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Detection of a Gamma-Ray Flare from the High-redshift Blazar DA 193

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Abstract

High-redshift ($z > 2$) blazars are the most powerful members of the blazar family. Yet, only a handful of them have both X-ray and γ -ray detection, thereby making it difficult to characterize the energetics of the most luminous jets. Here, we report, for the first time, the *Fermi*-Large Area Telescope detection of the significant γ -ray emission from the high-redshift blazar DA 193 ($z = 2.363$). Its time-averaged γ -ray spectrum is soft (γ -ray photon index = 2.9 ± 0.1), and together with a relatively flat hard X-ray spectrum (14–195 keV photon index = 1.5 ± 0.4), DA 193 presents a case to study a typical high-redshift blazar with inverse Compton peak being located at MeV energies. An intense GeV flare was observed from this object in the first week of 2018 January, a phenomenon rarely observed from high-redshift sources. What makes this event a rare one is the observation of an extremely hard γ -ray spectrum (photon index = 1.7 ± 0.2), which is somewhat unexpected because high-redshift blazars typically exhibit a steep falling spectrum at GeV energies. The results of our multifrequency campaign, including both space- (*Fermi*, *NuSTAR*, and *Swift*) and ground-based (Steward and Nordic Optical Telescope) observatories are presented, and this peculiar γ -ray flare is studied within the framework of a single-zone leptonic emission scenario.

Key words: galaxies: active – galaxies: jets – gamma rays: galaxies – radiation mechanisms: non-thermal – relativistic processes

1. Introduction

The extragalactic high-energy γ -ray sky, as observed by the Large Area Telescope (LAT; Atwood et al. 2009) on board the *Fermi* Gamma-ray Space Telescope, is dominated by blazars. These are a peculiar class of active galactic nuclei (AGNs) that host powerful relativistic jets aligned close to the line of sight to the observer. Based on the rest-frame equivalent width (EW) of the emission lines, blazars are subclassified as flat spectrum radio quasars (FSRQs; $EW > 5 \text{ \AA}$) and BL Lac objects (Stickel et al. 1991). The optical spectrum of a FSRQ exhibits broad or strong emission lines, thus indicating the presence of an efficient accretion process surrounding the central black hole. On the other hand, observations of very weak or no emission lines ($EW < 5 \text{ \AA}$) in the optical spectra of BL Lac objects suggests either the dominance of the nonthermal jet emission, i.e., the power-law continuum, over emission lines and/or the inefficient and low accretion and thus a weak broadline region (BLR; Whiting 2005). Indeed, a division between FSRQ and BL Lac objects based on the luminosity of the BLR measured in Eddington units has been proposed by Ghisellini et al. (2011) with FSRQs exhibiting $L_{\text{BLR}}/L_{\text{Edd}} > 0.0005$.

The spectral energy distribution (SED) of a blazar is characterized by a double-peak structure and is governed by the bolometric luminosity of the source, also known as the blazar sequence (Fossati et al. 1998; Ghisellini et al. 1998; Donato et al. 2001; but see Giommi et al. 2012). It has been observed that the low-energy synchrotron peak of luminous blazars (generally FSRQs) lies at submm to infrared (IR)

frequencies, whereas, the high-energy inverse Compton (IC) emission peaks at \sim MeV energies. In general, high-redshift ($z > 2$) blazars are the most luminous ones. Therefore, in the broadband SED of high-redshift blazars, thermal emission from the accretion disk is visible in the optical-UV band due to shift of the synchrotron peak to lower frequencies (e.g., Ghisellini et al. 2010). Moreover, due to their IC emission peak lying at MeV energies, these distant sources are also called as “MeV” blazars (Bloemen et al. 1995).

Lacking an MeV all-sky instrument, the most efficient domain to detect and study high-redshift blazars is the hard X-ray ($> 10 \text{ keV}$) band. In this energy range, these objects display remarkably hard spectra (power-law photon indices $\lesssim 1.6$) that easily distinguish them from the other, more common, AGNs. *Swift*-Burst Alert Telescope (BAT; Barthelmy et al. 2005) has detected 22 such objects at $z \geq 2$, all with a luminosity $\text{Log} L_X \geq 47.5 \text{ erg s}^{-1}$ (Oh et al. 2018). Many of them were found to have larger than average jet powers ($> 10^{47} \text{ erg s}^{-1}$), accretion luminosities, Compton dominance (which is the ratio of IC to synchrotron peak luminosities), and black hole masses (Ghisellini et al. 2010; Tagliaferri et al. 2015; Sbarrato et al. 2016).

Though hard X-ray observing facilities, e.g., *NuSTAR* (3–79 keV; Harrison et al. 2013), are better suited to study high-redshift blazars, *Fermi*-LAT observations are still crucial to constrain the falling part of the IC spectrum and thus the location of the IC peak. More importantly, an unambiguous confirmation of the blazar nature of a high-redshift, radio-loud quasar itself can be made by the *Fermi*-LAT detection, which

provides strong evidences in support of the closely aligned relativistic jet. In this regard, the recently released Pass 8 photon data set, with an improved event-level analysis (Atwood et al. 2013), substantially enhances the LAT capability to detect spectrally soft, potentially high-redshift blazars that host massive black holes and the most powerful relativistic jets. Because blazars are highly beamed, the detection of a single blazar implies the existence of hundreds of quasars with similar properties, and at the same redshift, but with jets pointed in other directions. Therefore, the discovery of each new high-redshift blazar provides crucial constraints on the space density of massive black holes, hosted in radio-loud systems, in the early universe (Ajello et al. 2009; Ghisellini et al. 2010; Ackermann et al. 2017).

We are studying high-redshift blazars with the motivation to characterize their physical properties using *Fermi*-LAT and other multifrequency observations (see, Paliya 2015; Ajello et al. 2016; Paliya et al. 2016; Ackermann et al. 2017; Kaur et al. 2017, 2018; Marcotulli et al. 2017; Paliya et al. 2017). In this work, we present the results of our study on another high-redshift blazar DA 193 (also known as 0552+398; $z = 2.363$, Wills & Wills 1976; McIntosh et al. 1999), which we have found as a new γ -ray emitting object through our detailed *Fermi*-LAT analysis. Interestingly, this source exhibited a GeV flare in 2018 January (Angioni & Cheung 2018). To investigate and study this peculiar event in detail, we triggered target of opportunity (ToO) observations from the *Neil Gehrels Swift observatory* and *NuSTAR*, and also optical polarimetric and photometric measurements from the Steward observatory and Nordic Optical Telescope (NOT), respectively. In particular, optical follow-ups, including polarization measurements, are helpful in determining the relative dominance of the synchrotron emission and the accretion disk radiation used for the SED modeling. In Section 2, basic information of DA 193 are briefly described. The steps of data reduction and analysis are elaborated in Section 3. Results are presented and discussed in Section 4 and we summarize them in Section 5. Throughout, we assume a flat cosmology with $H_0 = 67.8 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and $\Omega_M = 0.308$ (Planck Collaboration et al. 2016).

2. Basic Multiwavelength Information

DA 193 lies close to the Galactic anti-center (Galactic longitude and latitude: $171^\circ.647$ and $7^\circ.284$, respectively) and is a bright radio quasar ($F_{1.4 \text{ GHz}} = 1516 \text{ mJy}$; Condon et al. 1998). It was the subject of various radio studies due to its peculiar Gigahertz peak spectrum (e.g., Schilizzi & Shaver 1981; Spangler et al. 1983; O’Dea et al. 1990). It is one of the MOJAVE-monitored blazars and the detection of superluminal motion has been reported at 15 GHz (apparent jet velocity $= 1.592 \pm 0.096 c$, Lister et al. 2016). Interestingly, by studying multi-epoch very long baseline interferometry observations, Wang et al. (2001) proposed the detection of an accelerated jet.

