017, 2024, and references therein). Flat spectrum radio quasars (FSRQs) and BL Lacertae objects (BLLs) are together referred to as blazars. In the composite optical/UV spectrum, BLLs show featureless or very faint emission lines with equivalent widths (EWs) ≤ 5 Å, whereas FSRQs show strong emission lines. Blazar spectral energy distributions (SEDs) exhibit a double-hump structure, with the low-energy and high-energy humps peaking in infrared (IR) to X-ray bands and γ -ray energies, respectively (e.g. G. Fosfati et al. 1998). Ultra-relativistic electrons in the jet are the source of the low-energy component of the SED via synchrotron radiation, and the high-energy component can usually be explained by inverse Compton (IC) emission, either via synchrotron self-

Compton or external Compton processes (e.g. M. Böttcher et al. 2013; R. Blandford, D. Meier & A. Readhead 2019; C. M. Raiteri 2025, and references therein).

The light curves (LCs) of X-ray binaries have frequently shown nearly periodic oscillations, also known as quasi-periodic oscillations (QPOs; R. A. Remillard & J. E. McClintock 2006). The literature has reported the detection of QPOs in blazars and other subclasses of AGN with diverse periods, despite the fact that the LCs of AGN are primarily non-periodic across the whole EM spectrum (e.g. L. Carrasco, D. Dultzin-Hacyan & I. Cruz-Gonzalez 1985; E. Valtaoja et al. 1985; F. Fiore et al. 1989; I. E. Papadakis & A. Lawrence 1993; K. Iwasawa et al. 1998, and references therein). After evidence of a QPO with a period of ~ 1 h was discovered in the X-ray LC of the AGN RE J1034+396 (M. Gierliński et al. 2008), the search for QPOs in various subclasses of AGN LCs has emerged as an important scientific project in extragalactic astronomy that has employed various analysis techniques. There have been strong claims of occasional QPO detection in several blazars on diverse time-scales ranging from a few minutes to days to weeks to months and even years in different EM bands, e.g. radio (O. G. King et al. 2013; J.-Y. Wang et al. 2014; A. Tripathi et al. 2024; A. C. Gupta et al. 2026, and references therein), infrared (IR)/optical (A. C. Gupta, A. K. Srivastava & P. J. Wiita 2009; A. Sandrinelli, S. Covino & A. Treves 2014; G. Bhatta et al. 2016; A. Sandrinelli et al. 2016; P. Zhang & Z. Wang 2022, and references therein), X-ray (P. Lachowicz et al. 2009; B. Rani, P. J. Wiita & A. C. Gupta 2009; E. Smith, L. Oramas & E. Perlman 2023; B.-K. Zhang et al. 2025, and references therein), and γ -rays (J. Zhou et al. 2018; G. Bhatta 2019; A. Roy et al. 2022; A. K. Das et al. 2023; P. Peñil et al. 2025, and references therein). There even have been

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some claims of blazar QPOs being detected simultaneously in more than one EM band (e.g. M. Ackermann et al. 2015; A. Sarkar et al. 2020, 2021; S. G. Jorstad et al. 2022, and references therein). Evidence for the detection of QPOs in a few other, less variable, subclasses of AGN has also been reported (e.g. M. Gierliński et al. 2008; W. N. Alston et al. 2014, 2015; H.-W. Pan et al. 2016; A. C. Gupta et al. 2018; L. Zhu et al. 2025, and references therein).

Detection of flares in blazars on diverse time-scales in different EM bands is very common. In general, blazars can be said to be in one of three different flux states, namely, quiescent, pre- and/or post-flare, and outbursting or flaring (e.g. A. Sillanpää et al. 1996; C. M. Raiteri et al. 2013; S. G. Jorstad et al. 2022; K. Dogra et al. 2025; A. Manzoor et al. 2026, and references therein). In flare and outburst states, the emission is due to nonthermal processes, but in the quiescent states, the observed flux of a blazar can be a mixture of thermal and nonthermal emission. There have been quite a few detections of flares in many blazars in different EM bands on diverse time-scales (e.g. F. Montagni et al. 2006; F. Aharonian et al. 2007; H. Gaur et al. 2010; A. Pandey, A. C. Gupta & P. J. Wiita 2017; S. G. Jorstad et al. 2022; S. Kishore et al. 2024a; S. Kishore, A. C. Gupta & P. J. Wiita 2024b, and references therein). In simultaneous multiwavelength (MW), observations of blazars flares are typically detected in different EM bands with different amplitudes, with interband temporal lags varying from essentially zero to a few hundreds of days (e.g. C. M. Urry et al. 1997; P. Giommi et al. 2006; C. M. Raiteri et al. 2007, 2013, 2024; F. Aharonian et al. 2009; S. G. Jorstad et al. 2010, and references therein).

PKS 0735+178 is a BLL at redshift $z = 0.45 \pm 0.06$, as estimated from the detection of its host galaxy (K. Nilsson et al. 2012). Using about a century (1906–2001) of optical data, B. Qian & J. Tao (2004) reported a dominant QPO period of 13.8 yr. The source has been extensively studied in search of its optical flux, colour, and polarization variability and has shown variations of these physical properties on diverse time-scales (e.g. S. Ciprini et al. 2007; A. Goyal et al. 2009; L. O. Takalo et al. 2010; Y. H. Yuan & J. H. Fan 2021; C. McCall et al. 2024, and references therein). It has also shown significant flux and spectral variations in its MW observations (e.g. A. Goyal et al. 2017; Y. Fang et al. 2022; A. Acharyya et al. 2023; A. M. Bharathan et al. 2024; R. Prince et al. 2024, and references therein). Several neutrino events detected by the IceCube, Baikal, Baksan, and KM3NeT neutrino telescopes during the blazar PKS 0735+178's December 2021 flare in the γ -ray, X-ray, ultraviolet, and optical bands may be linked to this object. This blazar was thoroughly studied in order to look into the spectral and temporal variations in the MW emission during the neutrino events (A. Acharyya et al. 2023; N. Sahakyan et al. 2023; A. M. Bharathan et al. 2024). Superluminal motion has been detected by very long baseline interferometry (VLBI) studies of PKS 0735+178's parsec-scale jet, yielding estimates of the jet viewing angle, $\Theta = 5.7 \pm 1.4$ deg, and Doppler factor $\delta = 8.5 \pm 4.0$ (S. G. Jorstad et al. 2017).

