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Episodic Variability of Gamma Rays in Quasar 3C 273 Based on Fermi-LAT Statistical Analysis

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Highlights

- *3C 273 exhibits significant gamma-ray fluctuations (average flux 6.22 ×10 $^{-7}$ph/cm²/s).*
- *38 episodic flares were detected during 3.14% of the observation time.*
- *Variability is stochastic, with no clear periodicity.*
- *This study systematically quantifies the dynamics of the quasar core*

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A B S T R A C T

Quasar 3C 273 *is one of the brightest quasars, known for its active core and relativistic jets that produce intense gamma-ray emissions. This study aims to analyze the gamma-ray variability of* 3C 273 *using* Fermi-LAT *data* (0.1–300 GeV)*, detect episodic flares, and understand the physical mechanisms in the quasar core. Data were collected through Xamin Search at coordinates* J2000 RA = 187.278° *and Dec* = 2.052°*, cleaned of observations with offsets* >0.05° *or missing flux, then analyzed for average flux, standard deviation, variance, fluctuation amplitude, and gamma-ray luminosity. Flares were identified as flux* >2σ *above the average, while periodicity was tested using the Lomb-Scargle periodogram. Results show that from* 1,212 *observations, the average flux was* 6.22×10^{-7} ph/cm²/s *with a standard deviation of* 4.53×10^{-7} ph/cm²/s*, and a fluctuation amplitude of* 4.90×10^{-6} ph/cm²/s*. Thirty-eight flares* (>2σ) *were detected during* 3.14% *of the observation time. The periodogram showed a broad power distribution without any apparent periodicity, confirming the stochastic variability dominated by sporadic flares. This study closes the gap in the quantification of episodic gamma-ray flares with systematic statistical analysis. In conclusion,* 3C 273 *exhibits significant variability and sporadic flares, consistent with the relativistic jet and accretion instability models. The novelty of this study is the integration of quantitative analysis of gamma-ray fluctuations to systematically assess the dynamics of the quasar core.*

1. Introduction

Quasar 3C 273 is one of the brightest objects in the sky, demonstrating the highly dynamic activity of the galactic core [1,2]. The variability in the radiation intensity of this quasar is thought to be a complex physical process around the supermassive black hole, including relativistic jet activity and accretion instability. The sporadic radiation fluctuations indicate episodic particle acceleration and magnetic field interactions in the relativistic jet, but the underlying mechanism of this phenomenon is not yet fully understood [3,4]. In addition, the variability of quasar radiation does not always show a clear periodic pattern, so the nature of its energy change tends to be stochastic [5,6]. This requires an appropriate statistical analysis approach to understand dynamic characteristics and detect episodic phenomena that may arise. Accurate processing of observational data is an important aspect of this study, as raw data often contains observations with positional offsets or missing flux values, which can affect the interpretation of the physical behavior of quasars. With proper processing, radiation variations can be linked to the energy released by the quasar core and physical phenomena around the relativistic jet. As a relatively nearby and bright quasar, 3C 273 is a natural laboratory for studying active galactic nucleus (AGN) phenomena, including gamma-ray flares and relativistic jet physics. This research is expected to expand our understanding of active galactic nucleus dynamics and particle acceleration mechanisms in the extreme environment surrounding supermassive black holes.

The study aims to analyze the variability of gamma-ray flux in quasar 3C 273 using Fermi-LAT data, with a focus on identifying fluctuations and episodic flares. Statistical parameters such as average flux, standard deviation, variance, and flux amplitude are calculated to assess the activity of the quasar core, while also linking flux changes to the energy released through gamma-ray luminosity calculations. Lomb-Scargle periodogram analysis is used to evaluate the presence of periodic patterns or random fluctuation properties, as well as to understand the physical mechanisms in the quasar core, including the role of relativistic jets and accretion instabilities around supermassive black holes. The results also provide information about the stochastic versus periodic nature of quasar variability, serve as a reference for comparison with other quasars or multiwavelength studies, and contribute to the development of quasar physics and relativistic jet dynamics theories.