DA 193 is well detected in the 2MASS (Skrutskie et al. 2006) and *Wide-field Infrared Survey Explorer* (*WISE*; Wright et al. 2010) surveys. The optical spectroscopic observations of this object led to the detection of broad emission lines, which supports the case for an extremely massive black hole at the center ($M_{\text{BH}} \approx 5 \times 10^9 M_\odot$; Yuan & Wills 2003; Torrealba et al. 2012). Moreover, optical polarimetric measurements from

McDonald observatory resulted in the detection of low polarization of $\sim 1.5\%$ (Wills et al. 2011).

DA 193 has also been studied at X-ray frequencies to understand the soft X-ray absorption typically observed in many high-redshift, radio-loud quasars (e.g., Eitan & Behar 2013; Arcodia et al. 2018). This object is luminous at hard X-rays and exhibits a relatively flat X-ray spectrum above 10 keV ($L_{14-195 \text{ keV}} = 10^{48} \text{ erg s}^{-1}$, $\Gamma_{14-195 \text{ keV}} = 1.5 \pm 0.4$; Oh et al. 2018), typical of a powerful MeV blazar. However, it is not present in any of the published γ -ray catalogs.

3. Data Reduction

3.1. Gamma-Ray Analysis

We analyze *Fermi*-LAT Pass 8 data of DA 193 following the standard data reduction procedure⁹ and briefly describe it here. In the energy range of 0.1–300 GeV, we consider only SOURCE class events (`evclass=128`) covering the period MJD 54683–58137 (2008 August 5–2018 January 19) and adopt a relational filter “`DATA_QUAL>0` and `LAT_CONFIG==1`” to select good time intervals. Only events passing the cut “`zmax < 90°`” are considered, to avoid Earth limb γ -ray contamination. A circular region of interest (ROI) is defined with the radius of 15° centered at DA 193 (R.A.: $05^{\text{h}}55^{\text{m}}30^{\text{s}}.806$, J2000; decl.: $+39^{\text{d}}48'49''165$, J2000; Lister et al. 2016) and a background model is generated consisting of all 3FGL sources (Acero et al. 2015) present within the ROI and the Galactic diffuse and extragalactic isotropic background emission templates¹⁰ (Acero et al. 2016). The spectral shapes of all the sources are the same as those adopted in the 3FGL catalog and associated parameters are left free to vary when performing the binned likelihood fitting. We determine the significance of the γ -ray signal by deriving the maximum likelihood test statistic $\text{TS} = 2 \Delta \log(\mathcal{L})$ where \mathcal{L} is the likelihood value between models with and without a γ -ray source at the position of DA 193. As the target object is not present in the 3FGL catalog, we parameterize its spectral shape by a power-law model and the prefactor and photon index of the model are allowed to vary during the optimization.

We follow an iterative approach to search for unmodeled γ -ray sources present in the data but not in the model, as the time period covered is much longer than that considered in the 3FGL catalog. This is done by generating a residual TS map and scanning it to identify excess emission peaks with $\text{TS} > 25$ ($\sim 4.2\sigma$ significance; Mattox et al. 1996). Once found, they are modeled with a simple power law and included in the sky model. This process is repeated until there is no source with $\text{TS} > 25$ left to model.¹¹ When using the whole data set, a new source is found at the position of DA 193, as fully described in Section 4.1.

To generate the γ -ray light curves and spectra, we allow the spectral parameters of the source of interest and all other background objects, lying within 10° from the ROI center, to vary freely. We compute 2σ flux upper limits in time/energy bins in which the source TS is found to be < 9 or $\Delta F_\gamma / F_\gamma > 0.5$,

⁹ <https://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/>

¹⁰ <https://fermi.gsfc.nasa.gov/ssc/data/access/lat/BackgroundModels.html>

¹¹ We have verified our results by considering the sources not present in 3FGL, but with those in recently released *Fermi*-LAT 8 yr preliminary list (FL8Y) to populate the model file. No significant changes in the optimized spectral parameters are found with respect to those derived from the 3FGL + TS map approach.

where ΔF_γ is the uncertainty in the 0.1–300 GeV γ -ray flux, F_γ . Unless otherwise noted, all the statistical uncertainties are estimated at 1σ confidence level.

3.2. Hard X-Ray Analysis

DA 193 is included in the 105 month *Swift*-BAT catalog (Oh et al. 2018), and we use the publicly available 14–195 keV spectrum for SED modeling.

DA 193 underwent a huge GeV flare in the first week of 2018 and a ToO observation with *NuSTAR* was performed on MJD 58126–58127 (2018 January 8–9, PI: V. S. Paliya) to follow the flaring blazar. The net exposure of the observation was ~ 28 ksec. *NuSTAR* data are reduced following the standard guidelines.¹² In particular, we use the *NuSTAR* Data Analysis Software (NUSTARDAS version 1.8.0) to analyze the Focal Plane Module A (FPMA) and Focal Plane Module B (FPMB) data. Considering the latest *NuSTAR* calibration files (CALDB version 20180419) and standard filtering criteria, the event data files are cleaned and calibrated using the task `nupipeline`. We consider the source region as a circle of $30''$ centered at DA 193 and also use a background (source-free) region of $70''$ from the same chip. We then use the task `nuproducts` to generate source and background spectra and ancillary and response matrix files. The source spectrum is binned to have at least 20 counts per bin using the task `grppha`.

3.3. Soft X-Ray Analysis

Prior to our three ToO observations in 2018 January, DA 193 was observed by *Swift* twice in 2007 and 2010 and three times in 2011. All of the X-ray Telescope (XRT; Burrows et al. 2005) observations were taken in the standard photon counting mode (standard grade selection 0–12). We downloaded all the available data sets from HEASARC archive and analyzed it using the HEASoft (v 6.22) and calibration files updated on 2018 March 5. The event files are cleaned and calibrated using the task `xrtpipeline` and then summed using `xselect`. We combine exposure maps using the `ximage` tool. To extract the source and background spectra from the summed event file, we consider a circular region of $55''$ radius centered at the target quasar. The background region is taken as an annular ring centered at DA 193, with inner and outer radii as $110''$ and $220''$, respectively. An ancillary response file is generated using `xrtmkarf`. Finally, a source spectrum is binned to have at least 20 counts per bin using `grppha`. The Galactic neutral hydrogen column density ($N_{\text{H}} = 2.73 \times 10^{21} \text{ cm}^{-2}$) is taken from Kalberla et al. (2005), and we perform the spectral fitting using XSPEC (Arnaud 1996).

3.4. Optical-UV Analysis

Individual *Swift* UltraViolet Optical Telescope (UVOT; Roming et al. 2005) snapshots are first combined with the task `uvotimsum` and source magnitudes are extracted using `uvotsource`. For the latter, we consider a source region of $5''$ radius, and the background is chosen from a nearby region of $30''$ free from source contamination. We de-absorb the magnitudes for Galactic extinction following (Schlafly & Finkbeiner 2011) and convert them to energy flux units using the zero points provided in Breeveld et al. (2011).