In this paper, we report the detection of a two-component flare spanning around 4.5 d in composite, and a QPO with a period of around 11.2 h in the *Transiting Exoplanet Survey Satellite* (*TESS*) optical LC of the blazar PKS 0735+178. Variability with time-scales of less than a day is often called intraday variability (IDV; S. J. Wagner & A. Witzel 1995) and is one of the most puzzling issues in blazar astrophysics.

In Section 2, we provide information about the *TESS* optical data and Fermi γ -ray data we have investigated. In Section 3,

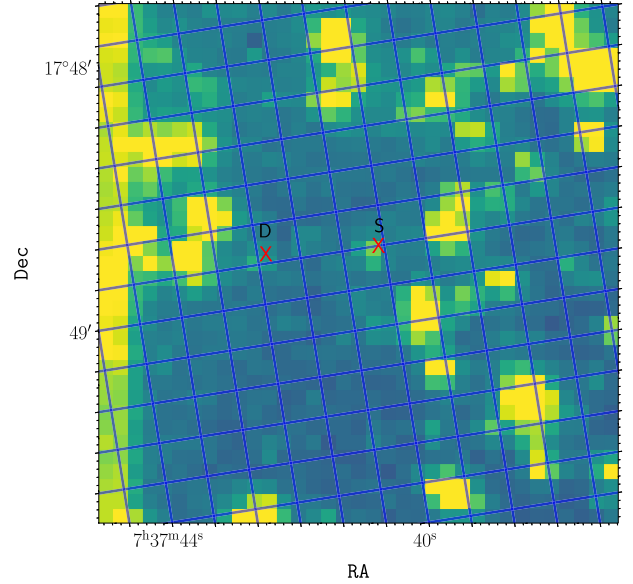


Figure 1. A 35×35 pixel cutout of sector 71 *TESS* field of view, including the source ('S') and the comparison star ('D').

different analysis techniques that we implemented on the optical data are presented. In Section 4, we present the results with the optical data. The γ -ray data show an almost invariable behavior, so we give only a qualitative comparison between these bands in Section 4. A discussion and conclusions are presented in Section 5.

2 DATA ACQUISITION

2.1 Optical data set

TESS observes in a survey mode, covering the whole sky through a total of 26 sectors. It continues to observe each sector for ~ 27 d (J. M. Jenkins et al. 2016). We obtained an 11×11 pixel cutout of the full frame images (FFI) of the portion of sky pointing towards PKS 0735+178, centred at the source, or 'S', which was observed in sectors 71 and 72 (2023 October 19th to 2023 December 7th). Additionally, we obtained a similar cutout of the FFI of the comparison star 'D' during sectors 71 and 72 to perform and obtain normalized differential photometric LCs of PKS 0735+178 (see fig. 1 of P. S. Smith et al. 1985, for the field of view PKS 0735+178 and the nearby comparison star 'D'). The star 'D' was selected for the differential photometry because of its being relatively less crowded than other possible comparison stars, so we could neglect other flux contributions from its vicinity.

For differential photometry, an optimal aperture was chosen for both PKS 0735+178 and star 'D' at the center of the respective cutouts, such that the pixel flux value exceeds the background by at least 2σ levels, after which aperture photometric LCs were obtained for the source and 'D' in each sector. Since the source and 'D' are not very distant ($(\Delta\alpha, \Delta\delta) = (0.003862^\circ, 0.044377^\circ)$; Fig. 1 demonstrates the positions of the source and 'D' in a 35×35 cutout of the full frame image in sector 71), it is safe to assume that any instrumental artefact would affect PKS 0735+178 and 'D' in a similar manner. We then obtained the background LCs to obtain background-subtracted LCs of the source and 'D' in the

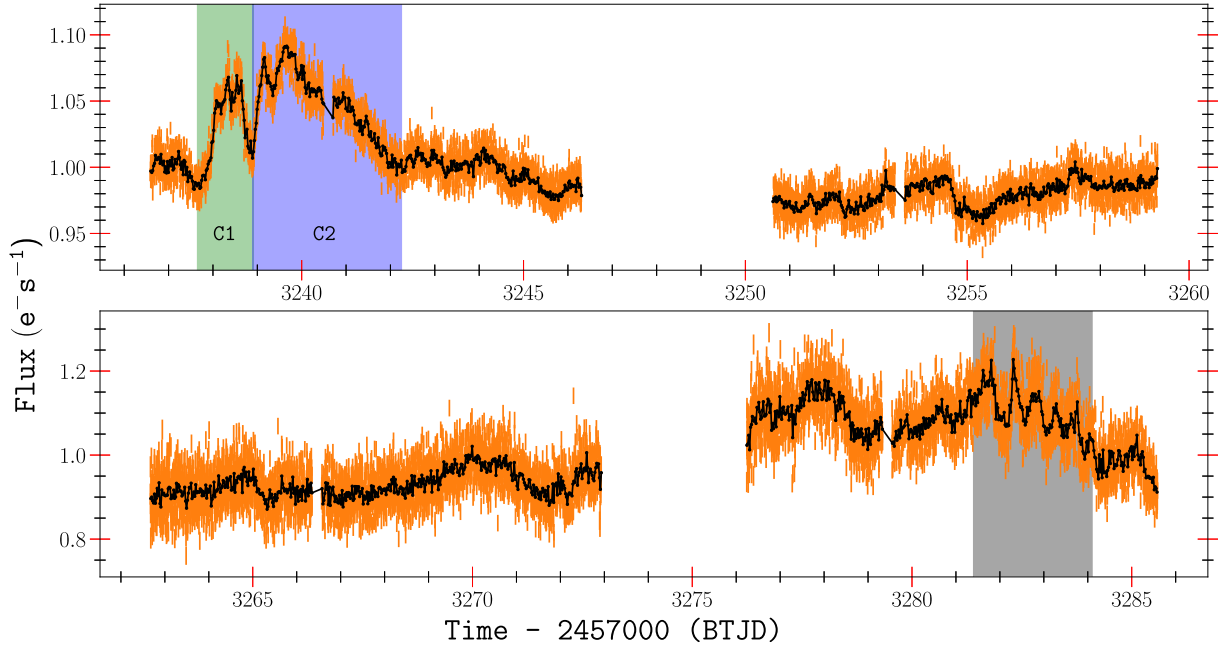


Figure 2. Normalized LCs of PKS 0735+178 observed in sectors 71 (upper panel) and 72 (lower panel); High scattered points (orange) have a cadence of 200s, which we have used in our analysis; less scattered points (black) are 30-min binned LCs, overplotted here to demonstrate the flux variations more clearly. Shaded regions C1 and C2 denote the two components of the strongest flare during these observations; the shaded region in sector 72 LC highlights the span where the QPO search was conducted.

two sectors. Each of the sectoral ‘D’ LCs was then divided by its corresponding median flux value to make a normalized ‘D’ LC. Since the comparison star remains invariable, the behaviour of the normalized ‘D’ LC mimics the pixel response function throughout the sectoral observation, and should ideally be unity. However, near the ends of each segment of both sectors, this normalized LC shows relatively high values, so we further made a cutoff of 15 per cent about unity to the pixel response function values, along with additional cuts where they show a sharp change, to discard any contingent behaviour of the pixels, and eliminate those data points from the ‘D’ and ‘S’ LCs.