Limitations in this research include several important aspects that need to be considered. Gamma-ray data were obtained with a search radius corresponding to the Fermi-LAT resolution, so signals outside the instrument's resolution were not detected. To maintain statistical accuracy, observations with offsets greater than 0.05° or missing flux values were removed, meaning that some potential observations were not analyzed. Observation times were converted to POSIXct format, but the intervals were not always uniform, which may have affected the analysis of periodic variability. The calculation of the average flux as a baseline did not fully capture sporadic extreme fluctuations, and the analysis was limited to gamma rays in the 0.1–300 GeV range, without considering other energy bands such as X-rays, UV, or radio. Flare identification is only performed if the flux exceeds a statistical threshold of two standard deviations, so weaker phenomena may be missed. The use of standard deviation also assumes that the flux distribution is approximately normal, whereas the actual data may have outliers or a non-normal distribution. The luminosity calculation assumes that the luminosity distance and average photon energy are constant, which simplifies the actual physical variations in the quasar core. Periodicity analysis using the Lomb-Scargle periodogram shows very small and physically unrealistic periods, indicating the limitations of data resolution in capturing periodic fluctuations.

Previous studies of the quasar 3C 273 have shown significant gamma-ray variability, with sporadic fluctuations thought to originate from relativistic jet activity and accretion instabilities around the supermassive black hole [1,7,8]. However, several limitations remain. First, some studies use raw Fermi-LAT data without rigorous cleaning of position offsets and missing flux values, which can affect the accuracy of episodic fluctuation measurements. Second, lightcurve analysis is often visual or uses simple statistics, rarely performing systematic measurements such as flux amplitude, variance, or standard deviation-based flare thresholds, so quantitative understanding of the strength of fluctuations is still limited. Third, most studies have not explicitly linked flux variations to quasar gamma-ray luminosity, so the episodic energy released during flares has not been fully characterized. Previous periodogram analyses often produced physically unrealistic peaks due to time resolution or numerical methods, so the stochastic and periodic nature of gamma-ray flares is not yet fully understood.

This study fills the previous gap with a more comprehensive and methodological approach. First, the data was rigorously cleaned by removing observations with offsets >0.05° or missing flux values, making the detected fluctuations more accurate and representative. Next, gamma-ray variability was analyzed quantitatively using flux mean, standard deviation, variance, and flux amplitude, with flares identified objectively using a threshold >2σ, providing a strong statistical basis. Flux changes were also converted into gamma-ray luminosity, allowing for a physical interpretation of each flare, rather than just an observational one. Periodicity analysis via the Lomb-Scargle periodogram revealed a broad power distribution and physically unrealistic peak frequencies, confirming that the variability of 3C 273 is stochastic and episodic. This study also found 38 flares (>2σ) occurring in only 3.14% of the total observation time, confirming that quasar gamma-ray flares are rare but highly energetic, consistent with the theory of magnetic field interaction and particle acceleration in relativistic jets.

2. Method

The study used gamma-ray data from the quasar 3C 273 obtained from the Fermi-LAT archive via Xamin Search, with coordinates J2000 RA = 187.278° and Dec = 2.052° and a search radius corresponding to the instrument's resolution [9], [10]. The data collected included gamma-ray flux in the energy range 0.1–300 GeV, along with measurement uncertainties, observation times, and position offsets relative to the source center.