The NOT observations were made using the Andalucia Faint Object Spectrograph and Camera (ALFOSC) instrument at four epochs between MJD 58128–58138 (2018 January 10–20). Standard IRAF¹³ data reduction (de-biasing and flat-field correction with twilight flats) is carried out and differential photometry is performed. The brightness is estimated against five SDSS r' stars between 15.3 and 17.4 mag. The standard deviation of the zero-point is measured as 0.02 mag.

Optical polarimetric observations of DA 193 were taken on MJD 58130–58131 (2018 January 12–13) from SPOL CCD Imaging/Spectropolarimeter attached to 1.54 m Kupier telescope. The details of the data reduction procedure can be found in Smith et al. (2009); here, we directly use the publicly available V-band polarization data.

4. Results and Discussion

4.1. A New γ -Ray Emitting Blazar

DA 193 is not present in any of the published *Fermi*-LAT catalogs. This suggests that either it is a γ -ray faint blazar or it remained in quiescence for a long time. Contrarily, it is bright in hard X-rays (Oh et al. 2018) which indicates it to be a typical high-redshift MeV blazar.

We search for γ -ray emission from DA 193 using the Pass 8 data set covering more than nine years of the *Fermi*-LAT operation. We start by considering only 3FGL sources within the ROI and generate TS maps to search unmodeled γ -ray sources that have $\text{TS} > 25$. A γ -ray bright source with $\text{TS} = 671$ is identified whose optimized position (corresponding to the maximum of the TS map, R.A.: $05^{\text{h}}55^{\text{m}}36^{\text{s}}.1$, J2000; decl.: $+39^{\circ}49'12''.0$, J2000) is found to be spatially consistent with the radio position of DA 193. The angular separation between the radio and the optimized γ -ray coordinates is derived as $0^{\circ}02'$, while the 95% error radius of the optimized γ -ray position is $0^{\circ}05'$. This suggests a positional association of DA 193 with the γ -ray source (see the left panel of Figure 1). We also generate an X-ray counts map by combining all of the *Swift*-XRT pointings of DA 193 and show it in the right panel of Figure 1. As can be seen, there is only one bright X-ray source present within the 95% error circle, which is DA 193. This observation provides further evidence of DA 193 being a new blazar in the γ -ray sky.¹⁴

The γ -ray spectral parameters of DA 193 are as follows: 0.1–300 GeV flux = $(5.2 \pm 0.6) \times 10^{-8} \text{ ph cm}^{-2} \text{ s}^{-1}$, photon index = 2.9 ± 0.1 . These are similar to those typically observed from luminous high-redshift blazars (Paliya et al. 2016; Ackermann et al. 2017). Its 0.1–300 GeV spectrum is very soft, and together with a relatively flat X-ray spectrum as observed from the *Swift*-BAT, this implies the IC peak to be located at \sim MeV energies. Furthermore, we also searched for curvature in the γ -ray spectrum. This is done by fitting a log-parabola model and comparing the likelihood value (\mathcal{L}_{LP}) with that obtained from the power-law fit (\mathcal{L}_{PL}). Following Nolan et al. (2012), we compute TS of the curvature: $\text{TS}_{\text{curve}} = 2(\log \mathcal{L}_{\text{LP}} - \log \mathcal{L}_{\text{PL}})$. The derived TS_{curve} is < 1 and therefore no significant curvature is found.

Using the optimized γ -ray coordinates derived above, we also performed the data analysis for the first four years of the *Fermi* mission, i.e., the time period covered in the 3FGL

¹² https://heasarc.gsfc.nasa.gov/docs/nustar/analysis/nustar_swguide.pdf

¹³ <http://iraf.noao.edu/>

¹⁴ A γ -ray source positionally consistent with DA 193 is present in the recently released FL8Y with name FL8Y J0555.6+3948.

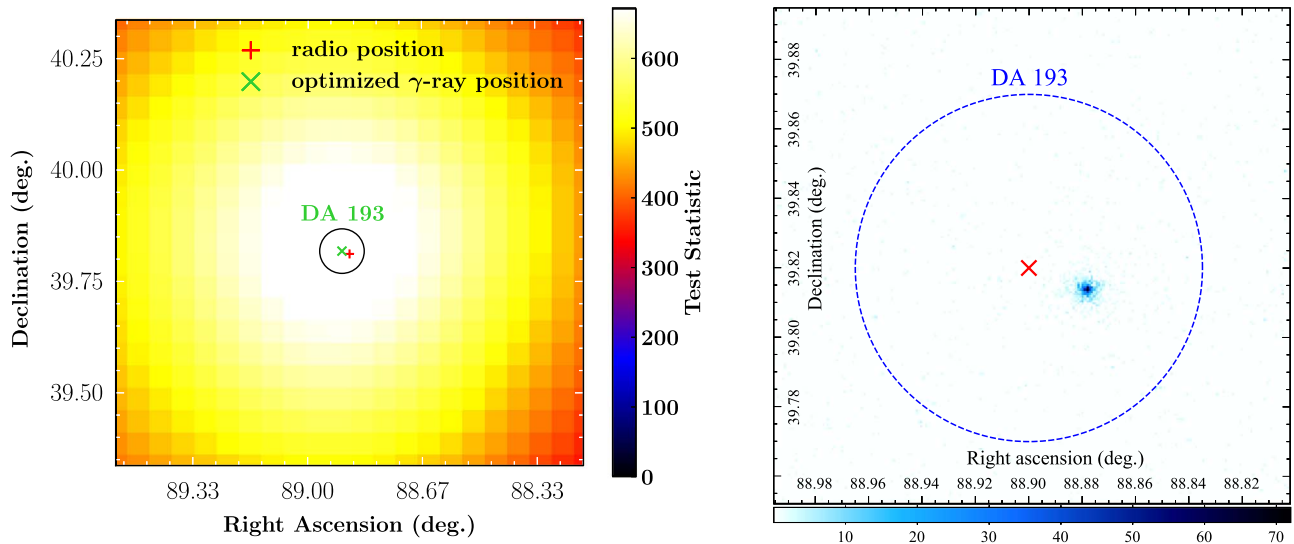


Figure 1. Left: 0.1–300 GeV test statistic map of DA 193, generated for the period MJD 54683–58137. Image scale is $0^{\circ}05$ per pixel, and the black circle denotes the 95% positional uncertainty derived from the *Fermi*-LAT data analysis. The radio and optimized γ -ray positions are also shown as labeled. Right: the X-ray counts map of the DA 193 field generated by combining all *Swift*-XRT pointings. The blue dashed circle denotes the 95% error uncertainty in the optimized γ -ray position, which is shown with the red cross. The color bar has the unit of counts per pixel. The spatial position of the bright X-ray source present in the field is consistent with DA 193.

