Effect of Particle Acceleration in the Jet of 3C 279

Abstract

Three high-energy gamma-ray flares were detected from the radio galaxy 3C 279 in the Fermi-LAT mission data. The first flare was observed in April 2009, the second in June 2011, and the third in March 2015. The flares were characterized by a significant increase in the gamma-ray flux above 100 MeV, with fluxes reaching $10^{-6}$ ph cm$^{-2}$ s$^{-1}$ above 100 MeV. These flares were the highest gamma-ray flux ever observed from 3C 279.

1. Introduction

3C 279 is an active galaxy with a supermassive black hole at its core, which accretes matter and forms an accretion disk around the core. AGNs are believed to be powered by the accretion of matter onto a supermassive black hole, which converts the gravitational potential energy into relativistic jets and high-energy particle plasma. The mechanisms of particle acceleration in the jet, the line of sight of the observer, and the underlying causes of variability in the jet emission over time scales are still not well understood. The multiwavelength observational data are necessary to understand the physics of these objects.

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PKS 0903-57 is a BL Lac object detected by the Parkes Observatory in 1990. It was also observed by the Australia Telescope Compact Array (ATCA) in 2007 and by Fermi-LAT in 2010. The source has a high gamma-ray flux above 100 MeV, which is consistent with the gamma-ray latent spectra of the source. The observed gamma-ray flux is significantly higher than the average flux reported in the Fermi-LAT and H.E.S.S. catalogs.
Fermi-LAT also reported very-high-energy (VHE) gamma-ray emission from PKS 0903-57 on 2020 April 1 (Buson 2020). Preliminary analysis of Fermi-LAT data reported several high-energy (>10 GeV) photons that were positionally consistent with this source. It was found that an association of those high-energy photons with this source was highly probable. Among them, a 106 GeV photon was detected on 2020 March 31 at 13:56:27.000 UTC. This was the first evidence of VHE gamma-ray emission from PKS 0903-57 by Fermi-LAT.

On 2020 April 13, for the first time H.E.S.S. reported the detection of VHE gamma-ray during a follow-up observation from the intermediate BL Lac object PKS 0903-57 (Wagner 2020). ATCA monitored this source periodically. On 2020 April 15, ATCA released a report on the recent activity of this source (Stevens et al. 2020). They observed this source on 2020 April 2 in six radio bands with a duration of 10 minutes in each band and reported the fluxes in each band.

DAMPE reported the detection of gigaelectronvolt gamma-rays from the source PKS 0903-57 on 2020 April 17 (Duan et al. 2020) with daily average flux \( \sim 5.9 \pm 2.3 \times 10^{-7} \text{ph cm}^{-2} \text{s}^{-1} \).

The underlying mechanism of flux variability of the blazars is still unknown to the community. Many models have been proposed to explain the variability in short timescales but the models are highly flare dependent and in some cases also source dependent. The total spectral energy distributions (SEDs) of blazars show two hump-like structures. The first hump covering the optical-UV and soft X-ray part of the electromagnetic spectrum is produced by synchrotron emission of relativistic leptons in the jet’s emission region. The second hump covers a broader energy range, from soft X-ray to VHE gamma-ray emissions. In the leptonic model, the second hump is explained by inverse Compton (IC) emission of relativistic leptons. The seed photons for the IC emission may be the synchrotron photons emitted by relativistic leptons; in this case, the IC emission is known as synchrotron self-Compton (SSC) emission. This mechanism explains the second humps in the SEDs of most BL Lacs. In FSRQs, the IC emission may occur with the seed photons outside the jet, which is known as external Compton (EC) emission. Since our source is a BL Lac, we focus on the SSC emission to explain the second hump of the SEDs.

In our 12 yr long Fermi-LAT gamma-ray data analysis we identified two flares: Flare-1 and Flare-2. Further smaller binning of the gamma-ray light curve prominently reveals the substructures. Flare-1 has one substructure, consisting of two phases. Flare-2 has two substructures: Flare-I and Flare-II; the first one has five phases and the latter one has three phases. These phases consist of preflare, flares, and postflare states. The flaring phases have been fitted with a sum of exponential equations to calculate the rise and decay times of the peaks of the phases. Thereafter, we calculated the gamma-ray variability time, which is found to be hour scale. We fitted the gamma-ray SEDs of different phases with different models, PowerLaw (PL), LogParabola (LP), BrokenPowerLaw (BPL), and PowerLaw Exponential Cutoff (PLEC) to find the model that represents the data best. We do not find any specific hardening or softening pattern in the fitted spectrum. On the basis of the maximum likelihood analysis, LP is the best-fitted model, which we have used in modeling the multiwavelength SED with the help of a time-dependent code. Our results show that the one-zone leptonic model is sufficient to model the multiwavelength SED. For a better understanding of the physical processes, more simultaneous multiwavelength data is required.

In this paper, we have studied the gamma-ray data from 2008 August 4–2021 January 6. After identifying significant flares in the gamma-ray data, we included the multiwavelength data from several instruments and modeled the flaring phases. In Section 2, we discuss the multiwavelength data analysis. In Section 3, we identify the flares and their substructures from the gamma-ray light curve. In Section 4, we discuss the method of identification of different phases of the flares and the fitting of the gamma-ray light curve with a functional form to compute the rise and decay timescale of the flaring phases. In Section 5, we discuss the gamma-ray flares, their substructures, and phases in detail. In Section 6, we discuss the fitting of the gamma-ray SEDs with different functional forms, i.e., PL, LP, BPL, and PLEC. In Section 7, we have done time-dependent modeling of the multiwavelength SEDs with GAMERA and calculated the total jet power required in our model. We discuss our results in Section 8 and the conclusion is given in Section 9.

2. Data Analysis

2.1. Fermi-LAT Data Analysis

Fermi-LAT is one of the two instruments on board the Fermi Gamma-Ray Space Telescope (Atwood et al. 2009). It is an imaging, pair-conversion, high-energy gamma-ray telescope that can detect photons of energy from 20 MeV to more than 1 TeV, whose field of view is 2.7 sr at 1 GeV and above (Abdollahi et al. 2020). It scans the whole sky every 3 hours. It was launched in 2008 June in the near-earth orbit and is still in operation. PKS 0903-57 has been continuously monitored by Fermi-LAT since 2008 August 4, 15:43:36 UTC and is also listed in their regularly monitored source list. The Pass 8 Fermi-LAT gamma-ray data of PKS 0903-57 was extracted from Fermi Science Support Center (FSSC) data server for a period of more than 12 yr (2008 August–January 2021) and the analysis was done with Fermi Science Tools software package FTools v11r5p3 (Fermi-LAT Collaboration 2018), following the unbinned likelihood analysis method. We used Pass 8 data where the photon-like events are classified as evclass = 128 (the Fermi-LAT Collaboration recommends using the SOURCE event class for relatively small regions of interest (ROIs) (<25°)) (Bruel et al. 2018). We used the P8R3_SOURCE event class for which evclass has to be set to a value of 128 and evtype = 3 (each event class includes different event types, which allows us to select events based on different criteria. The standard value of evtype is 3, which includes all types of events, i.e., front, and back section of the tracker (denoted FRONT + BACK), for a given class.). We extracted the Fermi-LAT gamma-ray data from FSSC considering a search radius of 20° around the source PKS 0903-57. During the data preparation, we selected a ROI of 10°, as suggested in Fermi’s Data Preparation page. As per the analysis method, NewMinuit should be converged. We followed the steps outlined in the Fermi data analysis manual and finally NewMinuit converged