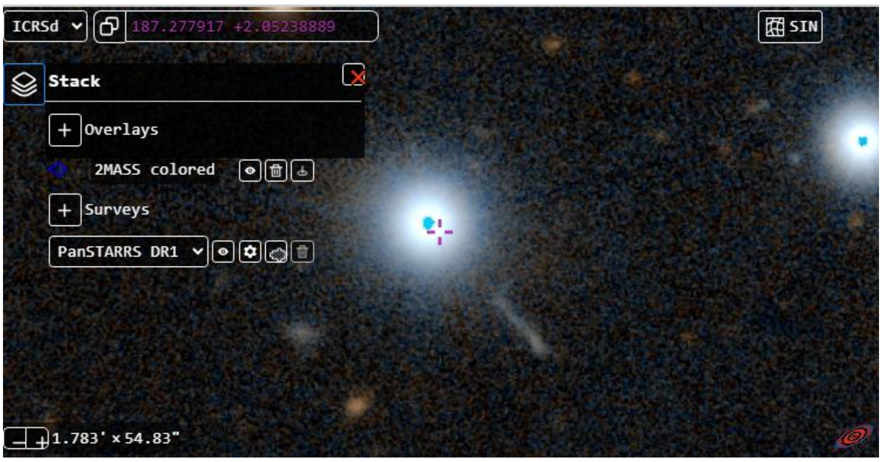

Figure 1. Citra 3C 273 shows a bright quasar core, the host galaxy's halo, and traces of relativistic jets

Figure 1 showed that 3C 273 appears as a very bright optical source at the center, surrounded by a faint halo from the host galaxy, with a trail that is likely a relativistic jet indicating intense quasar core activity [1,11].

To ensure the accuracy of the analysis, the data was cleaned by removing observations with offsets greater than 0.05° or missing flux values [12]. This step ensured that statistical calculations were not distorted by outliers or significant measurement errors. Next, the observation times were converted to POSIXct format, so that the time difference between observations could be calculated consistently using ($\Delta t_i = t_i - t_0$), with (t_0) as the first observation time. This transformation enabled chronological analysis of flux variability and preparation of data for periodogram calculations.

The average flux $\langle F \rangle$ was calculated to represent the mean value of all observations through the equation

$$\langle F \rangle = \frac{1}{N} \sum_{i=1}^{N} F_i \tag{1}$$

where (N) is the number of valid observations and (F_i) is the flux at the i-th observation. This average served as a baseline for detecting significant fluctuations and episodic flares. The flux spread was measured using the standard deviation (σ_F), which was mathematically expressed as:

$$\sigma_F = \sqrt{\frac{1}{N-1} \sum_{i=1}^{N} (F_i - \langle F \rangle)^2} \tag{2}$$

This standard deviation represented the intrinsic fluctuations of gamma-ray emissions that could be linked to relativistic jet activity or accretion instabilities around supermassive black holes. The flux variance was then obtained as the square of the standard deviation:

$$\mathrm{Var}(F) = \sigma_F^2 \tag{3}$$

The flux amplitude (A_F) was measured as the difference between the maximum flux ($F_{\max}$) and the minimum flux ($F_{\min}$):

$$A_F = F_{\max} - F_{\min} \tag{4}$$

The amplitude physically represented the extreme energy released during episodic gamma-ray flares, and could be compared to theoretical predictions from particle acceleration models in quasar jets [13]. The observed flux variability was related to the gamma-ray luminosity (L_γ) of the quasar center using the luminosity distance (D_L) and the average photon energy $\langle E_\gamma \rangle$:

$$L_\gamma = 4\pi D_L^2 \langle E_\gamma \rangle F_i \tag{5}$$

With this calculation, changes in flux could be translated into the energy released by the system, allowing the detected episodic flares to be linked to the physical mechanisms in the quasar core [14]. Flares were identified when the flux exceeds a statistical threshold of two standard deviations above the mean, ($F_i > \langle F \rangle + 2\sigma_F$). This phenomenon marked an episode of intense particle acceleration, possibly due to magnetic field reconnection or instabilities in relativistic jets, which far exceed normal random fluctuations [15].