The background-subtracted LCs of the source are then divided by these pixel response function values at corresponding epochs, followed by a further division by the mean sectoral flux counts of the source to obtain its sectoral normalized differential photometric LCs. In the appendix, we present the background LC, the normalized LC of ‘D’, the raw LC of PKS 0735+178, and the pixel response function corrected LC of the source in sectors 71 and 72 (Fig. A1 and A2). The sectoral normalized LCs of the source in Fig. 2 are simply obtained by dividing the pixel response function corrected LC by their sectoral mean values. The data acquisition and handling were performed using the LIGHTKURVE (Lightcurve Collaboration 2018) PYTHON package. Fig. 2 presents the thus obtained normalized LCs of the source PKS 0735+178 in the two sectors 71 and 72. The *TESS* observations have a default gap of 2-4 d in the middle of each sector during which it sends the observed data to Earth or waits for any instructions to be uploaded, creating a default unevenness in cadences that makes it difficult to search for possible periodicities when an entire sector is considered. Thus, we divided the two sectoral LCs into four segments: 1/71, 2/71, 1/72, and 2/72, for the purpose of our analysis.

2.2 γ -ray data set

For this work, we analysed *Fermi*-LAT Pass 8 γ -ray data of PKS 0735+178 obtained from the Fermi Science Support Center (FSSC) server (Fermi Science Support Center 2026), covering a period of 69 d (2023 October 9th to 2023 December 17th). The data were extracted from a circular region of a radius 30° , centred on PKS 0735+178, covering the energy range 0.1–300 GeV. The *Fermi*-LAT is a space-based high-energy gamma-ray instrument capable of observing photons over an energy range between 20 MeV–300 GeV. It is an imaging, pair-conversion telescope with a wide-field-of-view (2.7 sr at 1 GeV and above (W. B. Atwood & others 2009)), monitoring the entire sky approximately every three hours in this γ -ray band.

The dataset was analysed using an open-source PYTHON package FERMIPY (v1.0.1; M. Wood et al. 2017). For analysis, we defined a square region of $10^\circ \times 10^\circ$ centred on the source of interest. An energy cut between 0.1 GeV and 300 GeV was applied, while to reduce contamination from the Earth’s limb gamma-rays, a zenith angle cut above 90° was also imposed. For event selection, we used `evclass=128` and `evtype = 3` corresponding to the ‘P8R3_SOURCE’ class, including both front & back events. To ensure high-quality data collection, we applied `DATA_QUAL > 0` & `LAT_CONFIG == 1`.

We used the *Fermi*-LAT Fourth Source Catalog Data Release 4 (4FGL-DR4; `gll_psc_v35.fits`; J. Ballet et al. 2023), along with the Galactic diffuse emission described by the `gll_iem_v07` template (F. Acero et al. 2016) and the isotropic extragalactic background modelled using `iso_p8r3_source_v3_v1.txt`. During the likelihood analysis, the parameters of the target source, 4FGL J0738.1+1742, together with the normalizations of the isotropic (isodiff) and Galactic diffuse (galdiff) components, were left free.

The target source was modelled with a log-parabola spectrum, with its normalization, spectral index (alpha), and curvature

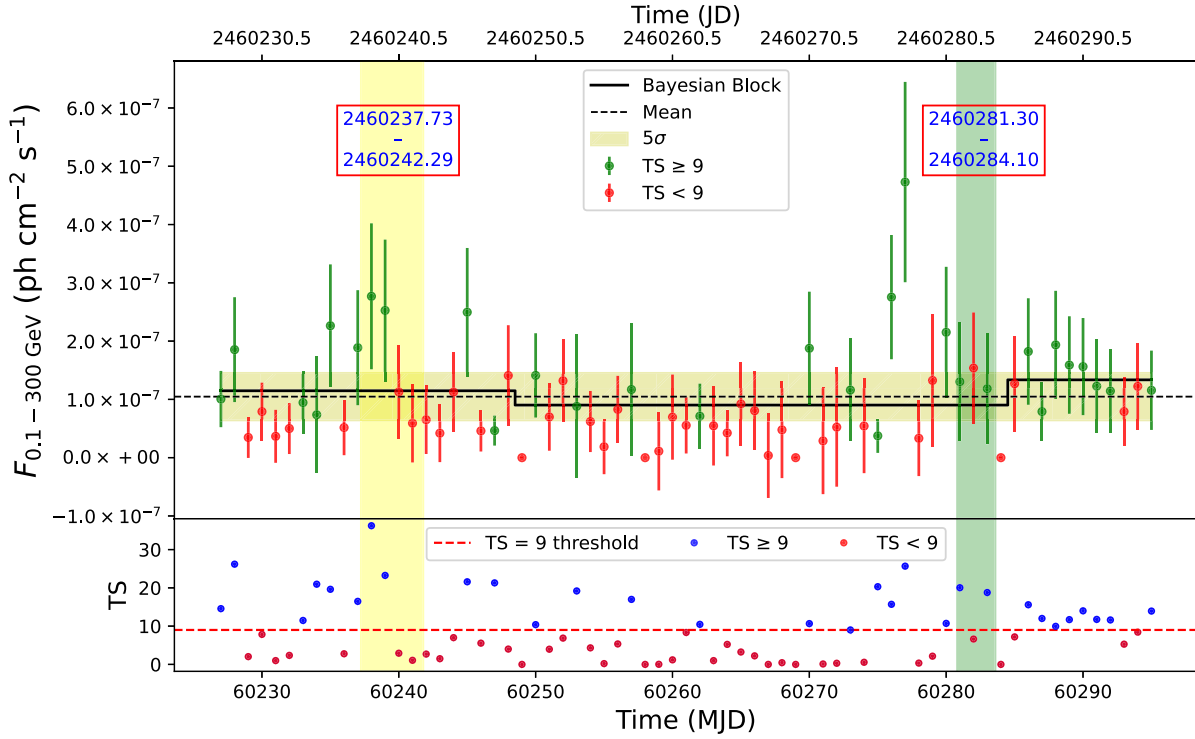


Figure 3. γ -ray LC of PKS 0735+178 during the time window of *TESS*'s sectors 71 and 72; the vertical shaded regions (left: yellow and right: green) respectively mark the epochs of the optical flare and QPO. Data points are colour-coded by statistical significance: red indicates $TS < 9$, while significant detections ($TS \geq 9$) are shown in green (upper panel) and blue (lower panel). The horizontal red-dashed line in the lower panel marks the $TS = 9$ threshold.