3 https://fermi.gsfc.nasa.gov/ssc/data/access/lat/mstlc/source/PKS_0903-57
4 https://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/Cicerone/Cicerone_Data/LAT_DP.html
5 https://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/Cicerone/Cicerone_Data_Exploration/Data_preparation.html
Table 1

| Sr. No. | Instrument          | Observation ID | Starting Time (MJD) | XRT Exposure (ks) | UVOT Exposure (ks) |
|---------|---------------------|----------------|---------------------|-------------------|--------------------|
| 1       | SWIFT-XRT/UVOT      | 00033856003    | 58221.739           | 1.9               | 1.9                |
| 2       | SWIFT-XRT/UVOT      | 00033856004    | 58222.872           | 1.7               | 1.7                |
| 3       | SWIFT-XRT/UVOT      | 00033856005    | 58223.133           | 1.3               | 1.3                |
| 4       | SWIFT-XRT/UVOT      | 00033856009    | 58937.110           | 1.9               | 1.9                |
| 5       | SWIFT-XRT/UVOT      | 00033856010    | 58938.176           | 1.9               | 1.9                |
| 6       | SWIFT-XRT/UVOT      | 00033856011    | 58941.496           | 1.7               | 1.7                |
| 7       | SWIFT-XRT/UVOT      | 00033856012    | 58944.154           | 2.2               | 2.1                |
| 8       | SWIFT-XRT/UVOT      | 00033856014    | 58945.890           | 1.9               | 1.9                |
| 9       | SWIFT-XRT/UVOT      | 00033856015    | 58946.817           | 1.9               | 1.9                |
| 10      | SWIFT-XRT/UVOT      | 00033856013    | 58947.474           | 0.6               | 0.5                |
| 11      | SWIFT-XRT/UVOT      | 00033856016    | 58951.978           | 1.9               | 1.9                |
| 12      | SWIFT-XRT/UVOT      | 00033856017    | 58953.051           | 1.9               | 1.9                |
| 13      | SWIFT-XRT/UVOT      | 00033856018    | 58954.436           | 0.7               | 0.7                |
| 14      | SWIFT-XRT/UVOT      | 00033856019    | 58955.171           | 2.0               | 1.9                |
| 15      | SWIFT-XRT/UVOT      | 00033856020    | 58956.360           | 1.9               | 1.9                |

for a ROI = 7°. Further study is done considering the photons from a ROI of 7° around the source, and the maximum zenith angle of 90° was chosen to avoid earth limb contamination in our analysis.

Moreover, we used the Fermi-LAT Fourth Source Catalog (4FGL; Abdollahi et al. 2020) and the galactic diffuse emission model (gll_iem_v07.fits) and extragalactic isotropic diffuse emission model (iso_P8R3_SOURCE_V2_v1.txt) to build the model xml file. After selection of the events based on the cuts, good time interval data, livetime, exposure map, and diffuse response of the instrument were eventually computed for each event with the instrument response function P8R3_SOURCES_V2_v1.txt. The model xml file would have many sources within the ROI and the likelihood analysis optimizes the spectral parameters of all the sources. The model xml file also has sources outside the ROI, which are generally fixed to their 4FGL catalog values. For localization of the source a quantity, Test Statistics (TS) is generally computed, and defined as

\[ TS = -2 \log \frac{L_0}{L_1}, \]

where \( L_0 \) and \( L_1 \) are the maximum likelihood value for a model without (null hypothesis) and with a point-like source at the position of the source, respectively. The higher is the TS value, the more is the probability that the source is present there. To generate the light curve, we fixed all the parameters of all the sources in our radius of interest except our source of interest from the 4FGL catalog. In this paper, we have generated gamma-ray light curve in five different time bins: 7 and 1 days, 12, 6, and 3 hr and subsequently generated SEDs of different activity periods.

2.2. Swift-XRT and Ultraviolet/Optical Telescope (UVOT) Data Analysis

Swift is a multiwavelength space-based observatory with three instruments on board: BAT, XRT, and UVOT (Burrows et al. 2005). It observes the sky in hard X-ray, soft X-ray, ultraviolet (UV), and optical wave bands. PKS 0903-57 was monitored by Swift during its flaring states. The details of the observations are tabulated in Table 1. Nearly 15 observations are found to correspond to the detected gamma-ray flares.

In the Swift-XRT data, we used clean event files corresponding to the photon-count (PC) mode, which we obtained using the task xrtpipeline version 0.13.5. Calibration file version 20190910 and other standard screening criteria have been applied to the cleaned data. A ROI of 20–30 pixels has been considered to mark the source region; the radius of the background region is also the same, but it is far away from the source region. With the help of the xselect tool, we selected a source region and background region and saved the spectrum files of the corresponding region. Then, the xrtmkarf and grppha tools were used to generate an ancillary response file and to group the spectrum file with the corresponding response matrix file; thereafter, addspec and mathpha were used. The SEDs corresponding to different flaring phases were obtained. Thereafter, the spectra was modeled with xspec version 12.11.0 tools (Arnaud 1996). During the fitting, we considered neutral hydrogen column density, \( n_H = 2.6 \times 10^{21} \text{cm}^{-2} \). These X-ray SEDs have been shown in the multiwavelength SEDs corresponding to their flaring phases.

PKS 0903-57 has also been monitored by Swift-UVOT in all six filters: U (3465 Å), V (5468 Å), B (4392 Å), UVW1 (2600 Å), UVM2 (2246 Å), and UVW2 (1928 Å). The source

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6 https://heasarc.gsfc.nasa.gov/cgi-bin/Tools/w3nh/w3nh.pl
3. Flaring States of PKS 0903-57

We have analyzed the gamma-ray light curve of PKS 0903-57 observed over 12 yr in different time bins. Figure 1 shows 7 day binning of the gamma-ray light curve of this source, which was observed by Fermi-LAT from MJD 54682.65 (2008 August 4; 15:43:36 UTC) to 59220 (2021 January 6; 00:00:00 UTC). As can be seen in Figure 1, we have identified two flaring states (denoted by a pair of vertical red-dotted lines for each flaring state). We have denoted these two flaring states as Flare-1 and Flare-2, which were observed from MJD 58216.5–58230.0 and MJD 58920.0–58976.0, respectively. Our work is focused on the flaring states; hence, a detailed analysis has been carried out on the flaring states only. Within a larger flare, there are smaller flares, i.e., preflare and postflare states, before and after them, respectively. A substructure consists of multiple phases of flare, preflare, and postflare. We studied the flares in a 1 day time bin to detect their substructures and different phases; thereafter, we analyzed them in 12, 6, and 3 hr time bins to detect the substructures and phases more precisely. Flare-1 has only one substructure (Figure 3), whereas Flare-2 has two substructures (Figure 4), labeled as Flare-I and Flare-II.

For some phases, the error bars on the data points in their 3 hr binned gamma-ray light curves are larger compared to those in their 6 hr binned gamma-ray light curves. However, in their 6 hr binned gamma-ray light curves, the flaring segments have comparatively fewer data points compared to those in their 3 hr binned gamma-ray light curves. If the number of data points is not sufficient, it is hard to determine the position of the peak in the light curve during a flare. Hence, we used the 3 hr binned gamma-ray light curves in our study, although their data points have comparatively larger error bars in some cases.

Throughout the paper, the gamma-ray fluxes have been reported in units of $10^{-6}$ ph cm$^{-2}$ s$^{-1}$ in the text; in the figures, the unit is denoted in brackets.

4. Method of Identification of Different Activity Phases and Temporal Evolution of the Gamma-Ray Light Curve During the Flares

We studied each flare and its activity states or phases (e.g., preflare, flare, and postflare) separately as shown in Figures 3, 6, and 7 for Flare-1, Flare-I, and Flare-II respectively. There are several methods to define the different phases of a source. We have discussed the following two methods to define the different phases of this source:

1. We used the Bayesian Block method (Scargle et al. 2013) to determine the flaring phases. We applied this method to Flare-1 and Flare-2 (shown in Figure 1, the application of this method on both of the flares has been shown separately in Figures 2 and 5, respectively). In every case, a segment can be called flare when the flux value is above 5σ about the mean flux.