3. Results and Discussions

3.1 Results

Data processing and statistical analysis were performed using a reproducible computational workflow in R/RStudio. Raw Fermi-LAT data obtained via Xamin Search were imported in table format, checked for missing values and inconsistent records, and filtered to exclude observations with missing flux values or angular deviations greater than ($0.05°$). Observation times are converted to the POSIXct format and transformed into the number of days elapsed relative to the first valid observation. Gamma-ray variability was quantified using the average flux, standard deviation, variance, minimum flux, maximum flux, and total flux amplitude. Episodic flares were identified using a threshold ($F_i > \langle F \rangle + 2\sigma_F$). Gamma-ray light curves were then plotted to visualize the temporal distribution of normal and flare states. A Lomb–Scargle periodogram was applied to the irregularly sampled time series to evaluate the possibility of periodic or quasi-periodic variability in the gamma-ray emission from 3C 273.

Based on the analysis of gamma-ray data from 3C 273 obtained from Fermi-LAT, there were a total of 1,212 observations that had been cleaned of large offsets and missing flux values. The recorded average flux is 6.22×10^{-7} ph/cm^2/s with a standard deviation of 4.53×10^{-7} ph/cm^2/s, indicating that the gamma-ray intensity of 3C 273 varies significantly around its average value. The calculated flux variance of 2.05×10^{-13} ph^2/cm^4/s^2 reinforces the indication of considerable fluctuations over the observation period. The highest flux value recorded was 4.97×10^{-6} ph/cm^2/s, while the lowest value was only 7.72×10^{-8} ph/cm^2/s, so that the amplitude of flux variation reached nearly five million per second per square centimeter, indicating a period of strong flares. From the overall data, there were 38 flare events that met the criteria of more than two standard deviations above the average, representing about 3.14% of the total observation time, indicating that flares are a relatively rare but significant phenomenon in the behavior of this gamma-ray quasar.

Table 1. Summary of Gamma-ray Variability Parameters for 3C 273

Parameters	Value
Number of observations (N)	1,212
Average flux	6.22×10^{-7} ph/cm²/s
Standard deviation of flux	4.53×10^{-7} ph/cm²/s
Flux variance	2.05×10^{-13} ph²/cm⁴/s²
Maximum flux	4.97×10^{-6} ph/cm²/s
Minimum flux	7.72×10^{-8} ph/cm²/s
Flux amplitude	4.90×10^{-6} ph/cm²/s
Number of flares (>2σ)	38
Time fraction in flare	3.14%

Table 1 shows that 3C 273 exhibits significant gamma-ray variability with an average flux of 6.22×10^{-7} ph/cm²/s and an amplitude of 4.90×10^{-6} ph/cm²/s, as well as sporadic flares (>2σ) occurring in 3.14% of the observation time.

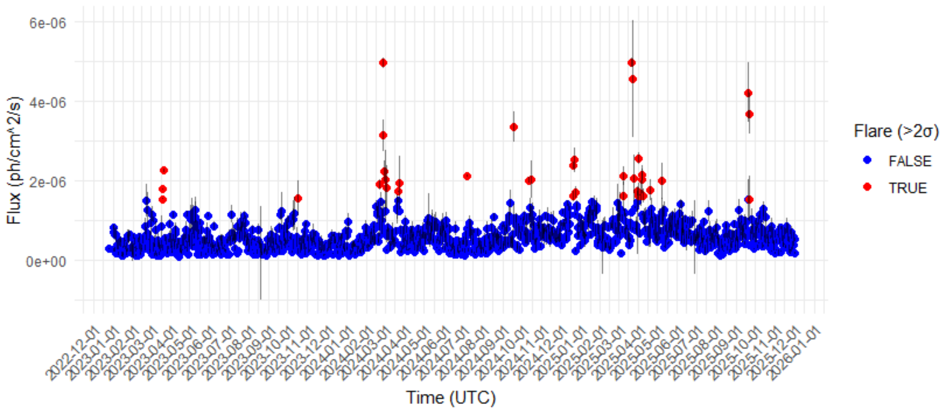

Figure 2. Lightcurve Gamma-ray 3C 273

As can be seen in Figure 2, which is a light curve, the gamma-ray intensity of 3C 273 shows significant variation throughout the observation period. The blue dots indicate normal observations around the average flux, while the red dots mark flares that exceed the 2σ threshold, indicating sharp but sporadic flux spikes. The error bars displayed at each point provide an indication of measurement uncertainty, and although most observations are close to the average, several flares stand out well above normal levels, revealing the dynamic activity of the quasar center.