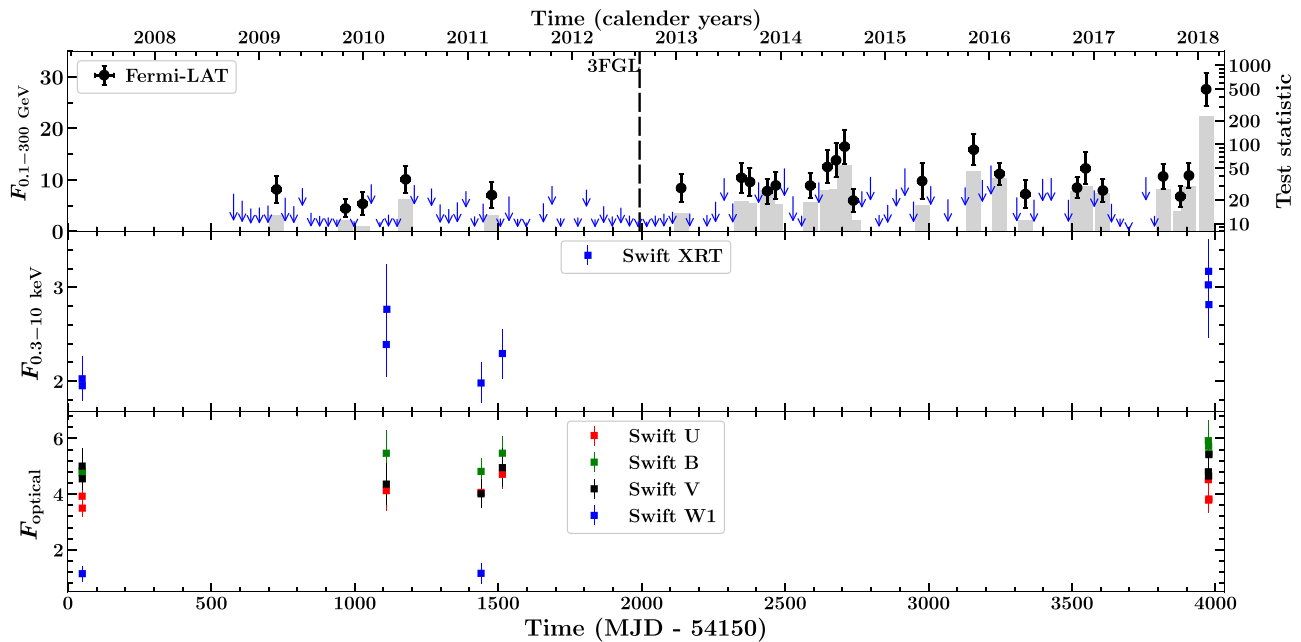


Figure 2. Top: monthly binned γ -ray light curve of DA 193. Black circles represent the source photon flux for time bins with TS > 9 . For TS < 9 , we derive 2σ flux upper limits, which are shown with blue downward arrows. Vertical dashed line denotes the time period covered in the 3FGL catalog since the beginning of the *Fermi* mission. Light-gray bars represent the TS values in bins with TS > 9 . Middle and bottom: *Swift*-XRT and UVOT observations of DA 193 with each data point corresponds to one observation id. The right-most points denote three *Swift* pointings taken during our ToO campaign in 2018 January. *Fermi*-LAT data points are in units of 10^{-8} ph cm $^{-2}$ s $^{-1}$, whereas both XRT and UVOT data have the units of 10^{-12} erg cm $^{-2}$ s $^{-1}$.

catalog. This exercise reveals a TS = 21, which is less than the threshold (25) set in the LAT catalogs and thus explains the reason of DA 193 not included in them.

4.2. γ -Ray Variability

Once we establish the identity of DA 193 as a γ -ray emitting blazar, we explore its temporal behavior in the γ -ray band. This is done by generating a monthly binned light curve, which is shown in Figure 2. We find hints of low-level activity during the time period covered in the 3FGL catalog; however, in none of the time bins is the source detection found to be $>5\sigma$

significant. There are some moderate level temporal flux variations after that, mainly around MJD 56880 (2014 August). The source entered in its brightest γ -ray flux state (until now) in the last time bin, i.e., at the beginning of 2018 January.

DA 193 became active in the first week of 2018, and its daily binned γ -ray flux exceeded 1×10^{-6} ph cm $^{-2}$ s $^{-1}$ on MJD 58123 (2018 January 5). Interestingly, the γ -ray spectrum is found to be extremely hard with photon index < 2 , i.e., a rising spectrum in νF_ν versus ν SED notation (Angioni & Cheung 2018). To study this peculiar event in detail, we focus on the time period MJD 58122–58128, i.e., 2018 January 4–10. We generate γ -ray light curves in various time binning as shown in

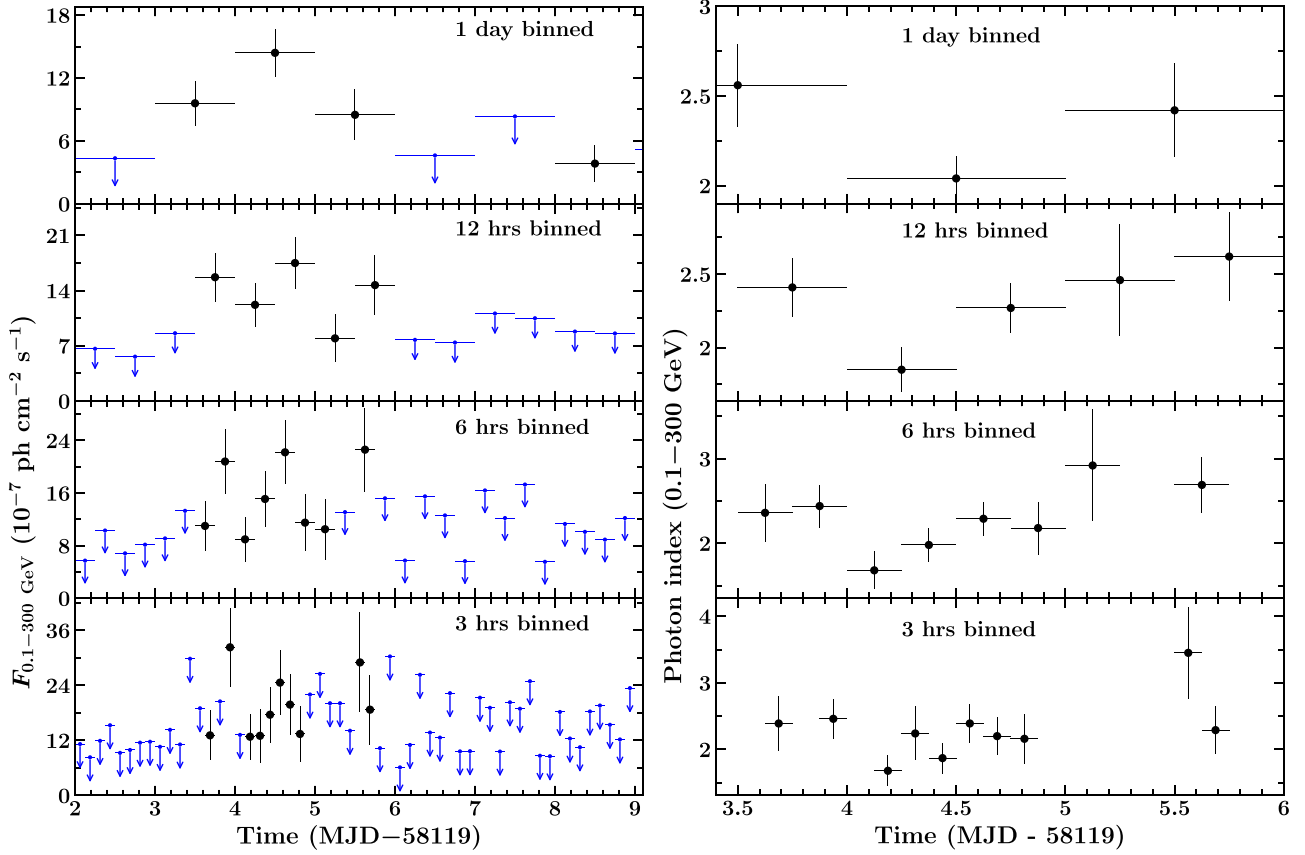


Figure 3. Left: the γ -ray light curve of DA 193 focusing on the flaring activity period. Adopted time bins are labeled in different panels. Integrated photon flux upper limits are computed at 2σ confidence level. Right: variation of the γ -ray photon index during the period of the high activity. MJD 58119 correspond to 2018 January 1.

the left panel of Figure 3 and scan them to search for rapid flux variations, but we find none.