(beta) allowed to vary. In addition, normalizations of all sources within the 5° around 4FGL J0738.1+1742 were kept free. The fit was performed using `gta.fit()` with the `NEWMINUIT` optimizer, iterating until the fit quality reached 3 to obtain the best-fitting model. After this step, following the `FERMIPY` user documentation (Fermipy Collaboration 2016), the 1-D binned *Fermi*-LAT gamma-ray light curve for PKS 0735+178 was extracted as shown in the upper panel of Fig. 3. The lower panel shows the test statistic (TS). Here, TS stands for test statistic. It is the primary numerical value used to quantify the statistical significance of a source detection. $TS = 25$ corresponds to 5σ detection, whereas $TS = 9$ corresponds to 3σ detection. In both panels, red points correspond to $TS < 9$, while points with $TS \geq 9$ are shown in green (upper panel) and blue (lower panel). In the upper panel, the horizontal dashed black line represents the average gamma-ray flux, the solid black line shows the Bayesian Block representation (J. D. Scargle et al. 2013), and the horizontal yellow band indicates the 5σ range about the mean flux. In the lower panel, the horizontal red-dashed line marks $TS = 9$. The vertical yellow and green bands denote the epochs of the optical flare and QPO, respectively.

3 DATA ANALYSIS

3.1 Fractional variability

Blazars show diverse variability properties all over the EM spectrum on all time-scales ranging from hours to years. When observed over appreciable timespans, they usually show both

variable and quiescent phases. The four segmented LCs presented in Fig. 2 show both quite variable and nearly non-variable states over spans of around 10 d. The root mean square variability amplitude or the square root of excess variance (S. Vaughan et al. 2003) provides a simple way to quantify the intrinsic variation of LCs for any timespan. Taking into account the associated uncertainty, it has the ability to discard the variations due to any instrumental Poisson noise. For any timeseries data, $y(t)$,

$$F_{\text{var}} = \sqrt{\frac{S^2 - \sigma_{\text{err}}^2}{\bar{y}^2}}, \quad (1)$$

$$S^2 = \frac{1}{n-1} \sum (y - \bar{y})^2 \quad (2)$$

and

$$(F_{\text{var}})_{\text{err}} = \sqrt{\left[\sqrt{\frac{1}{2n}} \frac{\sigma_{\text{err}}}{F_{\text{var}} \bar{y}^2} \right]^2 + \left[\sqrt{\frac{\sigma_{\text{err}}^2}{n}} \frac{1}{\bar{y}} \right]^2}, \quad (3)$$

here F_{var} is the fractional root mean square variability amplitude; $S^2 - \sigma_{\text{err}}^2$ is residual variability after removing the expected contribution from the associated uncertainties; $\bar{y}$, σ_{err}^2 and n respectively denote the mean flux, mean square uncertainty and the number of data points. We examined the segmented LCs with the above variability test and present them in Table 1. Additionally, we examined separately the flaring region of the first segment of sector 71, evaluating F_{var} with respect to a nominal mean flux before the onset of the flare.

Table 1. Segmentwise statistical characteristics of the LCs of sectors 71 and 72.

Segment	Epochs (BTJD)	F_{var} (%)	A	Power-law parameters	
				α	c
1/71	3236.588-3246.304	3.01 ± 0.01	$1.38^{0.16}_{0.15} \times 10^1$	$2.27^{0.07}_{0.07}$	$7.30^{0.36}_{0.36} \times 10^{-2}$
2/71	3250.628-3259.289	1.15 ± 0.01	$1.28^{0.24}_{0.20} \times 10^1$	$2.13^{0.16}_{0.14}$	$4.88^{0.23}_{0.23} \times 10^{-1}$
1/72	3262.667-3272.930	4.73 ± 0.03	$6.77^{1.45}_{1.19}$	$2.01^{0.22}_{0.19}$	$6.54^{0.28}_{0.28} \times 10^{-1}$
2/72	3276.238-3285.587	6.46 ± 0.03	$1.89^{0.26}_{0.23} \times 10^1$	$1.97^{0.09}_{0.08}$	$3.38^{0.17}_{0.16} \times 10^{-1}$

3.2 Weighted wavelet Z analysis (WWZ)

To inspect for the existence of a periodic or quasi-periodic component in any timeseries data, multiple techniques have been formulated. One commonly employed technique is the WWZ method, which has the ability to dissociate the timeseries into time and frequency domains simultaneously. This method utilizes the convolution of a mother wavelet with the timeseries to produce a two-dimensional map of normalized power as a function of time and temporal frequency, utilizing scale and location parameters of the mother wavelet. The WWZ technique has an advantage over other approaches because it can clearly reveal the length of time any periodic fluctuation persists in the timeseries and is very helpful in detecting and assessing any transient QPOs, which are the type typically seen in blazars. The two-dimensional map can also be utilized to visually segment a specific portion of the timeseries where the periodic fluctuation is maximum and to evaluate its significance.

We considered the Morlet wavelet, given by $f(z) = e^{-cz^2} (e^{iz} - e^{-1/4c})$, as the mother wavelet to convolve with the LC, using $z = \omega(t - \tau)$. We then can evaluate the WWZ map, which is given as

$$W[\omega, \tau : x(t_\alpha)] = \omega^{1/2} \sum_{\alpha=1}^N x(t_\alpha) f^*[\omega(t_\alpha - \tau)], \quad (4)$$

where $x(t_\alpha)$, ω , τ , and N are the flux at the timestamp t_α , angular frequency, wavelet location, and number of data points, respectively. Because of the finite data length, an edge effect, known as the region of influence (ROI) comes into play while evaluating the WWZ map. We employed this test over the oscillatory fluctuations observed in sector 72. As this feature in the second segment of sector 72 appears from BTJD ~ 3281 to 3284, to encounter the edge effect, we conservatively employed the WWZ analysis between the epochs BTJD 3280.47 and 3285.65. The resultant map is presented in the upper left panel of Fig. 4, where the mildly white shaded region denotes the ROI, where the signal is unreliable.