2. Estimation of each phase’s average flux (preflare, flare, etc.) and compare their values. If the average flux of a particular phase is more than 3–4 times of the average flux during preflare or postflare that particular phase can be defined as a flare. We tabulated the average gamma-ray flux of different phases in Table 2, where we can see

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Footnote:

7 https://extinction.readthedocs.io/en/latest/
the average gamma-ray flux of the flaring phases are 3–4 times higher than the preflare or postflare states.

We studied the temporal evolution of each flaring phase separately. Each flaring phase consists of one or more peaks and there are rise and decay times corresponding to each peak and the data points below the detection limit of 3σ (TS < 9) have been rejected for the temporal study. We fitted the 3 hr binned gamma-ray light curve of each flaring phase with the sum of the exponential function. The functional form is given below (Abdo et al. 2010):

\[
F(t) = 2F_0 \left[ \exp \left( \frac{t_0 - t}{T_r} \right) + \exp \left( \frac{t - t_0}{T_d} \right) \right]^{-1},
\]

(2)

where \(t_0\) is the peak time when the gamma-ray flux is highest within a specific period, \(F_0\) is the flux observed at time \(t_0\) also referred to as peak flux, \(T_r\) is the rise time, and \(T_d\) is the decay time of the peak. Each of the figures (Figures 8–13) consist of three panels; the upper panel shows the gamma-ray light curve fitted with Equation (2), the middle one shows the residual plot, and the lower panel shows the TS plot of the data points. A horizontal dark-orchid line in the upper panel has been shown in Figures 8–13, which is the baseline flux. In a few cases, the light curve fittings seem to be overfitted due to the following reasons: if the peak that we defined during a flaring phase, consists of a single data point, then it is very difficult to fit that peak. Also, if the points include large error bars, then the fit may be overfitted. Both of which are true in our case. We have shown a residual plot corresponding to each fitted light curve where we have plotted time versus residue to show the quality of the fitting. The residue is defined as the ratio of the difference between model and observed flux to the flux error. It can be seen that the residual calculated for each data point is confined within the ±3σ confidence level. There are only very few points that are out of this zone. In the case of the TS plot, we have drawn a baseline of TS = 9 to show that the TS value of the data points are much higher than 9, i.e., they are detected with a much higher confidence level, so their detection is highly significant.

5. Description of Flares

In this section, we discuss the flares in detail.

5.1. Flare-1

Figure 3 shows the gamma-ray light curve of Flare-1 in time bins of 1 day, and 12, 6, and 3 hr corresponding to the flaring activity of PKS 0903-57 from MJD 58216.5–58230.0. Only one substructure has been detected. Also phases, which can be seen in Figure 3, are prominently visible in 12, 6, and 3 hr time bins. The flaring activity of Flare-1 can be divided into two phases: Flare-1A and Flare-1B. The gamma-ray flux before Flare-1A and after Flare-1B are too low for analysis, so we have not considered any of the two regions as preflare or postflare. This activity was observed by Fermi-LAT (Ciprini 2018) in 2018 May. We used

![Flare detection with the help of the Bayesian Block method during Flare-1.](image)

**Figure 2.** Flare detection with the help of the Bayesian Block method during Flare-1.

**Table 2**

| Activity  | Period (MJD) | Average Gamma-Ray Flux (10^{-6} ph cm^{-2} s^{-1}) |
|-----------|--------------|-------------------------------------------------|
| Flare-1A  | 58217.5–58220.0 | 1.8 ± 0.5                                       |
| Flare-1B  | 58220.9–58225.3 | 0.6 ± 0.4                                       |
| Preflare-I| 58920.0–58932.5 | 0.9 ± 0.6                                       |
| Flare-IA  | 58932.5–58941.7 | 3.6 ± 1.0                                       |
| Flare-IB  | 58941.7–58947.0 | 3.9 ± 1.2                                       |
| Flare-IC  | 58947.0–58957.6 | 4.6 ± 1.2                                       |
| Postflare-I| 58957.6–58961.3 | 1.1 ± 0.7                                       |
| Preflare-II| 58961.3–58962.0 | 1.2 ± 0.6                                       |
| Flare-II  | 58962.0–58965.0 | 4.6 ± 1.0                                       |
| Postflare-II| 58965.0–58976.0 | 1.1 ± 0.7                                       |
the Bayesian Block method to detect different activity phases as shown in Figure 2.

Flare-1A was observed from MJD 58217.5–58220.0 and persisted for ∼3 days. Figure 8 shows the temporal evolution of the gamma-ray flux during Flare-1A, where we can see two major peaks: P1 and P2 around MJD 58218.59 and MJD 58219.08 with flux 4.06 ± 0.75 and 3.27 ± 0.53, respectively. The average gamma-ray flux during this flare is 1.8 ± 0.5. Similarly, Figure 9 shows the temporal evolution of the gamma-ray flux during Flare-1B, which was observed from MJD 58220.9–58225.3, where we can see a single peak, P1 at MJD 58223.28 with flux 2.32 ± 0.48. And the average flux during this period is 0.6 ± 0.4.

The flares have been fitted with Equation (2). The decay time and the rise time of the peaks are tabulated in Tables 3 and 4 for Flare-1A and Flare-1B respectively.

5.2. Flare-2

From MJD 58920.0–58976.0, another flaring activity, Flare-2, of PKS 0903-57 has been observed as shown in Figure 1. In shorter time binning, we found that Flare-2 has two substructures, as shown in Figure 4, denoted as Flare-I and Flare-II. In shorter time bins, the phases of Flare-I and Flare-II are more prominent and are shown in Figures 6 and 7, respectively.

This flaring activity of PKS 0903-57 was reported (from the end of 2020 March–2020 April) by Fermi-LAT (Mereu 2020; Buson 2020), AGILE (Lucarelli et al. 2020), H.E.S.S. (Wagner 2020), and DAMPE (Duan et al. 2020). This was reported as the brightest flare ever detected by Fermi-LAT from this source.

In Figure 5, we show the application of the Bayesian Block method to detect different activity phases of Flare-2.

Flare-I has five distinct phases: Preflare-I, Flare-IA, Flare-IB, Flare-IC, and Postflare-I as shown in Figure 6. Each region is prominently visible in the gamma-ray light curve in shorter time bins.

Preflare-I has been observed from MJD 58920.0–58932.5 over 12 days where the gamma-ray flux is very low; after this phase, a rise in the gamma-ray flux was observed. The average flux during this period is 0.9 ± 0.4.

Preflare-I is followed by three flaring phases. These three flaring segments are Flare-IA, Flare-IB, and Flare-IC respectively. Flare-IA was observed from MJD 58932.5–58941.7, which persisted for almost 9 days. Figure 10, we can see five peaks, P1, P2, P3, P4, and P5, at MJD 58936.90, 58937.38, 58938.10, 58939.50, and 58940.22, respectively, and the corresponding fluxes are 5.10 ± 0.95, 6.54 ± 1.08, 6.77 ± 1.55, 13.59 ± 1.37, and 9.86 ± 1.34, respectively. In Figure 10, we show the light...
curve fitted with Equation (2) and the decay and rise times are reported in Table 5. The average gamma-ray flux during this period is 3.6 ± 1.0.

Flare-IB has been observed from MJD 58941.7–58947.0. The temporal evolution of Flare-IB is shown in Figure 11 with two peaks. The highest peak occurred at MJD 58943.76 with the flux 14.13 ± 2.46 and is denoted as P1 and the second peak, P2, is observed at MJD 58944.50 with flux 7.64 ± 1.16. The decay and rise times corresponding to P1 and P2 are shown in Table 6. The average gamma-ray flux during this period is 3.9 ± 1.2.

Flare-IC has been observed from MJD 58947.0–58957.6. This phase persisted for almost 10 days. Figure 12 shows four peaks, P1, P2, P3, and P4, at MJD 58948.19, 58951.31, 58953.10, and 58953.75, respectively, and the corresponding

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**Figure 4.** Gamma light curve of PKS 0903-57 during Flare-2 (MJD 58920.0–58976.0). The two substructures of Flare-2 are Flare-I and Flare-II.