The brightest γ -ray flux, estimated using the 3 hr binned light curve, is $F_\gamma = (3.2 \pm 0.9) \times 10^{-6} \text{ ph cm}^{-2} \text{ s}^{-1}$ in the bin centered at MJD 58122.937. The associated photon index is noted as 2.5 ± 0.3 with $\text{TS} = 49$. This implies an isotropic γ -ray luminosity $L_\gamma = (1.3 \pm 0.4) \times 10^{50} \text{ erg s}^{-1}$. Though the observed L_γ is less than the maximum ever observed from a non-gravitationally lensed blazar (3C 454.3, $L_\gamma \approx 2 \times 10^{50} \text{ erg s}^{-1}$; Abdo et al. 2011), a different scenario emerges when we compare the emitted powers in the jet-frame. Lei & Wang (2014) reported a bulk Lorentz factor $\Gamma_b = 22$ by modeling the SED of 3C 454.3 during the flaring period in 2010 November (see also Wehrle et al. 2012). This, in turn, gives $L_{\text{jet}} = L_\gamma / 2\Gamma_b^2 \simeq 2 \times 10^{47} \text{ erg s}^{-1}$. For DA 193; on the other hand, the power emitted during the flare is $L_{\text{jet}} \simeq 5 \times 10^{47} \text{ erg s}^{-1}$, assuming $\Gamma_b = 11$ (Section 4.6), which is about two-times larger than that observed from 3C 454.3. Orienti et al. (2014) studied the γ -ray outburst of another high-redshift blazar TXS 0536+145 ($z = 2.69$) and reported $L_\gamma = 6.6 \times 10^{49} \text{ erg s}^{-1}$ and $\Gamma_b = 30$. In addition to that, $L_\gamma = 1.6 \times 10^{50} \text{ erg s}^{-1}$ and $\Gamma_b = 19$ was reported for the 2011 December γ -ray flare of the bright high-redshift blazar S5 0836+71 ($z = 2.17$, Paliya 2015). In the jet-frame, this gives $L_{\text{jet}} \simeq 4 \times 10^{46} \text{ erg s}^{-1}$ and $2 \times 10^{47} \text{ erg s}^{-1}$, respectively for TXS 0536+145 and S5 0836+71, which are smaller than that found for DA 193. Therefore, the γ -ray flaring activity of DA 193 was intrinsically more powerful than the brightest γ -ray

flare from 3C 454.3 or probably other high-redshift blazars studied so far.

The right panel of Figure 3 represents the spectral behavior of the source during the flaring episode. As can be seen, the γ -ray spectrum significantly ($>5\sigma$) hardens during the flare. In particular, a photon index of 1.7 ± 0.2 was noted on MJD 58123.187, with $F_\gamma = (1.3 \pm 0.5) \times 10^{-6} \text{ ph cm}^{-2} \text{ s}^{-1}$ and $\text{TS} = 67$. Such a hard γ -ray spectrum is typically observed from high-synchrotron peaked BL Lac objects (e.g., Ackermann et al. 2015) and, to our knowledge, has never been observed from a $z > 2$ blazar.

The detection of the GeV flare from a high-redshift blazar is a rare phenomenon, due to these objects being faint in the γ -ray band. What makes this peculiar flaring activity even rarer is the observation of an extremely hard γ -ray spectrum, as described above. This is due to two reasons. First is the K -correction: for increasing redshifts (Hogg et al. 2002), which makes the IC peak to be located closer to the hard X-ray band and hence brighter with respect to *Fermi*-LAT energy range. The shift of the SED peaks to lower frequencies with the increase in the bolometric luminosity, is another effect which makes high-redshift blazar fainter with steeper spectrum in γ -rays.

With the motivation to perform a comparative study of different activity states of DA 193, we define two time periods. MJD 54683–58118 (2008 August 8 to 2017 December 31) is adopted as a low-activity period, and MJD 58122–58128 (2018 January 4–10) is assumed to cover the flaring episode. We note that the adopted low-activity duration may not represent the true quiescence of the blazar because a few sparse moderate level flux enhancements are observed (Figure 2).

Table 1
Summary of the SED Analysis

Activity State	Time Bin (MJD)	<i>Fermi</i> -LAT $\Gamma_{0.1-300 \text{ GeV}}$	$F_{0.1-300 \text{ GeV}}$ ($10^{-8} \text{ ph cm}^{-2} \text{ s}^{-1}$)	TS
Flare	58122–58128	2.32 ± 0.10	79.6 ± 10.2	235
Low activity	54683–58118	2.88 ± 0.06	4.8 ± 0.6	566
<i>NuSTAR</i> + <i>Swift</i> -XRT				
Activity state		$\Gamma_{0.3-79 \text{ keV}}$	Norm $_{0.3-79 \text{ keV}}$ ($10^{-4} \text{ ph cm}^{-2} \text{ s}^{-1} \text{ keV}^{-1}$)	Statistics χ^2/dof
Flare		$1.58_{-0.08}^{+0.07}$	$4.93_{-0.73}^{+0.85}$	150.73/120
<i>NuSTAR</i>				
Activity state	Exp. (ksec)	$\Gamma_{3-79 \text{ keV}}$	Norm $_{3-79 \text{ keV}}$ ($10^{-4} \text{ ph cm}^{-2} \text{ s}^{-1} \text{ keV}^{-1}$)	Stat. χ^2/dof
Flare	28.56	$1.57_{-0.07}^{+0.08}$	$4.89_{-0.72}^{+0.89}$	141.92/109
<i>Swift</i> -XRT				
Activity state	Exp. (ksec)	$\Gamma_{0.3-10 \text{ keV}}$	Norm $_{0.3-10 \text{ keV}}$ ($10^{-4} \text{ ph cm}^{-2} \text{ s}^{-1} \text{ keV}^{-1}$)	Stat. χ^2/dof
Flare	5.64	$1.62_{-0.24}^{+0.25}$	$4.62_{-0.87}^{+0.92}$	8.72/10
Low activity	17.64	$1.22_{-0.12}^{+0.12}$	$2.44_{-0.29}^{+0.30}$	24.23/26
<i>Swift</i> -UVOT				
Activity state	V ($10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$)	B ($10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$)	U ($10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$)	$UVW1$ ($10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$)
Flare	4.96 ± 0.18	5.71 ± 0.34	4.04 ± 0.21	...
Low activity	4.58 ± 0.27	5.07 ± 0.26	4.07 ± 0.23	1.24 ± 0.23

Note. For the low-activity state, we combine a total of seven *Swift* observations (observation id: 00036315001–2, 00036315004–8). On the other hand, flaring state X-ray spectrum is generated by adding three ToO observations (observation id: 00036315009–11).

However, a true quiescence may not serve the purpose as we need to generate a meaningful γ -ray SED. Therefore, we can call MJD 54683–58118 a low-activity period with respect to the GeV flare observed in 2018 January. The spectral parameters derived from the *Fermi*-LAT data analysis for these two periods are presented in Table 1.