3.3 Lomb–Scargle periodogram

To further confirm the apparent QPO signal against the background power spectrum, we utilized the well-known and traditionally utilized generalized Lomb–Scargle periodogram (e.g. N. R. Lomb 1976; J. D. Scargle 1982; M. Zechmeister & M. Kürster 2009, and references therein). This method allows the estimation of the intrinsic power spectral density (PSD) or periodogram shape of any timeseries data, along with the detection of any periodic behavior in it. A possible QPO appears as a peak in the periodogram. The PSDs of blazars are most commonly described at temporal frequencies (ν) by a red noise power law shape (e.g. S. Vaughan 2005) given as

$$P(\nu) = A\nu^\alpha + c, \quad (5)$$

where A , α , and c respectively denote the normalization constant, PSD slope, and white noise level. Other shapes have also been used to describe the PSD shapes on time-scales of a few days (e.g. S. Kishore, A. C. Gupta & P. J. Wiita 2026, and references therein). In addition to indicating whether any QPOs are present, the PSD is also helpful in extracting information on the source of emission as different physical models for AGN variability can yield distinct ranges for the PSD slopes (e.g. P. Mohan & A. Mangalam 2015; M. Pollack, D. Pauls & P. J. Wiita 2016; Y. Li et al. 2018; A. E. Wehrle, M. Carini & P. J. Wiita 2019). Hence, apart from applying this test for the oscillatory nature in sector 72, we made segment-wise LSP analyses of the source's *TESS* LCs. We fit the PSD of the respective LC using minimization of negative log-likelihood method to derive the free parameters of the fitting PSD model. The joint log-likelihood statistic ($\mathcal{L}$) is given as

$$\mathcal{L} = -2 \sum_j \frac{I_j}{P_j} + \log P_j \quad (6)$$

where I_j and P_j denote the observed periodogram and the model spectrum, respectively. The corresponding uncertainties of the fitting parameters were evaluated following O. González-Martín & S. Vaughan (2012).

3.4 Phase dispersion minimization (PDM)

Apart from the PSD investigation, which is a Fourier-based approach, PDM is another tool well suited for searching for any periodic variations in a LC (R. F. Stellingwerf 1978). It has the ability to handle an unevenly sampled data set with varying time gaps. Additionally, it is effective with sparse data and is particularly useful for non-sinusoidal variations. It minimizes the dispersion of a data set at constant phase, defined by the statistic $\Theta = s^2/\sigma^2$, where σ^2 is the variance of the dataset. Here we take M distinct samples of the dataset, having similar phases with variances s_j^2 ($j = 1, \dots, M$) and n_j data points, and s^2 is the overall variance of the samples, given as

$$s^2 = \frac{\sum (n_j - 1) s_j^2}{\sum n_j - M}. \quad (7)$$

The goal of this method is to minimize the variance of the dataset over different trial periods with respect to the mean LC. We have utilized PYASTRONOMY (S. Czesla et al. 2019) python package to estimate the Θ -statistic at different trial frequencies.

4 RESULTS

4.1 QPO features

Looking at the WWZ map in Fig. 4, a region of high power consistent with a transient QPO signal can be observed at $\approx$