**Figure 5.** Flare detection with the help of the Bayesian Block method during Flare-2.
gamma-ray fluxes are 5.78 ± 1.22, 13.44 ± 1.37, 7.39 ± 1.25, and 6.84 ± 1.65, respectively. The decay and rise times are tabulated in Table 7. The average gamma-ray flux in this phase is 4.6 ± 1.2.

A postflare phase (Postflare-I) is observed from MJD 58957.6–58961.3 with the average flux 1.1 ± 0.7. Just after Postflare-I, a rise in the gamma-ray flux is seen from MJD 58961.3–58976.0. This state is defined as Flare-II and the corresponding gamma-ray light curve is shown in Figure 7. The gamma-ray light curves in 1 day, 12, 6, and 3 hr time bins are shown here. This flare consists of three phases: Preflare-II, Flare-II and Postflare-II. The preflare phase lasted for only 1.3 days (MJD 58961.3–58962.0); during this period, the average gamma-ray flux is found to be 1.2 ± 0.6. Preflare-II is followed by a flaring phase (MJD 58962.0–58965.0) that is also very short (~2 days). In Figure 13, we show the flare in the 3 hr time bin, with a single peak P_5 observed at MJD 58962.94 with flux value 7.78 ± 1.01. The decay and rise times are shown in Table 8. The average gamma-ray flux during this period is 4.6 ± 1.0. After the flaring phase, Postflare-II is observed from MJD 58965.0–58976.0 with an average flux 1.1 ± 0.7.

5.3. Variability Time

Variability time is a measure of the timescale of variation in flux during flares.

\[ F(t_2) - F(t_1) = 2^{\frac{t_2-t_1}{T_{d/h}}} \]

where \( F(t_1) \) and \( F(t_2) \) are the fluxes measured at two consecutive time instants \( t_1 \) and \( t_2 \), respectively, \( T_{d/h} \) denotes

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|}
\hline
Peak & \( t_0 \) (MJD) & \( F_0 \) \text{ (10}^{-6} \text{ ph cm}^{-2} \text{ s}^{-1}) & \( T_r \) (hr) & \( T_d \) (hr) \\
\hline
P_1 & 58936.90 & 5.10 ± 0.95 & 13.4 ± 1.8 & 3.0 ± 0.9 \\
P_2 & 58937.38 & 6.54 ± 1.08 & 0.5 ± 0.3 & 3.9 ± 1.5 \\
P_3 & 58938.10 & 6.77 ± 1.55 & 3.8 ± 2.0 & 8.2 ± 1.9 \\
P_4 & 58939.50 & 13.59 ± 1.37 & 5.8 ± 1.1 & 1.6 ± 0.4 \\
P_5 & 58940.22 & 9.86 ± 1.34 & 5.0 ± 2.0 & 4.3 ± 1.8 \\
\hline
\end{tabular}
\caption{Rise and Decay Times for Flare-IA}
\end{table}

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|}
\hline
Peak & \( t_0 \) (MJD) & \( F_0 \) \text{ (10}^{-6} \text{ ph cm}^{-2} \text{ s}^{-1}) & \( T_r \) (hr) & \( T_d \) (hr) \\
\hline
P_1 & 58948.19 & 5.78 ± 1.22 & 7.7 ± 1.5 & 9.2 ± 1.8 \\
P_2 & 58951.31 & 13.44 ± 1.37 & 15.2 ± 1.3 & 11.8 ± 1.2 \\
P_3 & 58953.10 & 7.39 ± 1.25 & 3.0 ± 1.0 & 1.3 ± 0.4 \\
P_4 & 58953.75 & 6.84 ± 1.65 & 2.9 ± 0.8 & 6.7 ± 1.1 \\
\hline
\end{tabular}
\caption{Rise and Decay Times for Flare-IC}
\end{table}

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|}
\hline
Peak & \( t_0 \) (MJD) & \( F_0 \) \text{ (10}^{-6} \text{ ph cm}^{-2} \text{ s}^{-1}) & \( T_r \) (hr) & \( T_d \) (hr) \\
\hline
P_1 & 58943.76 & 14.13 ± 2.46 & 1.4 ± 0.3 & 4.4 ± 0.6 \\
P_2 & 58944.50 & 7.64 ± 1.16 & 2.8 ± 0.8 & 5.4 ± 1.4 \\
\hline
\end{tabular}
\caption{Rise and Decay Times for Flare-IB}
\end{table}
flux doubling or halving time, which is tabulated in Table 9 (positive and negative values of $T_d/h$ in the table denotes doubling and halving time, respectively). Two criteria have been kept in mind during the scanning of the gamma-ray light curve (Prince et al. 2017):

1. Only those consecutive time instants will be considered that have TS $> 25$ (> $5\sigma$ detection; Mattox et al. 1996).
2. The flux ratio between these two time instants should be greater than 2 (rise part) or less than half (decaying part).

There are several consecutive time instants with a flux ratio greater than 2 or less than half, but the TS value of those observations are less than 25, so we have not included these cases.

In our 12 yr gamma-ray light curve study, the shortest gamma-ray flux doubling/halving time ($T_{d/h}$) is found to be 1.7 $\pm$ 0.9 hr (listed in Table 9, during Flare-I for MJD 58935.688 and 58935.813).

6. Gamma-Ray SED of Different Flaring Phases

We fitted different phases (e.g., preflare, flare, and postflare) of the activity periods with four different spectral models. The details of the models are the following:

1. PL: The functional form of the PL is the following:

$$\frac{dN}{dE} = N_0 \left( \frac{E}{E_o} \right)^{-\Gamma},$$

where $N_0$ is the prefactor, $\Gamma$ is the PL index, and $E_o$ is the scaling factor or pivot energy. We kept a fixed value of $E_o$ which is 1155.4126 MeV (Abdollahi et al. 2020) for all the gamma-ray SEDs of this source.

2. LP: The functional form of the LP is the following:

$$\frac{dN}{dE} = N_0 \left( \frac{E}{E_o} \right)^{-(\alpha + \beta \log(E/E_o))},$$

where $N_0$ is the prefactor, $\alpha$ is the photon index, $\beta$ is the curvature index. Scaling factor ($E_o$) is fixed to 1155.4126 MeV similar to the PL function.

3. BPL: The functional form of the BPL is the following:

$$\begin{align*}
\frac{dN}{dE} &= N_0 \left( \frac{E}{E_b} \right)^{-\Gamma_1}, & \text{for } E < E_b \\
\frac{dN}{dE} &= N_0 \left( \frac{E}{E_b} \right)^{-\Gamma_2}, & \text{otherwise}
\end{align*}$$

where $N_0$ is prefactor, $\Gamma_1$ and $\Gamma_2$ are spectral indices , $E_b$ is the break energy.

4. PLEC: The functional form of the PLEC is the following:

$$\frac{dN}{dE} = N_0 \left( \frac{E}{E_c} \right)^{-\Gamma_{\text{PLEC}}} \exp\left(-\left( \frac{E}{E_c} \right)\right),$$

where $N_0$ is the prefactor, $\Gamma_{\text{PLEC}}$ is the PLEC index, $E_c$ is the pivot energy, which is fixed at 1155.4126 MeV similar to the PL, and $E_c$ is the cutoff energy.
Table 9
Gamma-Ray Flux Doubling/Halving Time ($T_{\text{d/h}}$) for Each Flare