4.3. X-Ray Analysis

In the middle panel of Figure 4, we show 0.3–10 keV count rate measured from the three *Swift*-XRT observations taken during the GeV flare. Comparing the X-ray light curve with the γ -ray one (top panel), we find that we were able to follow the source during the decaying phase of the flare. Moreover, no significant flux variability is observed; therefore, we combine all of the three *Swift*-XRT observations to improve the photon statistics and generate a 0.3–10 keV spectrum representing the flaring period. Following a similar approach, we add all of the previous *Swift*-XRT measurements to generate an X-ray SED corresponding to the low-activity state (see the middle panel in Figure 2). We fit an absorbed power-law model to derive the spectral parameters for both X-ray SEDs and provide them in Table 1.

A simple power-law model explains the *NuSTAR* spectrum reasonably well and the associated spectral parameters are shown in Table 1.

We also perform a joint *NuSTAR* and *Swift*-XRT fitting using the data taken during the flaring period and adopt an absorbed power-law model with neutral hydrogen column density fixed to the Galactic value. An intercalibration constant

is considered while performing the fit, to allow for the cross-calibration uncertainties between *NuSTAR* (FPMA and FPMB) and *Swift*. This constant is fixed to unity for FPMA and left free to vary for FPMB and *Swift*-XRT spectra. It is found to be 0.98 ± 0.04 and 0.91 ± 0.10 for FPMB and *Swift*-XRT, respectively. The spectral parameters are provided in Table 1 and the spectra, along with the best-fitted model, are shown in Figure 5. Because high-redshift blazars typically exhibit a significant soft X-ray spectral break (e.g., Fabian et al. 2001; Worsley et al. 2004), we also test an absorbed broken power-law model ($\chi^2/\text{dof} = 138/118$); however, we do not find a significant improvement with respect to an absorbed power-law model (F-test probability = 0.01).

4.4. Optical-UV Observations

In the bottom panel of Figure 4, we show the temporal variation of the optical flux in the V , B , U , and $W1$ bands as observed from the *Swift*-UVOT. The source, on the other hand, is not detected in $M2$ and $W2$ filters. As evident from this plot, DA 193 did not show any significant flux variability during the γ -ray flaring period. Similar results are derived from optical photometric observations taken from NOT (see Figure 6). The lack of the optical flux variability can be explained on the basis of two facts: either the source returned to faint state and/or the optical-UV emission is dominated by thermal radiation from the accretion disk, which is not expected to vary on short timescales. In fact, our SED modeling results confirms that the IR–UV spectrum of DA 193 is indeed dominated by the accretion disk emission (see below). Furthermore, on the nights

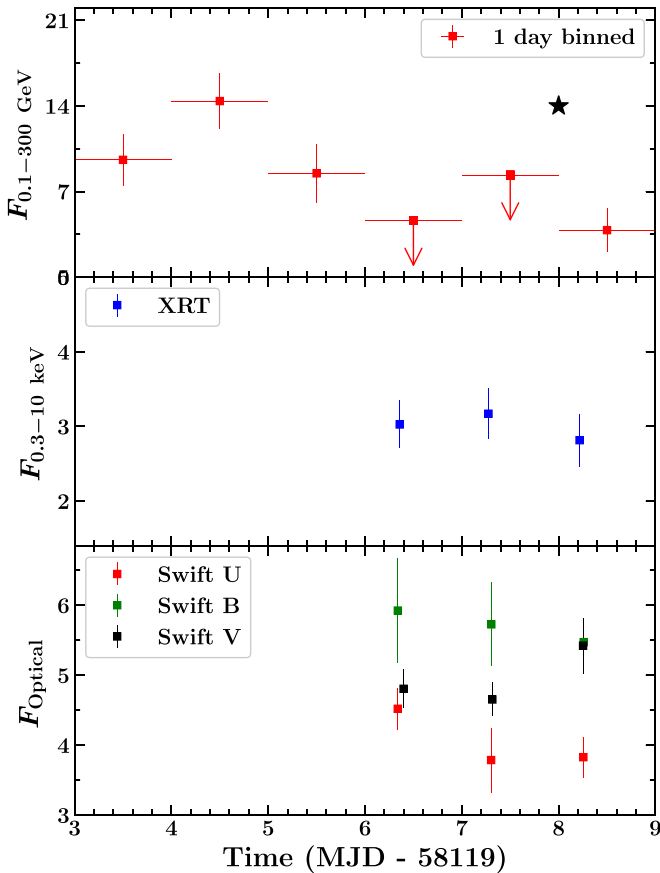


Figure 4. Multiwavelength light curve showing the *Fermi*-LAT and *Swift* observations of DA 193 during GeV flare. *Fermi*-LAT data points are in units of 10^{-7} ph cm^{-2} s^{-1} , whereas, *Swift*-XRT and UVOT fluxes are in units of 10^{-12} erg cm^{-2} s^{-1} . Black star in the top panel represent the time of *NuSTAR* ToO observation.

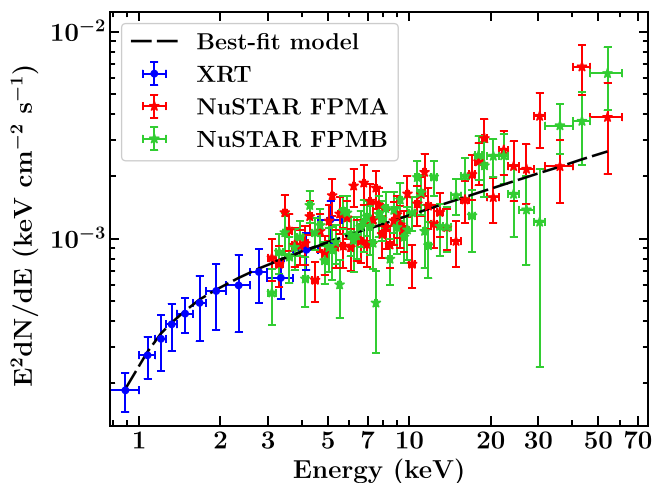


Figure 5. Plot representing the joint *Swift*-XRT and *NuSTAR* spectrum of DA 193 taken during the GeV flare. The best-fit absorbed power-law model is shown with the dashed line. The fitting is performed in 0.3–79 keV and the joint spectrum is rebinned to have at least 5σ significance in each bin. The source is well detected by *NuSTAR* up to 70 keV.

of MJD 58130 and 58131 (2018 January 12–13), Steward observatory detected V-band polarization of $2.33 \pm 0.25\%$ and $1.66 \pm 0.19\%$, respectively. The associated optical polarization angles are 142.7 ± 3.1 and 165.2 ± 3.3 , respectively. Such a

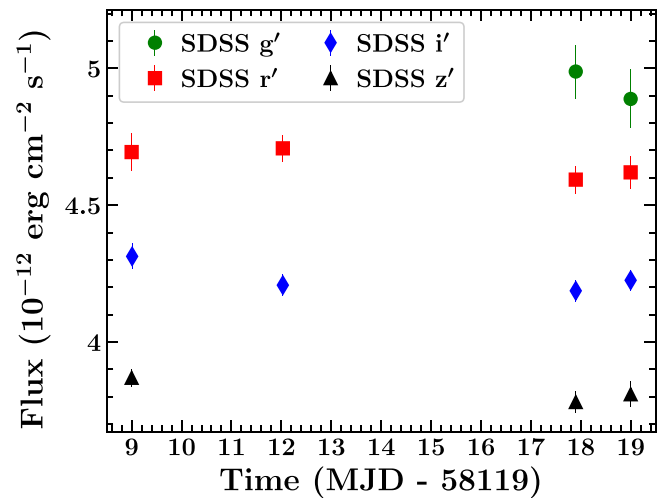


Figure 6. Multiband optical light curve of DA 193 taken from Nordic Optical Telescope during the decaying phase of the GeV flare in 2018 January. The filters used are SDSS g' , r' , i' , and z' . No significant variability is detected.

low degree of the optical polarization further provides supportive evidences for the accretion disk origin of the optical radiation. There were a few multiwavelength campaigns where a significant optical- γ -ray correlation and a systematic rotation of the optical polarization angle were noted during the γ -ray flaring episodes (e.g., Marscher et al. 2008; Abdo et al. 2010; Larionov et al. 2013). Unlike them, we do not have a dense sampling of the optical flux and polarization measurement and hence a definitive conclusion about the origin of the optical emission and also a connection between the optical/ γ -ray activity and the jet and accretion disk cannot be made. As can be seen in the bottom right panel of Figure 2, previous *Swift*-UVOT observations do not show any significant variability and therefore we combine them to generate low-activity state optical SED.