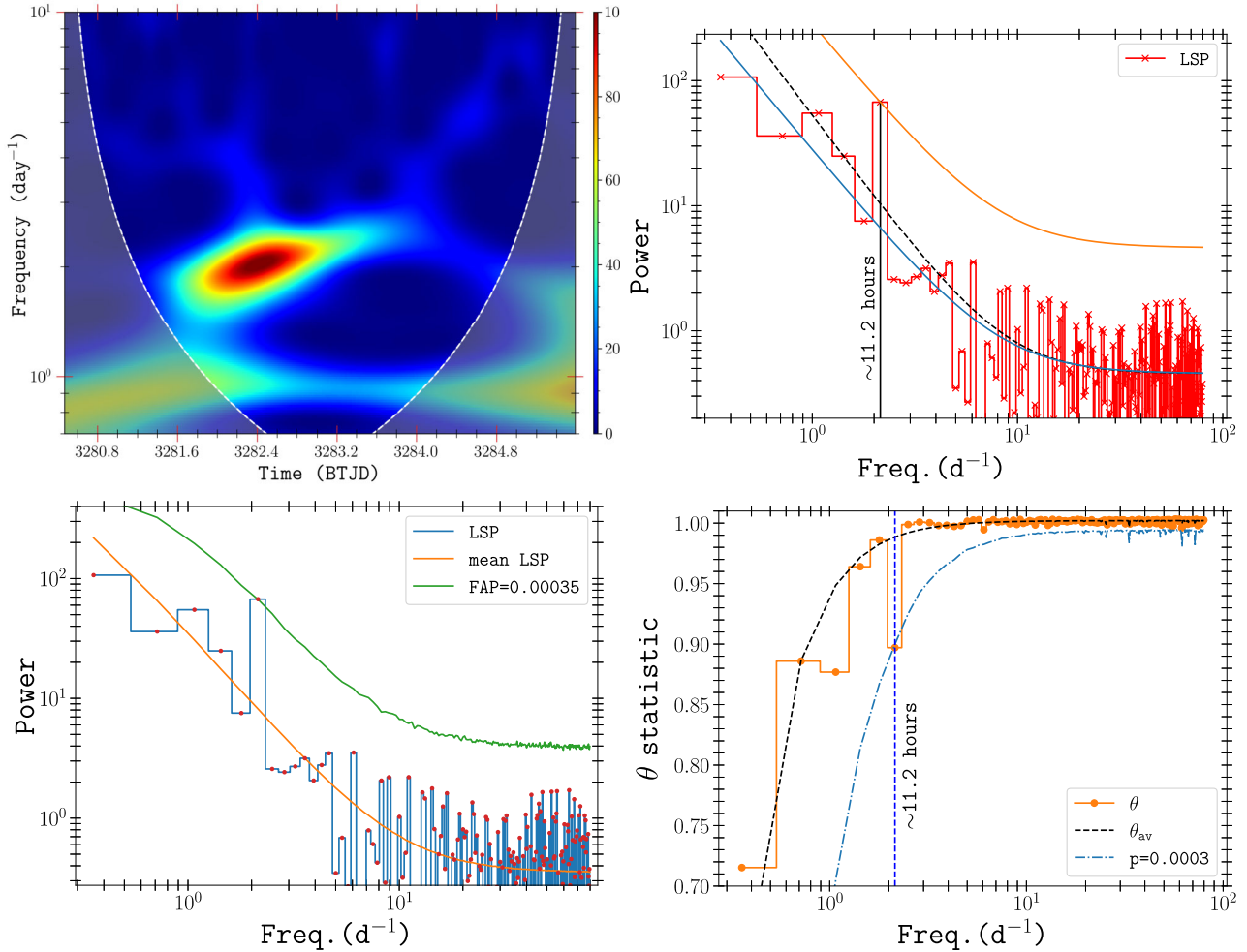


Figure 4. Upper left panel: WWZ plot for the epoch 3280.47–3285.65 BTJD, showing the apparent presence of a transient QPO signature; the mildly shaded portion below the white dashed lines highlights the ROI. Upper right panel: LSP plot for the epoch 3281.3–3284.1 BTJD, where the PSD shows a strong peak at ~ 11.2 h. The black dashed, and the blue lines respectively denote the LSP fitting with and without taking the peak frequency of ~ 2.2 d^{-1} into account. The QPO peak is found to be at around 4.11σ local significance and 3.06σ global significance levels as indicated by the orange line. Lower left panel: Similar to the upper right panel, where we first simulated 10^5 LCs having similar statistical features as those of LC between the epochs mentioned above, followed by computation of LSPs of those LCs; the LSP peak is found at false alarm probability (FAP) of 0.00035 ($\sim 3.58\sigma$). Lower right panel: Phase dispersion minimization analysis showing a significant dip in that statistic. The mean statistic and the percentile confidence p -value have been estimated from simulating 10^5 LCs and evaluating their individual PDMs, similarly to the treatment of the LSP.

2.04 d^{-1} , with a maximum around BTJD 3282.43. We then computed the LSP of the portion of the LC in sector 72 between BTJD 3281.3 and 3284.1 to try to confirm the existence of the QPO feature and to determine the local and global significance levels of the prominent frequency peak. The upper right and lower left panels of Fig. 4 include the periodogram of this selected portion of the LC, which can be seen to be well described by a simple power-law at lower frequencies with Poisson noise dominating at higher frequencies. The peak with the greatest power is at 2.15 d^{-1} . To estimate its significance, we implemented two distinct approaches to find the intrinsic PSD shape during fitting the periodogram, first including the peak frequency and then excluding it, employing the negative log-likelihood minimization method to derive the free parameters following S. Vaughan (2010). The two sets of parameters were further tested for their goodness of fit using the Bayesian Information Criterion (BIC) approach, which relies on the negative log-likelihood

minimization method and is given as

$$BIC = k \cdot \ln(n) - \mathcal{L} \quad (8)$$

where k and n respectively are the number of free parameters and the number of frequency points. We find that excluding the peak frequency bin during the fit offers a lower BIC value for PSD shape, hence it is considered here a better fit than the one that includes it. The determination of significance levels corresponding to a model spectrum requires consideration of the number of independent frequencies that are examined and is given by (see equation (16) and related discussion in S. Vaughan 2005)

$$\gamma_{\epsilon} = -2 \ln [1 - (1 - \epsilon_{n'})^{1/n'}], \quad (9)$$

where $\epsilon_{n'}$ is the probability values (for 95 percent significance level, $\epsilon_{n'} = 0.05$), and n' is the number of independent trials or frequencies. The PSD shape in the upper right panel of Fig. 4 is found to be dominated by Poisson noise beyond $\sim 10 \text{ d}^{-1}$, so

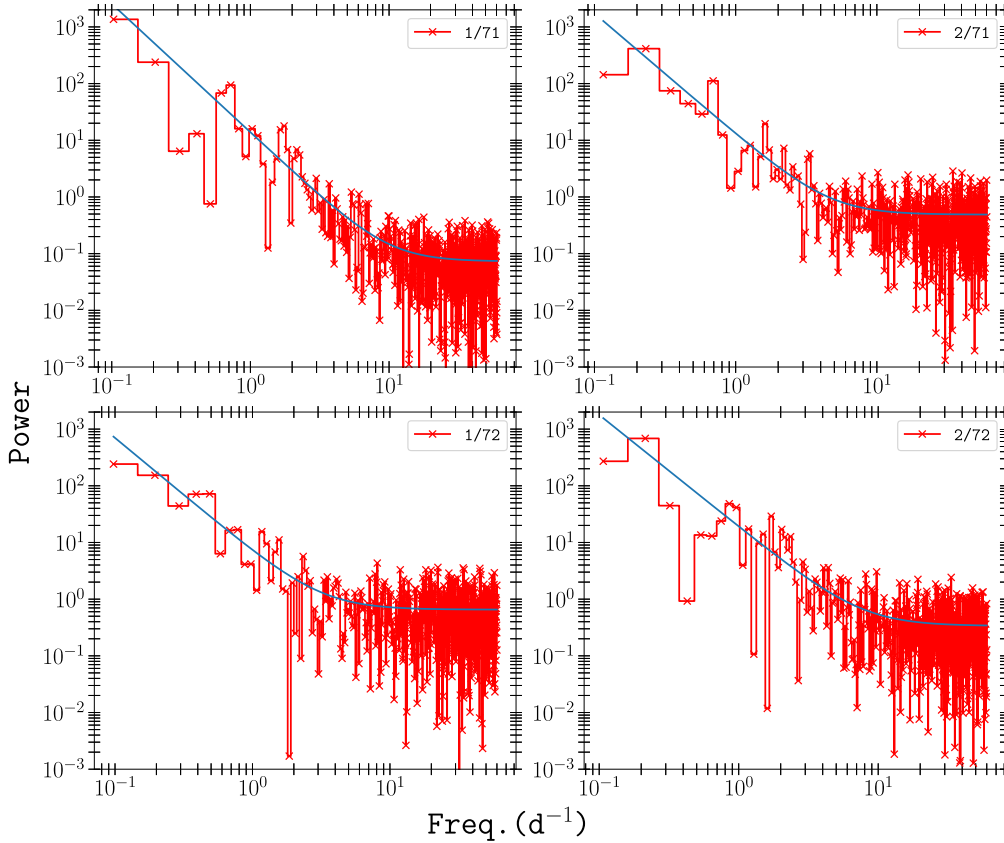


Figure 5. Segmentwise LSP plots of PKS 0735+178, along with their fitting with equation (5); the labels are in the form segment/sector.

we conservatively put a nominal cutoff frequency of 20 d^{-1} to set n' (set to 55). Though higher values of n' reduce the global significance of any prominent peak, with this choice, following S. Vaughan (2005), we found that the LSP gives a reliable QPO feature of period $\sim 11.2 \text{ h}$ at around 4.11σ and 3.06σ local and global significance levels, respectively.