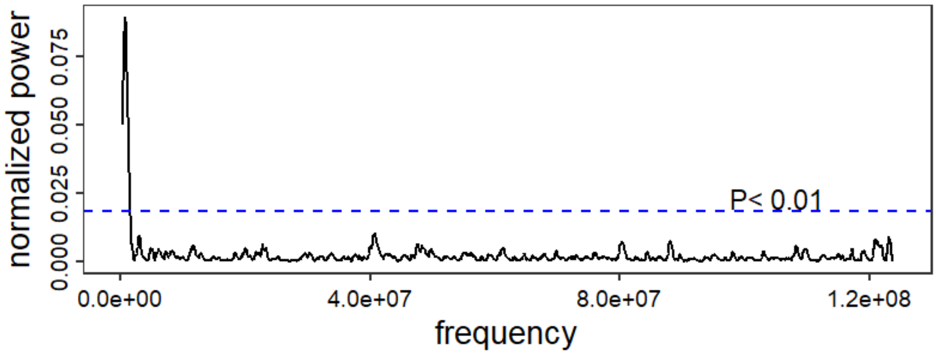

Figure 3. Lomb-Scargle Periodogram of Gamma-ray 3C 273

Figure 3 shows the results of the Lomb–Scargle periodogram analysis of the gamma-ray flux from 3C 273. This method was used because the Fermi-LAT data have observation time intervals that are not always uniform. The periodogram results show a broad power distribution across various frequencies, with no strong, narrow peaks that would be conclusive evidence of a periodic signal.

The highest power peak appears at a frequency of approximately (7.15×10^{5} day^{-1}), corresponding to a period of about (1.40×10^{-6}) days (≈0.12 s). This value is physically unrealistic for quasar emission variations, suggesting the presence of numerical artifacts, a mismatch in time units, an excessively high frequency range, or the effects of uneven data sampling. The gamma-ray variability of 3C 273 tends to be stochastic and is dominated by episodic flares, rather than by stable periodic patterns.

3.2 Discussion

Analysis of Fermi-LAT data shows that the quasar 3C 273 exhibits strong gamma-ray variability during the observation period. The average flux of (6.22×10^{-7} ph cm^{-2} s^{-1}), the standard deviation of (4.53×10^{-7} ph cm^{-2} s^{-1}), and a flux amplitude of (4.90×10^{-6} ph cm^{-2} s^{-1}) indicate that the gamma-ray emission from the core of 3C 273 is not in a stable state. The detection of 38 flares with fluxes exceeding the threshold ($\langle F \rangle + 2\sigma$), accounting for approximately 3.14% of the total valid observations, indicates that intense activity occurs infrequently but results in a very large increase in emission. This pattern confirms that the active nucleus 3C 273 is a highly dynamic system, with episodic releases of high-energy radiation.

Physically, the gamma-ray flare at 3C 273 is most likely associated with relativistic jet activity originating from the environment of a supermassive black hole. In an active galactic nucleus (AGN), matter from the galaxy's surroundings can fall toward the black hole through an accretion disk [16]. Some of the gravitational energy from this accretion process can then be converted into a strong magnetic field and a jet-shaped flow of relativistic plasma. The jet moves at speeds approaching the speed of light, and in the case of 3C 273, its orientation is estimated to be relatively close to the observer's line of sight. This causes the jet's emission to undergo relativistic Doppler boosting, that is, an apparent increase in radiation intensity due to the jet's plasma moving very rapidly toward the observer [17], [18].