4.5. Black Hole Mass and Accretion Disk Luminosity

The central black hole mass can be calculated from the single epoch optical spectroscopic emission line information, assuming that the BLR is virialized (e.g., Shen et al. 2011). We use the C IV emission line parameters provided by Torrealba et al. (2012) and adopt empirical relations of Shen et al. (2011). The black hole mass is derived as $(5.5 \pm 0.9) \times 10^9 M_{\odot}$. Moreover, we can derive the BLR luminosity from the emission line luminosity by following the scaling relations of Francis et al. (1991) and Celotti et al. (1997). The accretion disk luminosity can then be inferred assuming that the BLR reprocesses 10% of the accretion disk emission. With this approach, we determine the accretion disk luminosity as $(1.3 \pm 0.1) \times 10^{47}$ erg s^{-1} .

Another method to derive the black hole mass and the accretion disk luminosity is by modeling the IR–UV spectrum by a standard, optically thick, geometrically thin disk (Shakura & Sunyaev 1973). However, the primary constraint with this technique is that the accretion disk emission (big blue bump) should be visible. When this condition is met, the parameters derived from the disk modeling reasonably agree with that computed from the conventional optical spectroscopic method (e.g., Paliya et al. 2017). The flux variability could affect the parameter estimation, however, it is not expected to be a major factor because the disk emission usually does not vary over

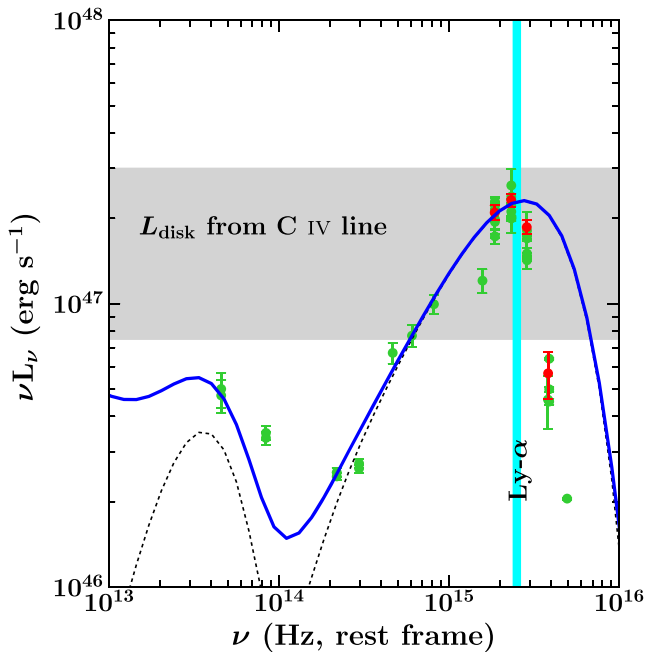


Figure 7. Rest-frame IR–UV SED of DA 193 along with the standard accretion disk model. Only data points redward to the Ly α frequency (vertical cyan line) are considered for the modeling. Black dashed line shows the thermal radiation from the torus and the accretion disk. Blue solid line is the total emission considering also the nonthermal jetted radiation. The shaded region corresponds to the peak disk luminosity derived from the C IV emission line parameters and we assume an uncertainty of 0.3 dex. See the text for details.

short timescales. The IR–UV emission from DA 193 shows a prominent bump, which we interpret as being due to an accretion disk, and show it in Figure 7. To model the observed bump, we do not consider data points blueward of the hydrogen Ly α frequency (vertical cyan line), due to possible absorption by intervening Ly α clouds whose nature is uncertain. We find a black hole mass of $3 \times 10^9 M_{\odot}$, and a disk luminosity of $3 \times 10^{47} \text{ erg s}^{-1}$, which matches within a factor of two and three, respectively, with that determined from the optical spectroscopic method.

4.6. SED

4.6.1. Modeling

We generate the broadband SED of DA 193 covering the low and flaring activity states following the procedure outlined in Section 3. We also consider the archival measurements from ASDC SED builder.¹⁵ We note that the low-activity state SED, which is generated by averaging years of the multiwavelength data, provides us with information about an overall average physical behavior of the blazar and may not represent any specific activity state. For the flaring state, on the other hand, we have used available near-simultaneous observations. DA 193 is not detected above 10 GeV and hence EBL absorption is negligible.

Broadband SEDs are then modeled using a one-zone, leptonic radiation model (see, e.g., Finke et al. 2008; Dermer et al. 2009; Ghisellini & Tavecchio 2009). We assume a spherical emission region located at a distance, R_{dist} , from the black hole and move along the jet-axis with a bulk Lorentz

factor, Γ_b . Considering a uniform but randomly oriented magnetic field, relativistic electrons, following a broken power-law energy distribution, radiate via synchrotron and IC processes. For the latter, we consider low-energy seed photons originated both inside the jet (synchrotron photons) and outside of it, i.e., from the accretion disk, BLR, and torus. The radiation profile of the accretion disk is assumed to follow a multicolor blackbody pattern (Frank et al. 2002). Both the BLR and the torus are considered as spherical blackbodies peaking at Ly α frequencies and a characteristic torus temperature, T_{IR} , respectively. The jet is assumed to have a conical shape with a semi-opening angle of 0.1 rad and the emission region covers the entire cross-section of the jet. We calculate various jet powers following Celotti & Ghisellini (2008) and, in particular, kinetic jet power is derived by assuming equal number density of electrons and cold protons. The modeled SEDs are shown in Figure 8, and the parameters are reported in Table 2.

4.6.2. Interpretation

The low-activity SED of DA 193 (Figure 8, left panel) resembles well with that typically observed for other high-redshift blazars (e.g., Tagliaferri et al. 2015). The synchrotron spectrum peaks at \sim submm wavelengths, and the optical-UV emission is dominated by the accretion disk (see also Figure 7). We reproduce entire X-ray to γ -ray SED with external Compton (EC) mechanism with seed photons primarily originating from the BLR with some contribution from the torus (see also Figure 9). A flat X-ray spectrum also hints for the EC origin of the radiation, rather than it being due to a synchrotron self Compton (SSC) process, which predicts a relatively softer X-ray spectrum. The requirement to keep SSC below the observed X-ray spectrum, in turn, constrains the magnetic field strength and the size of the emission region. Furthermore, in our SED model, radiative energy densities are a function of R_{dist} (following prescriptions of Ghisellini & Tavecchio 2009), hence the level of the EC spectrum provides further clues about the location of the γ -ray emitting region (Figure 9). The shapes of the X-ray and γ -ray spectra enable us to reliably determine the slopes of the underlying electron energy distribution before and after the break energy (γ_{bk}).