| $T_{\text{rise}}$(i) (MJD) | $T_{\text{rise}}$(f) (MJD) | Flux$_{\text{rise}}$(F(i)) (10$^{-6}$ ph cm$^{-2}$ s$^{-1}$) | Flux$_{\text{rise}}$(F(f)) (10$^{-6}$ ph cm$^{-2}$ s$^{-1}$) | $T_{\text{d/h}}$ (hr) | $\Delta T_{\text{d/h}}$ (hr) | Rise/Decay |
|-----------------------------|-----------------------------|-------------------------------------------------|-------------------------------------------------|-----------------|-----------------|-------------|
| Flare-I                     |                             |                                                 |                                                 |                 |                 |             |
| 58218.463                   | 58218.588                   | 1.93 ± 0.47                                    | 4.06 ± 0.75                                     | 2.8 ± 1.2       | 1.6 ± 0.7       | R           |
|                             |                             |                                                 |                                                 |                 |                 |             |
| Flare-I                     |                             |                                                 |                                                 |                 |                 |             |
| 58922.438                   | 58922.563                   | 1.26 ± 0.53                                    | 2.94 ± 0.95                                     | 2.5 ± 1.6       | 1.5 ± 0.9       | R           |
| 58934.313                   | 58934.438                   | 1.51 ± 0.68                                    | 3.19 ± 0.67                                     | 2.8 ± 1.9       | 1.6 ± 1.1       | R           |
| 58935.563                   | 58935.688                   | 2.61 ± 0.68                                    | 1.02 ± 0.50                                     | −2.2 ± 1.3      | −1.3 ± 0.8      | D           |
| 58935.688                   | 58935.813                   | 1.02 ± 0.50                                    | 3.45 ± 1.23                                     | 1.7 ± 0.9       | 1.0 ± 0.5       | D           |
| 58939.563                   | 58939.688                   | 7.50 ± 1.07                                    | 2.97 ± 0.66                                     | −2.2 ± 0.6      | −1.3 ± 0.4      | D           |
| 58940.188                   | 58940.313                   | 9.86 ± 1.34                                    | 4.45 ± 0.98                                     | −2.6 ± 0.8      | −1.5 ± 0.5      | D           |
| 58940.888                   | 58940.913                   | 5.77 ± 1.18                                    | 2.60 ± 0.82                                     | −2.6 ± 1.2      | −1.5 ± 0.7      | D           |
|                             |                             |                                                 |                                                 |                 |                 |             |
| Flare-II                    |                             |                                                 |                                                 |                 |                 |             |
| 58962.688                   | 58962.813                   | 1.82 ± 0.92                                    | 3.82 ± 1.29                                     | 2.8 ± 2.3       | 1.7 ± 1.4       | R           |
| 58962.813                   | 58962.938                   | 3.82 ± 1.29                                    | 7.78 ± 1.01                                     | 2.9 ± 1.5       | 1.7 ± 0.9       | R           |
| 58963.688                   | 58963.813                   | 3.32 ± 1.11                                    | 8.01 ± 2.18                                     | 2.4 ± 1.2       | 1.4 ± 0.7       | R           |
| 58963.938                   | 58964.063                   | 6.35 ± 0.93                                    | 2.99 ± 0.62                                     | −2.8 ± 0.9      | −1.6 ± 0.6      | D           |
| 58964.313                   | 58964.438                   | 3.53 ± 0.71                                    | 1.56 ± 0.57                                     | −2.5 ± 1.3      | −1.5 ± 0.8      | D           |

Note. $\Delta T_{\text{d/h}}$ is redshift corrected doubling/halving time. “R” denotes the rise part and “D” denotes the decay part.

We used the maximum likelihood fitting to determine the best-fit model. In Figure 14, we show Fermi-LAT SEDs of Flare-I for its two substructures: Flare-IA and Flare-IB. Both SEDs have been fitted with four spectral models: PL, LP, BPL, and PLEC. Black, red, magenta, and blue are used to denote the fitting of the spectral points with PL, LP, BPL, and PLEC, respectively.

Figure 14 contains all the parameter values that have been used to fit the Fermi-LAT gamma-ray spectral points of Flare-IA and Flare-IB with the above-mentioned spectral models. In this table, we have listed the fitted flux, spectral indices, TS, and −log(Likelihood) values.

We have also calculated the $\triangle$log(Likelihood) value (Britto et al. 2016), which is defined as $\triangle$log(Likelihood) = (−log(Likelihood)$_{\text{PL/BPL/PLEC}}$)−(−log(Likelihood)$_{\text{LP}}$).

In Figure 15, we show Fermi-LAT gamma-ray SEDs of the five phases of Flare-I. Similarly, all the SEDs have been fitted with the same four spectral models and the fitted parameter values are tabulated in Table 11.

In Figure 16, SEDs of three activity phases of Flare-II are shown, which are fitted with the same four spectral models, i.e., PL, LP, BPL, and PLEC, and Table 12 contains all the fitted parameter values.

In the case of Flare-I, as the source transits from Flare-IA ($\Gamma = 1.98 \pm 0.05$) to Flare-IB ($\Gamma = 1.93 \pm 0.07$), the gamma-ray spectral index remains almost constant.

Flare-I shows spectral hardening when the source transits from Preflare-I ($\Gamma = 2.08 \pm 0.06$) to Flare-IA ($\Gamma = 1.91 \pm 0.02$), which can be seen from Table 11. However, during the transition from Flare-IA ($\Gamma = 1.91 \pm 0.02$) to Flare-IB ($\Gamma = 1.94 \pm 0.03$) and Flare-IB ($\Gamma = 1.94 \pm 0.03$) to Flare-IC ($\Gamma = 1.90 \pm 0.02$), the spectral index remains almost constant. The spectrum softens when the source transits from Flare-IC ($\Gamma = 1.90 \pm 0.02$) to Postflare-I ($\Gamma = 2.08 \pm 0.10$). For Flare-II, the spectrum softens as the source transits from Preflare-II ($\Gamma = 1.82 \pm 0.10$) to Flare-II ($\Gamma = 1.92 \pm 0.03$).

From the above gamma-ray SED analysis of the source PKS 0903-57, we can see that the gamma-ray spectrum may harden or soften or remain almost unchanged during the transition from one phase to another. Earlier, Das et al. (2020) found spectral hardening to be an important feature of the source 3C 454.3. However, we observed all the possibilities for the source.
PKS 0903-57, and in some cases we saw brighter-when-harder scenario, in some cases brighter-when-softer scenario, and in some other cases the spectral index remains almost unchanged.

From the maximum likelihood analysis using different spectral models during the different activity phases, we find that BPL is the best-fit model for Flare-I and Flare-II, whereas LP is the best-fit model for Flare-I. We have multiwavelength data for only these four phases: Flare-1B, Flare-IA, Flare-IB, and Flare-IC. For three of them (Flare-IA, Flare-IB, and Flare-IC) LP is the best-fit model. However, in case of Flare-1B the $\Delta$ log(Likelihood) values are very close to each other (see Table 10) for LP and BPL, and hence both models are preferred. Therefore, we used the LP model to fit the multiwavelength SEDs of all four phases in this work.

### 7. Multiwavelength Study of PKS 0903-57

In this section, we discuss the multiwavelength study of the source PKS 0903-57. From the gamma-ray light curve we detected different phases of the source. Then we searched for multiwavelength data for this source. Here, we used X-ray, UV, and optical data from Swift-XRT and UVOT, respectively, and radio data collected by ATCA (Stevens et al. 2020). Only Flare-1B, Flare-IA, Flare-IB, and Flare-IC have simultaneous multi-wave band data corresponding to their gamma-ray flaring activity which only spans 4.4, 9.2, 5.3, and 10.6 days, respectively. Moreover, the number of observations is few in Swift-XRT and Swift-UVOT.

### 7.1. Multiwavelength Light Curve of PKS 0903-57

Figure 17 shows the multiwavelength light curve of the source PKS 0903-57 during Flare-I. Simultaneous multiwavelength data is only available for Flare-1B, one of the phases of Flare-I, corresponding to MJD 58220.9–58225.3 with a period of 4.4 days. In the same plot, we can see that there is no multiwavelength data corresponding to the gamma-ray light curve of Flare-1A. In the uppermost panel of the plot, 6 hr binned gamma-ray data is plotted. X-ray, UV, and optical data are shown in the following panels, i.e., in the second, third, and fourth panels, respectively. We could not get radio data or any data in other wave bands from any other instruments corresponding to Flare-1B. The number of observations in X-ray to optical wave bands is very low to fit the X-ray to optical light curve and calculate the variability time in X-ray to optical wave bands.