We also considered an alternative method to find the significance of the peak, by performing simulations of many similar LCs following D. Emmanoulopoulos, I. M. McHardy & I. E. Papadakis (2013). We simulated a total of 10^5 LCs having similar PSD shapes and probability distribution functions (PDFs) as the input LC. We then estimated the LSPs of those LCs to obtain a distribution of powers at each temporal frequency. The 11.2 h peak of the LSP was found to have a false alarm probability (FAP) of around 0.00035, as shown in the lower left panel of Fig. 4. The PDM analysis of the same dataset is presented in the lower right panel of Fig. 4, where we find a significant dip in the Θ statistic near an 11.2 h period. To estimate the false alarm probability levels, we calculated the Θ -statistic of all the 10^5 simulated LCs, similarly to the way we did for the LSPs. The 11.2 h signal has a FAP (p -value) ≈ 0.0003 .

4.2 Segmentwise light-curve features

Over the two consecutive *TESS* sectors, PKS 0735+178 exhibited both variable and quiescent phases. Segment 1/71 has an overall variability amplitude of ~ 3 per cent, though the flare region (C1 and C2) shows an amplitude of > 5 per cent, pointing to a relaxation in variability after the modest double flare. The quiescent

phase continues in segment 2/71, after which the source exhibits greater variability throughout sector 72, reaching an amplitude of ~ 6.5 per cent in segment 2/72, where, near the end of the observations, it shows a transient QPO signature of period $\sim 11.2 \text{ h}$. Fig. 5 presents the PSDs of the four individual segments, along with their red noise fits. Table 1 includes the parameters of these segmentwise PSDs sectors 71 and 72. Over the four segments, the source depicts a PSD slope of $\gtrsim 2$, which is typical of optical emission from blazars (e.g. A. E. Wehrle et al. 2019).

4.3 Comparison of γ -ray data with optical data

The γ -ray LC in Fig. 3 shows that the source was in a rather quiescent phase throughout the epochs of Sectors 71 and 72. During the flare and shortly before (but not during) the QPO timespan, modest increases in the one-day binned γ -ray flux appear to be present; however, the uncertainties are quite large. Hence, we cannot compute excess variances or variability time-scales, nor conduct periodicity tests, on these Fermi-LAT data.

5 DISCUSSION AND CONCLUSION

In this paper, we assessed the optical behavior of the blazar PKS 0735+178, observed in sectors 71 and 72 with *TESS*. The source showed a modest flare with apparently two components (C1 and C2) in segment 1/71, followed by a sharp decrease in its variability thereafter in Sector 71. While C1 appears quite symmetric, C2 is clearly asymmetric, with the decay slower than the rise. The source became more variable towards the end of segment 1/72,

and near the end of segment 2/72, it exhibited a strong QPO feature of a period of around 11.2 h. We employed WWZ, LSP, and PDM to analyse the LCs. The flare spans a total of around 4.6 d, with individual components of 1.25 d and 3.35 d. The QPO has local and global significance levels of around 4.11σ and 3.06σ with methods described in S. Vaughan (2005). Following D. Emmanoulopoulos et al. (2013), the peak was found to be at $\sim 3.58\sigma$. Through a non-sinusoidal analysis approach with the PDM, the QPO feature appears at $\sim 3.62\sigma$.

There are two major classes of emission models for AGN variability: those involving shocks or instabilities in jets and those invoking instabilities on or above accretion discs. The latter class must dominate when jets are weak or non-existent, while the former is expected to predominate in blazars (e.g. A. V. Mangalam & P. J. Wiita 1993; C. M. Urry & P. Padovani 1995; S. J. Wagner & A. Witzel 1995; R. Blandford et al. 2019; C. M. Raiteri 2025, and references therein). QPOs can be associated with the spin of the central SMBH of the blazar, resulting in instabilities that cause the accretion disc to precess and/or produce bright hot spots. The presence of a single dominant hot spot on the accretion disc close to the innermost stable circular orbit allowed by general relativity or pulsational modes in the disk, are the most simple explanations for the observation of QPOs in blazars on IDV time-scales (e.g. M. A. Abramowicz et al. 1991; S. K. Chakrabarti & P. J. Wiita 1993; A. V. Mangalam & P. J. Wiita 1993; C. Espaillat et al. 2008).

The turbulence behind a shock travelling down a jet can create dominant eddies, whose turnover times can result in QPOs in emission at various EM bands (e.g. A. P. Marscher, W. K. Gear & J. P. Travis 1992; A. P. Marscher 2014; M. Pollack et al. 2016). Additionally, QPOs may result from a relativistic shock propagating along a helical jet, which can be caused by precession or magnetohydrodynamical instabilities (P. E. Hardee & A. Rosen 1999). When a relativistic shock travels down such a perturbed jet, it will cause noticeably increased emission at the points where it meets an area of enhanced electron density and/or magnetic field that corresponds to such a non-axisymmetric structure (e.g. M. Camenzind & M. Krockenberger 1992; Gopal-Krishna & P. J. Wiita 1992). The observer can notice significant variations in the observed jet emission because Doppler boosting is a sensitive function of viewing angle.

The low variability in the γ -ray LC, with only modest rises in flux levels during the flare and near the QPO, may help constrain the location of the emission region of the observed flares and QPO features. This apparently weak correlation may indicate that the origins of the optical and γ -ray emissions are not necessarily at the same location.