Doppler boosting is one of the key mechanisms for explaining why physical changes occurring within a relatively small emission region can appear as gamma-ray flares with extremely high amplitudes [19], [20]. When the plasma flow velocity, jet direction, or Doppler factor changes even slightly, the flux received by an observer can increase significantly. Some of the flares detected in this study may be influenced by changes in the local geometry of the jet, such as changes in the direction of plasma elements, the propagation of disturbances along the jet, or temporary changes in the bulk plasma velocity. This mechanism is consistent with the relativistic AGN jet theory, which explains that emissions up to gamma-ray energies can be produced by high-energy plasma within a highly collimated jet [18].

The second physical mechanism that plays a significant role is the acceleration of particles via relativistic shock waves. In the shock-in-jet model, disturbances near the AGN core propagate outward along the jet and form a shock wave. As the plasma passes through this shock wave, electrons and positrons can be accelerated to relativistic energies through the Fermi acceleration process [4]. High-energy particles then interact with the photon field surrounding the jet, such as photons from the accretion disk, the broad-line region, the dusty torus, or internal synchrotron photons. These interactions can produce gamma rays through the inverse Compton scattering process, in which relativistic electrons transfer their energy to lower-energy photons, causing those photons to transform into X-rays or gamma rays [21, 22].

In the context of these research results, the flux amplitude of (4.90×10^{-6} ph cm^{-2} s^{-1}) reflects an episode during which the particle acceleration process became significantly more efficient than under normal conditions. When a shock wave strengthens the magnetic field and increases the density of relativistic electrons, gamma-ray production can increase sharply. After the disturbance weakens, the electrons lose their energy through radiative cooling, plasma expansion, or escape from the emission zone, causing the flux to return to near-average values. This pattern of sharp increase followed by a subsequent decrease is consistent with the episodic flare character observed in the light curve of 3C 273.

In addition to shock waves, gamma-ray flares can also be triggered by magnetic reconnection within jets. Magnetic reconnection occurs when oppositely directed magnetic field lines rapidly rearrange themselves, releasing large amounts of magnetic energy [23]. This energy can be directly converted into the kinetic energy of relativistic particles. In highly magnetized jets, magnetic reconnection can form small, extremely bright regions—often called plasmoids or mini-jets—that move relative to the main jet flow [24]. If one of the plasmoids moves toward the observer's line of sight, the additional Doppler boosting effect can produce a brief but extremely intense flare.

Magnetic reconnection mechanisms are relevant for explaining the nature of rare but intense solar flares [25]. Of the 1,212 valid observations, only 38 met the criteria for a flare greater than (2σ). This small proportion indicates that flares are not a normal emission condition, but rather special events that require specific physical conditions, such as the accumulation of magnetic energy, plasma compression, or interactions between structures within the jet. When these conditions are met, energy can be released rapidly, producing a surge in gamma-ray emission far above the average flux.

Relativistic jets do not always have a homogeneous structure; jets can contain turbulent cells with variations in plasma density, magnetic field strength, and particle energy distribution [26]. When a turbulent cell enters a shock region or a zone with a stronger magnetic field, the efficiency of particle acceleration can change abruptly. These conditions can produce random fluctuations in the light curve as well as flares that do not recur regularly. The dominance of turbulence and these local disturbances is consistent with the results of the Lomb–Scargle periodogram, which shows a broad spectral power distribution without strong, physically meaningful periodic peaks.

The absence of stable periodicity supports the interpretation that the gamma-ray flare from 3C 273 is not driven by a single cyclic mechanism. If the flare were primarily driven by periodic processes such as the binary orbit of supermassive black holes, stable jet precession, or repetitive accretion modulation, the periodogram would be expected to show narrow, significant peaks at specific frequencies. However, the results of this study show a broad power distribution and peaks with physically unrealistic periods. Therefore, the observed variability is more consistent with stochastic processes, such as turbulence, magnetic reconnection, shock wave propagation, and local changes in jet plasma conditions.