In Figure 18, we show a multiwavelength light curve for Flare-I (MJD 58920.0–58961.3). We have simultaneous multiwavelength data corresponding to Flare-IA, Flare-IB, and Flare-IC, i.e., MJD 58932.5–58957.6. Similarly, in the uppermost panel of the plot, a 6 hr binned gamma-ray light curve is shown, followed by X-ray, UV, and optical data in the following panels.

In Swift-XRT/UVOT we get 15 simultaneous observations corresponding to the flaring states observed in the gamma-ray. Out of 15, three observations correspond to Flare-1B, three observations correspond to Flare-IA, another three observations correspond to Flare-IB, and the remaining six observations correspond to Flare-IC.
The code solves time-dependent transport equation. It estimates the propagated electron spectrum and further it uses the propagated spectrum to calculate the synchrotron and IC emissions. The transport equation used in GAMERA is defined as

\[
\frac{\partial N(E, t)}{\partial t} = Q(E, t) - \frac{\partial}{\partial E} \left( b(E, t) N(E, t) \right) - \frac{N(E, t)}{\tau_{esc}(E, t)},
\]

(8)

where \(Q(E, t)\) is the input electron spectrum and \(b(E, t)\) corresponds to the energy loss rate by synchrotron and IC emissions, and can be defined as \(\frac{dE}{dt}\). In the last term, \(\tau_{esc}(E, t)\) denotes the escape time of electrons from the emission region.

Following Massaro et al. (2004), a LP photon spectrum can be produced by the radiative losses of a LP electron spectrum.

As we mentioned earlier, the number of observations in the X-ray to optical wave bands is very low; hence, it is not possible to do a detailed analysis of the light curve from the X-ray to the optical wave band, so only the gamma-ray light curve has been modeled in detail.

### 7.2. Multiwavelength SED Modeling

We modeled the multiwavelength SEDs with the code GAMERA (Hahn 2016). It is publicly available on github. The code solves time-dependent transport equation. It estimates the propagated electron spectrum \(N(E, t)\) for an input injected electron spectrum.
Flare-II 3.01
Activity
Post ± Pre
(\text{redshift of the source. We could not where})

10

Flare-II 2.99
Activity
IC emission

\text{Results of Fermi-LAT SEDs of Flare-II, Fitted with Different Spectral Models, i.e., PL, LP, BPL, and PLEC}

| Activity | $F_{0.1-300\text{ GeV}}$ ($10^{-6}\text{ ph cm}^{-2}\text{s}^{-1}$) | Index ($\Gamma$) | TS | $-\log(\text{Likelihood})$ |
|----------|---------------------------------|-----------------|-----|---------------------------|
| Preflare-II | $0.92 \pm 0.15$ | $1.82 \pm 0.10$ | 232.32 | 10,495.42 |
| Flare-II | $3.19 \pm 0.16$ | $1.92 \pm 0.03$ | 2288.81 | 15,193.42 |
| Postflare-II | $0.91 \pm 0.06$ | $2.15 \pm 0.05$ | 1166.98 | 49,385.92 |

| Activity | $F_{0.1-300\text{ GeV}}$ ($10^{-6}\text{ ph cm}^{-2}\text{s}^{-1}$) | $\alpha$ | $\beta$ | TS | $-\log(\text{Likelihood})$ | $\Delta\log(\text{Likelihood})$ |
|----------|---------------------------------|-------|-------|-----|---------------------------|-----------------------------|
| Preflare-II | $0.85 \pm 0.02$ | $1.78 \pm 0.01$ | $0.02 \pm 0.01$ | 244.00 | 10,450.08 | $-45.34$ |
| Flare-II | $3.01 \pm 0.16$ | $1.94 \pm 0.04$ | $0.08 \pm 0.02$ | 2302.13 | 15,186.76 | $-6.66$ |
| Postflare-II | $0.84 \pm 0.07$ | $2.21 \pm 0.06$ | $0.09 \pm 0.04$ | 1156.62 | 49,376.90 | $-9.02$ |

| Activity | $F_{0.1-300\text{ GeV}}$ ($10^{-6}\text{ ph cm}^{-2}\text{s}^{-1}$) | $\Gamma_1$ | $\Gamma_2$ | $E_o$ (GeV) | TS | $-\log(\text{Likelihood})$ | $\Delta\log(\text{Likelihood})$ |
|----------|---------------------------------|-------|-------|-----------|-----|---------------------------|-----------------------------|
| Preflare-II | $0.78 \pm 0.00$ | $1.36 \pm 0.00$ | $1.95 \pm 0.00$ | $0.61 \pm 0.00$ | 244.93 | 10,449.71 | $-45.71$ |
| Flare-II | $2.99 \pm 0.16$ | $1.62 \pm 0.11$ | $2.13 \pm 0.08$ | $0.65 \pm 0.20$ | 2304.57 | 15,185.54 | $-7.88$ |
| Postflare-II | $0.86 \pm 0.07$ | $2.00 \pm 0.08$ | $2.41 \pm 0.13$ | $1.07 \pm 0.11$ | 1158.88 | 49,377.54 | $-8.38$ |

| Activity | $F_{0.1-300\text{ GeV}}$ ($10^{-6}\text{ ph cm}^{-2}\text{s}^{-1}$) | $\Gamma_{\text{PLEC}}$ | $E_o$ (GeV) | TS | $-\log(\text{Likelihood})$ | $\Delta\log(\text{Likelihood})$ |
|----------|---------------------------------|-------|-----------|-----|---------------------------|-----------------------------|
| Preflare-II | $0.88 \pm 0.15$ | $1.72 \pm 0.11$ | $30.00 \pm 0.03$ | 228.14 | 10,497.51 | $2.09$ |
| Flare-II | $3.11 \pm 0.16$ | $1.83 \pm 0.05$ | $26.53 \pm 12.49$ | 2296.64 | 15,189.51 | $-3.91$ |
| Postflare-II | $0.87 \pm 0.06$ | $2.03 \pm 0.08$ | $13.94 \pm 8.04$ | 1163.43 | 49,377.84 | $-8.08$ |

We have considered the LP form of injection spectrum. The functional form of the electron spectrum is

$$Q(E) = L_o \left( \frac{E}{E_o} \right)^{-\alpha - \beta \log\left( \frac{E}{E_o} \right)},$$

where $L_o$ is the normalization constant and $E_o$ is the scaling factor. This code uses Klein-Nishina cross section to compute IC emission (Blumenthal & Gould 1970).

7.3. Physical Constraint for Multiwavelength SED Modeling

We used synchrotron and SSC emissions to model the SEDs. The size of the emission region ($R$) can be constrained from the causality relation

$$R \lesssim \frac{c t_{\text{var}} \delta}{1 + z},$$

where $t_{\text{var}}$ is the observed variability time, $\delta$ is the Doppler factor of the blob or emission region, and $z$ represents the redshift of the source. We could not find an estimate of Doppler factor (\text{\delta}) for PKS 0903-57 from earlier studies. The values of the Doppler factor for other flaring BL Lacs are found to be in the range of 20–40 in most cases. We used the Doppler factor close to 20 for PKS 0903-57. For Doppler factor 21.5 and redshift 0.695, the variability time is 1.7 ± 0.9 hour and the size of the emission region has an upper limit of 2.3 × 10^{15} \text{ cm}. But Equation (10) gives only an approximate constraint on the size of the emission region, as there are several other factors that may affect this estimate (Protheroe 2002).

7.4. Modeling the SEDs

Varying the fitting parameters in the code GAMERA we modeled multiwavelength SEDs. In this case, we considered the constant escape of leptons from the emission region with escape time, $\tau_{\text{esc}} \sim R/c$, where $R$ is the size of the emission region used in the fitting and $c$ is the speed of light in vacuum.