Estimation of the central black hole mass of BLLs, including PKS 0735+178, is quite difficult because of the absence of any broad spectral lines and because blazars are nearly face-on oriented. Thus, traditional primary methods of black hole mass estimation, such as stellar gas kinematics, reverberation mapping, and megamaser kinematics, cannot be employed as they are applicable only when one has, respectively, high-resolution spectroscopy of the host galaxy, detection of high ionization emission lines from the broad lines, or the source is oriented in an edge-on geometry. Other than these primary methods, secondary methods to deduce the masses include the assessment of the bulge velocity dispersion or luminosity, or the Sérsic index (e.g. M. Vestergaard 2004; C. J. Grier et al. 2013; T. S. Hamilton et al. 2021; V. N. Bennert et al. 2026), but they are also not applicable to PKS 0735+178.

A. C. Gupta et al. (2009) offered a means to estimate the black hole mass of an AGN using the period of a QPO signature, assuming that it originates from the orbital motion of some blob near the inner regions of the accretion disk (e.g. A. V. Mangalam & P. J. Wiita 1993), which is nominally taken as the marginally stable orbit, although emission from infalling matter at even smaller radii may be possible (M. A. Abramowicz & L. Nobili 1982). In this case, one can relate mass to periodicity via

$$M = \frac{3.23 \times 10^4 P}{(r^{3/2} + a)(1 + z)} M_{\odot}, \quad (10)$$

where P , r , a , and z are period (in seconds), radial distance (here set to the marginally stable orbit in units of gravitational radius: GM/c^2), spin parameter (often taken as 0 and 0.9982 for Schwarzschild and maximal Kerr black holes, respectively), and redshift of the source, respectively. Then the estimated mass of PKS 0735+178 is $(6.10 \pm 1.05) \times 10^7 M_{\odot}$ and $(3.88 \pm 0.67) \times 10^8 M_{\odot}$ for a spinless and a maximally rotating central supermassive black hole, respectively. An earlier estimation of the central SMBH mass of this blazar is $\approx 1.89 \times 10^8 M_{\odot}$ (corresponding to the Eddington luminosity $L_{\text{Edd}} = 2.5 \times 10^{46} \text{ erg s}^{-1}$), using the optical intraday variability time-scale and adopting a jet Doppler factor $\delta \approx 3.5$ (S. P. Gupta et al. 2012). This mass estimation is in the range of the present study. In a more realistic situation for a blazar, the fluctuations produced in the disk would be advected into the jet and amplified by Doppler boosting. In that case, the observed period would be reduced by a factor of δ from the inherent one, indicating that the actual black hole mass is actually increased by that δ factor. Then these two mass estimates are only compatible if the spin is small or the region of enhanced emission is further out than the marginally stable orbit.

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Software: LIGHTKURVE (Lightkurve Collaboration 2018), SCIPY (P. Virtanen et al. 2020), PYASTRONOMY (S. Czesla et al. 2019), FERMIPY (V1.0.1; <https://fermipy.readthedocs.io/en/latest/>; M. Wood et al. (2017)).

DATA AVAILABILITY

The optical data set from the *TESS* is public, including the cutouts of the FFI of sectors 71 and 72, and can be found in MAST through <https://mast.stsci.edu/tesscut/>. Additionally, the derived optical and γ -ray light-curve data can be made available upon reasonable request.

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APPENDIX

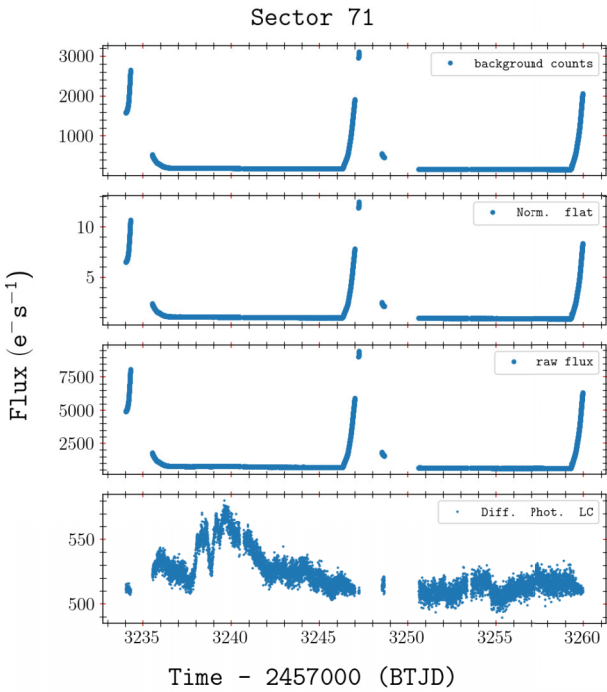


Figure A1. First panel shows the background LC, second panel shows the normalized LC of 'D' or the normalized flat or the pixel response function, third panel includes the raw LC of the source ('S'), fourth panel depicts the unnormalized pixel response function corrected LC of the source; all these plots correspond to sector 71; the pixel response function show significant variations from unity, so epochs for which they are between 0.85 and 1.15 (15 percent cuts) only were considered for correction of source raw flux; additionally epochs where the normalized flat follows a sharp increasing trend (near the end of each segments) were also discarded during LC analyses.

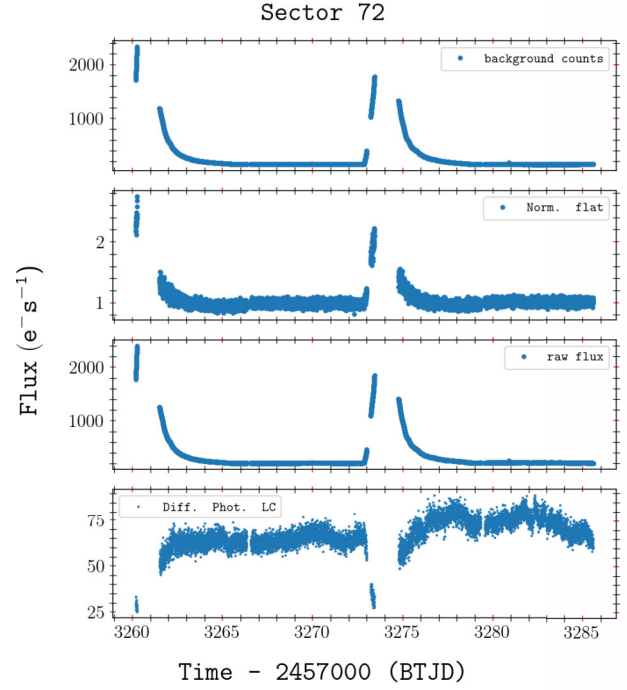


Figure A2. Same as Fig. A1, but for sector 72.

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