These findings are consistent with previous research on 3C 273. Studies of fast flares in 3C 273 indicate that gamma-ray activity can occur on very short timescales and is associated with dense, relatively small emission regions within the jet [27]. Multi-wavelength research has also shown that changes in the emission from 3C 273 are inseparable from jet dynamics, including the location of the emission regions, the evolution of plasma disturbances, and the relationship between radio and gamma-ray activity.

However, this study has not yet been able to identify a single dominant mechanism because the analysis relied solely on gamma-ray flux data in the 0.1–300 GeV energy range. Without detailed spectral information, photon indices, peak energy variations, or correlations with radio, optical, ultraviolet, or X-ray data, it is difficult to directly distinguish whether a flare is predominantly driven by shock waves, magnetic reconnection, turbulence, or changes in the external photon field. Using a flare threshold (>2σ) is effective for identifying large flux spikes, but it may still miss weaker flares or classify some extreme fluctuations as flares without likelihood-based evaluation.

Further research should incorporate multi-wavelength analysis, particularly data from radio, optical, ultraviolet, X-ray, and gamma-ray sources. Inter-band time correlations can help determine the location of flares and distinguish between emission mechanisms. A gamma-ray flare followed by a radio flare after a certain time delay may indicate the propagation of disturbances from jet regions closer to the core toward more distant radio regions. Spectral analysis during quiet and flare conditions is also needed to test whether flux changes are primarily controlled by changes in the number of relativistic electrons, variations in the magnetic field, changes in the Doppler factor, or changes in the intensity of the external photon field.

4. Conclusion

Research shows that the variability of gamma ray flux in quasar 3C 273 is dominated by stochastic fluctuations with the appearance of intense but relatively rare episodic flares. Statistical analysis of Fermi-LAT data successfully identified significant flux changes and linked them to energy release through gamma ray luminosity, reflecting dynamic activity in the quasar core. The Lomb-Scargle analysis results did not show strong periodicity, reinforcing the indication that emission variability is more influenced by particle acceleration in relativistic jets and accretion instability around supermassive black holes. Practically, this research provides a quantitative basis for measuring the characteristics of episodic flares, supports the validation of quasar jet physics models, and serves as a reference for studies of quasar variability and multiwavelength research on active galactic objects.

For further research, it is recommended to perform multiwavelength analysis by correlating the 3C 273 gamma-ray flare with X-ray (Swift XRT), UV/optical (Swift UVOT), and radio (IRAM 30m or VLA) data to understand the relationship between flares and physical mechanisms across different spectral bands. The results of the flare flux and amplitude can also be used for relativistic jet modeling, including particle acceleration and magnetic field reconnection, through general relativity-based magnetohydrodynamic simulations. Extending the observation period is important for detecting long-term variability or periodic patterns that may not be visible in the current data. Additionally, calculating the gamma-ray luminosity of flares can provide estimates of the total energy released, enabling the testing of accretion and jet efficiency theories in supermassive black holes. The application of advanced analysis techniques such as wavelet transform or Gaussian Process can help detect flares or hidden temporal trends in stochastic data.

CRediT Authorship Contribution Statement

Ruben Cornelius Siagian: Conceptualization of the study, data collection from Fermi-LAT via Xamin Search, data cleaning, statistical analysis including average flux, standard deviation, variance, fluctuation amplitude, and gamma-ray luminosity calculations, detection of episodic flares, Lomb-Scargle periodogram analysis, drafting the original manuscript, visualization of results, and final manuscript editing. The author is also responsible for corresponding with the journal.

Conflicts of Interest

The author declares that there are no conflicts of interest regarding the publication of this research. The research was conducted independently, and no financial, personal, or professional relationships influenced the study design, data collection, analysis, interpretation, or manuscript preparation.

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