We modeled multiwavelength SEDs of the four phases: Flare-IB, Flare-IA, Flare-IB, and Flare-IC as shown in Figures 19–22, respectively. For all the phases mentioned above, we plotted simultaneous data in different wave bands (Fermi-LAT gamma-ray: circular magenta points; Swift-XRT: green triangular points; Swift-UV: cyan triangular points; Swift-optical: red-circular points; and ATCA radio: blue inverted-triangle); also we have shown the nonsimultaneous data points in the gray square. We modeled considering the one-zone emission region. During the modeling, we adjusted the values of different parameters, e.g., the minimum and maximum Lorentz factors of the injected electrons ($\gamma_{\text{min}}$ and
Table 13
Results of Multiwavelength SED Modeling Shown in Figures 19–22

| Parameters | Symbol | Values | Time | Duration |
|------------|--------|--------|------|----------|
|            |        |        |      |          |
| Flare-IB   |        |        |      |          |
| Spectral index of injected electron spectrum (LP) | α | 1.7 | ... |
| Curvature index of injected electron spectrum | β | 0.20 | ... |
| Magnetic field in emission region | B | 0.25 G | ... |
| Size of the emission region | R | 3.0 × 10^{16} cm | 9.2 days |
| Doppler factor of emission region | δ | 21.5 | ... |
| Min. value of Lorentz factor of injected electrons | γ_{min} | 2.4 × 10^{2} | ... |
| Max. value of Lorentz factor of injected electrons | γ_{max} | 4.5 × 10^{4} | ... |

Flare-IA

| Parameters | Symbol | Values | Time | Duration |
|------------|--------|--------|------|----------|
|           |        |        |      |          |
| Spectral index of injected electron spectrum (LP) | α | 1.7 | ... |
| Curvature index of injected electron spectrum | β | 0.20 | ... |
| Magnetic field in emission region | B | 0.25 G | ... |
| Size of the emission region | R | 5.9 × 10^{16} cm | 9.2 days |
| Doppler factor of emission region | δ | 21.5 | ... |
| Min. value of Lorentz factor of injected electrons | γ_{min} | 2.4 × 10^{2} | ... |
| Max. value of Lorentz factor of injected electrons | γ_{max} | 4.5 × 10^{4} | ... |

Flare-IB

| Parameters | Symbol | Values | Time | Duration |
|------------|--------|--------|------|----------|
|            |        |        |      |          |
| Spectral index of injected electron spectrum (LP) | α | 1.7 | ... |
| Curvature index of injected electron spectrum | β | 0.17 | ... |
| Magnetic field in emission region | B | 0.19 G | ... |
| Size of the emission region | R | 8.0 × 10^{16} cm | 10.6 days |
| Doppler factor of emission region | δ | 21.5 | ... |
| Min. value of Lorentz factor of injected electrons | γ_{min} | 2.0 × 10^{2} | ... |
| Max. value of Lorentz factor of injected electrons | γ_{max} | 5.5 × 10^{4} | ... |

Flare-IC

| Parameters | Symbol | Values | Time | Duration |
|------------|--------|--------|------|----------|
|            |        |        |      |          |
| Spectral index of injected electron spectrum (LP) | α | 1.7 | ... |
| Curvature index of injected electron spectrum | β | 0.17 | ... |
| Magnetic field in emission region | B | 0.19 G | ... |
| Size of the emission region | R | 8.0 × 10^{16} cm | 10.6 days |
| Doppler factor of emission region | δ | 21.5 | ... |
| Min. value of Lorentz factor of injected electrons | γ_{min} | 2.0 × 10^{2} | ... |
| Max. value of Lorentz factor of injected electrons | γ_{max} | 5.5 × 10^{4} | ... |

... γ_{max}, magnetic field (B), size of the emission region (R), spectral index (α), curvature index (β), and Doppler factor (δ). All the values of the fitted parameters for the various phases are given in Table 13.

The highest energy photons detected from Flare-1B, Flare-IB, and Flare-IC have energies of 5.56, 6.67, and 29.33 GeV, respectively. The three highest energy photons have energies of 18.23, 37, and 81 GeV in Flare-IA. The optical depth correction due to extragalactic background light (EBL) at redshift 0.695 is negligible for tens of GeV energy (Gilmore et al. 2012) gamma-rays; hence, there is no significant attenuation in the SEDs. In Flare-IA (see Figure 20), the two highest energy data points show a rising trend in the SED; more observational data points are needed to confirm this trend in the future. We have not fitted these two highest energy data points in our model.

We calculated the total jet power using the following equation:

\[ P_{\text{tot}} = \pi R^2 \Gamma^2 c (U'_e + U'_B + U'_p). \]  

(11)

where \( P_{\text{tot}} \) is the total jet power; \( \Gamma \) is the bulk Lorentz factor; \( U'_e, U'_B, \) and \( U'_p \) are the energy density of the electrons (and positrons), magnetic field, and cold protons, respectively, in the comoving jet frame (prime denotes the comoving jet frame; unprime denotes the observer frame).

The power carried by the leptons is given by

\[ P_e = \frac{3 \Gamma^2 c}{4R} \int_{E_{\text{min}}}^{E_{\text{max}}} EQ(E) \, dE, \]  

(12)

where \( Q(E) \) is the injected particle spectrum; integration limits are calculated by multiplying the maximum and minimum Lorentz factor with the rest-mass energy of electron.

The power due to magnetic field is calculated by

\[ P_B = R^2 \Gamma^2 c \frac{B^2}{8}, \]  

(13)

where \( B \) is the magnetic field, used to model the SED.

The energy density in cold protons \( U'_p \) is calculated assuming the number ratio of electron-positron pair to proton is 10:1. We have maintained the charge neutrality condition in the jet. The jet power of protons is computed using the energy density of cold protons.

Subsequently, using Equation (11), we computed the total jet power of each of the flaring phases, tabulated in Table 14. We have not found any paper where the mass or the Eddington luminosity of this source is mentioned. The values of the jet power reported in Table 14 are lower than the typical Eddington luminosities of BL Lacs like Mrk 501, Mrk 421, and AP Librae, which are \((1.1\text{--}4.4) \times 10^{47} \text{erg s}^{-1}\) (Abdo et al. ...
Figure 8. Light curve fitted with Equation (2) of Flare-IA (MJD 58217.5–58220.0).

Figure 9. Light curve fitted with Equation (2) of Flare-IB (MJD 58220.9–58225.3).

Figure 10. Light curve fitted with Equation (2) of Flare-IA (MJD 58932.5–58941.7).

Figure 11. Light curve fitted with Equation (2) of Flare-IB (MJD 58941.7–58947.0).

Figure 12. Light curve fitted with Equation (2) of Flare-IC (MJD 58947.0–58957.6).

Figure 13. Light curve fitted with Equation (2) of Flare-II (MJD 58962.0–58965.0).
8. Summary and Discussion

PKS 0903-57 is a BL Lac type blazar, listed in Fermi’s regularly monitored source list and monitored continuously since 2008 August. Last year, i.e., in 2020, high flaring activity form this source has been detected by different telescopes in different wave bands. Such activity has also been reported before, e.g., in 2015 and 2018; a 7 day binned gamma-ray light curve (Figure 1) over the 12 yr does not show any significant activity around 2015. Some flaring states are observed in the gamma-ray light curve in 2018 and 2020. We continued our analysis focusing on these activity periods. In Figure 1, we show a 7 day binned gamma-ray light curve over 12 yr; from this figure (Figure 1), we have denoted two major flaring activities, Flare-1 and Flare-2. Further shorter time binning (1 day, and 12, 6, and 3 hr) reveals the substructures of these flares. Flare-1 has only one substructure, whereas Flare-2 has two substructures, i.e., Flare-I and Flare-II. In shorter time binned gamma-ray light curve, we detected different phases (preflare, flare, and postflare) of each substructure; even several distinctive peaks of each flare region have been detected. Flare-1 has two phases: Flare-1A and Flare-1B (Figure 3). Flare-1A has two peaks: P1 and P2 (Figure 8) and Flare-1B has only one peak: P1 (Figure 9). The gamma-ray SEDs of Flare-I have been fitted with PL, LP, BPL, and PLEC to check which spectral model gives the best fit to the spectral data (Figure 14). A similar procedure has been followed for Flare-I and Flare-II. In most cases, it has been found that the gamma-ray SEDs of the phases can be well described by the LP model. All the calculations done here are based on a 3 hr binned gamma-ray light curve. We calculated the shortest variability time in the gamma-ray, which is found to be 1.7 ± 0.9 hr. We also studied the rise time ($T_r$) and decay time ($T_d$) of the flaring phases with Equation (2), to check whether they follow any trend or not. The rise time and decay times have been calculated for each peak, listed in Tables 3–8. The rise and decay timescales found in our study are the order of hour scale. For comparative study, we have considered a quantity $\eta$ (Abdo et al. 2010),

$$\eta = \frac{T_d - T_r}{T_d + T_r},$$

where $-1 < \eta < 1$. Depending on the value of $\eta$, there are three scenarios:

1. If the rise and decay timescales are nearly equal, i.e., $T_r \sim T_d$, there is a symmetric temporal evolution. This can be seen in symmetric flares for which $-0.3 < \eta < 0.3$.
2. If the rise timescale is greater than the decay timescale, i.e., $T_r > T_d$, when $\eta < -0.3$, then the injection rate of the electrons is slower than the cooling rate of the electrons into the emission region.
3. If the decay timescale is greater than the rise timescale, i.e., $T_d > T_r$, when $\eta > 0.3$, this means the electrons take longer time to cool down into the emission region.

From our analysis, we found that out of a total of 15 peaks, six peaks have $T_d < T_r$, four peaks have $T_d > T_r$, and five peaks have $T_d \sim T_r$. It is clear that there is no particular pattern in rise and decay timescales for this source. A flaring part is denoted as a peak only when the light curve covered a sufficient number of points; if there are very few points, e.g., 2 or 3, we have not considered them a peak.

Simultaneous multiwavelength data are available only for four phases: Flare-1B, Flare-IA, Flare-IB, and Flare-IC in Swift-XRT, Swift-UVOT, and ATCA; though the data in UVOT and Radio are much less. We modeled these four phases with the time-dependent code GAMERA. GAMERA solves the transport equation for electrons; it also considers the energy loss by synchrotron and SSC processes and escapes from the emission region. We have considered a constant escape from the emission region where the escape timescale is $R/c \sim 10^6$ s. We modeled with a single-zone model. The details of the parameters are given in Table 13. We divided the total flaring duration into four equal time intervals for each of the four phases and we can see the distinct SEDs corresponding to each time interval. The total time durations of Flare-1B, Flare-IA, Flare-IB, and Flare-IC are 4.4, 9.2, 5.3, and 10.6 days, respectively.

To fit the gamma-ray light curve, we used Equation (2); the Blazar community uses this function to model the peaks in the gamma-ray light curve. The first part of the above-mentioned equation is used to fit the rise part, which gives the rise time. We can estimate the decay timescale by fitting the decaying part of a flare with the second part of the equation. If a flare contains more than one peak, in that case, we considered the
sum of the exponents of the rise and decay times to fit all the detected peaks in that phase. In this case, peak flux ($F_\circ$) and peak time ($t_\circ$) will be different for different peaks, which is already known from observation. There are several reasons for which the fit may not be good, e.g., low TS, fewer data points, and large error bars on the data points. In the case of rapid flux change, it is difficult to fit all the peaks (even the small peaks), which could be a possible reason behind the poor fitting.

The time binning of the gamma-ray light curve has not been chosen arbitrarily. It is done based on the quality of the data, i.e., the TS value of each data point. For a very bright gamma-ray source and very-high flux, the data may be of very good quality and we can bin the light curve up to minute timescale (Shukla et al. 2018). In our analysis, we scanned the 3 hr binned gamma-ray light curve for which TS $\geq 25$, i.e., the data points have $5\sigma$ significance. The gamma-ray flux error

Figure 15. Gamma-ray SEDs of five activity phases of Flare-I as shown in Figure 6. SEDs have been fitted with the four spectral models mentioned earlier.
increases as the bin size decreases (if we compare 3 and 6 hr time binning, we can easily notice this). Moreover, time binning shorter than 3 hr would be difficult for our analysis. Also, to define a peak, a fitting curve must cover a sufficient number of points, which is possible if we choose 3 hr time bin instead of a 6 hr time bin. The optical depth correction due to EBL is not important in our case as the energy of the observed highest energy photons is only a few gigaelectronvolts.

9. Conclusion

We analyzed the 12 yr (from 2008 August 4–2021 January 6) gamma-ray light curve of PKS 0903-57, from which we detected two flaring activities in 2018 and 2020. The gamma-ray flux was the highest in 2020. We identified two flares: Flare-1 and Flare-2. Flare-1 has one substructure, which has two phases: Flare-1A and Flare-1B. Flare-2 has two substructures: Flare-I and Flare-II, which have several phases. Flare-I has five phases: Preflare-I, Flare-IA, Flare-IB, Flare-IC, and Postflare-I. Flare-II has three phases: Preflare-II, Flare-II, and Postflare-II. We fitted Flare-1A, Flare-1B, Flare-IA, Flare-IB, Flare-IC, and Flare-II with Equation (2) and calculated the rise and decay times of the peaks of the flaring phases. We computed the gamma-ray variability time of this source, which is found to be $1.7 \pm 0.9$ hr. The different phases of the gamma-ray SEDs have been fitted with PL, LP, BPL, and PLEC to find the best-fitted spectral model.

Flare-1B, Flare-1A, Flare-IB, and Flare-IC have simultaneous multiwavelength data and for these phases LP is found to be the best-fitted model. The multiwavelength SEDs of these four phases have been modeled with the time-dependent code, GAMERA. Due to insufficient multiwavelength data, further multiwavelength analysis is not possible for this source. We have assumed the emissions are occurring from a single-zone. The total jet power required during the flaring phases is estimated to be a few times $10^{46}$ erg s$^{-1}$.

10. Software and Third-party Data Repository Citations

The Fermi-LAT gamma-ray data analysis was done with the Fermi Science Tools software FTools (Fermi-LAT Collaboration 2018). Swift X-ray, UV, and optical data have been analyzed with Heasoft.

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Multi-Wavelength Light Curve of PKS 0903-57 during Flare-I

Figure 17. Multiwavelength light curve of PKS 0903-57 during Flare-I. The green solid circle denotes Fermi-LAT data points in a 6 hr bin. Others are mentioned in the plots. UV data points are in the W1, M2, and W2 bands and optical data points are in the U, V, and B bands.

Figure 18. Multiwavelength light curve of PKS 0903-57 during Flare-I. The color codes are same as those in Figure 17.

Facilities: Fermi-LAT, Swift (XRT/UVOT), ATCA, DAMPE, AGILE.

Software: Fermi Science Tools or Fermitools (https://fermi.gsfc.nasa.gov/ssc/data/analysis/scitools/) Heasoft
Figure 19. Multiwavelength SED of Flare-1B. The color codes are as follows: gray square = archival data points/nonsimultaneous data points; red solid circle = optical (Swift); cyan triangle = UV (Swift); green triangle = X-ray (Swift); magenta solid circle = gamma-ray (Fermi-LAT).

Figure 20. Multiwavelength SED of Flare-IA. The color codes are the same as those in Figure 19, and radio data points are denoted by blue inverted triangles (ATCA).
Figure 21. Multiwavelength SED of Flare-IB. The color codes are same as as those in Figure 19.

Figure 22. Multiwavelength SED of Flare-IC. The color codes are the same as those in Figure 19.

Appendix

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References

Abdo, A. A., Ackermann, M., Ajello, M., et al. 2010, ApJ, 722, 520