Recently, Costamante et al. (2018) have reported that the γ -ray spectra of the bright *Fermi* blazars do not exhibit a break up to tens of GeV as expected if the seed photons for EC process are mainly provided by the BLR. This finding led them to conclude that the primary mechanism for the γ -ray production should be EC-torus instead of EC-BLR. DA 193, on the other hand, is not even detected above 5 GeV, thus indicating a possible BLR and/or EBL absorption of higher energy γ -ray photons. Using the EBL model of Finke et al. (2010), we find the EBL optical depth to be less than unity even for a 40 GeV photon at $z = 2.36$, thus suggesting a negligible EBL absorption. Therefore, nondetection of DA 193 above a few GeV suggests a possible attenuation of higher energy γ -ray photons by the BLR photon field. This sets the location of the emission region close to the BLR, which is also supported by our SED modeling results. Another important consequence of considering the EC-torus as the primary mechanism for the γ -ray production is the location of the high-energy peak. This is because, in the Thomson regime, $\nu_{\text{EC}} \propto \gamma_{\text{bk}}^2 \nu_{\text{seed}}$, where ν_{EC} is the EC peak frequency, and ν_{seed} is the characteristic frequency of the seed photon field. As γ_{bk} has a rather low value, constrained from the synchrotron peak location, and the fact

¹⁵ <https://tools.asdc.asi.it/>

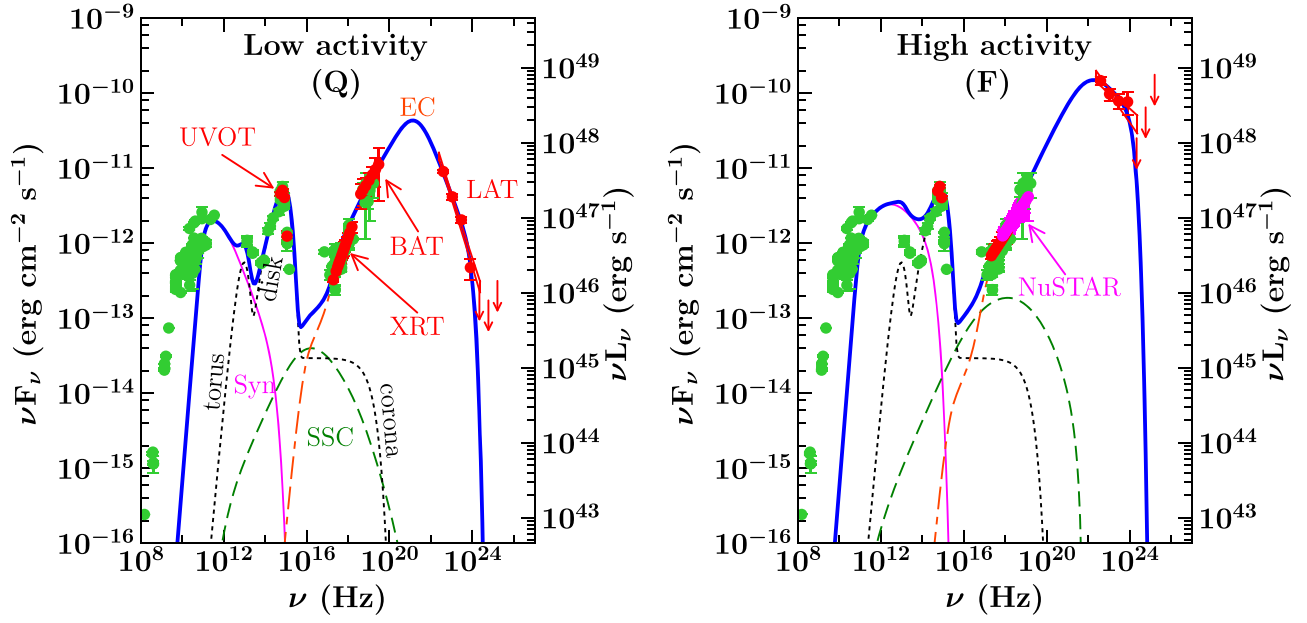


Figure 8. Left: broadband SED of DA 193 during the low-activity state. The data analyzed by us are shown with red circles, whereas archival observations are represented by green circles. In the LAT energy range, 2σ flux upper limits are denoted by downward arrows. The black dashed line corresponds to thermal emission from the torus, accretion disk, and X-ray corona, as labeled. Pink solid, green dashed, and orange dash-dashed-dotted lines represent synchrotron, synchrotron self Compton, and external Compton processes, respectively. The blue solid line is the sum of all the radiative components. Right: the elevated state SED of DA 193 generated by averaging the data for the whole flaring period (see Figure 4). The adopted time periods to generate both low- and high-activity SEDs are defined in Table 1. See the text for details.

Table 2
Summary of the Parameters Used/Derived from the Modeling of the SEDs

Parameter	Symbol	Low Activity (Q)	High Activity (F)
Slope of particle spectral index before break energy	p	1.7	1.8
Slope of particle spectral index after break energy	q	4.5	3.7
Minimum Lorentz factor of the particle distribution	γ'_{\min}	1	1
Break Lorentz factor of the particle distribution	γ'_{bk}	145	323
Maximum Lorentz factor of the particle distribution	γ'_{\max}	3000	3500
Magnetic field, in Gauss	B	0.6	0.6
Bulk Lorentz factor	Γ_b	11	11
Distance of the emission region from the black hole, in parsec	R_{dist}	0.72	0.66
Size of the BLR, in parsec	R_{BLR}	0.56	0.56
Compton dominance	CD	22	45
Jet power in electrons, in erg s^{-1} , in log scale	P_e	45.4	45.4
Jet power in magnetic field, in erg s^{-1} , in log scale	P_B	46.2	46.1
Radiative jet power, in erg s^{-1} , in log scale	P_r	47.1	47.6
Jet power in protons, in erg s^{-1} , in log scale	P_p	47.6	47.6

Note. The adopted time periods are defined in Table 1. We consider the central black hole mass and the accretion disk luminosity of $3 \times 10^9 M_{\odot}$ and $3 \times 10^{47} \text{ erg s}^{-1}$, respectively (Section 4.5), and assume the characteristic temperature of the IR-torus as 400 K. A viewing angle of 2° is adopted which is consistent with that typically observed from Blazars using radio studies (Jorstad et al. 2005; Lister et al. 2016). Note that the jet powers are computed by assuming a two-sided jet.

that the characteristic energy of BLR photons ($\sim 10 \text{ eV}$) is larger compared with torus ones ($\sim 0.1 \text{ eV}$), the *Swift*-BAT and *Fermi*-LAT data enable us to accurately constrain the IC peak which supports the EC-BLR as the primary mechanism (see also Figure 9). Finally, the results derived by modeling a sample of high-redshift blazars (Ghisellini et al. 2010) also indicates the BLR as a primary reservoir for the EC process and our findings are consistent with them.

We reproduce the elevated activity state SED (top right panel in Figure 8) by trying to change the minimum number of parameters with respect to that derived for the low state. We

notice a major change in the behavior of the electron population. During the GeV flare, not only the γ -ray flux level increases but also the spectrum significantly hardens. This indicates the hardening of the electron energy distribution after γ_{bk} , which itself shifts to higher energies (Table 2), possibly due to the injection of fresh, highly energetic electrons in the emission region. Interestingly, compared with the low-state SED, there are negligible variations at the optical and X-ray frequencies. The optical spectrum shows a bump, indicating the dominance of the accretion disk emission. The lack of substantial temporal variations observed from UVOT and

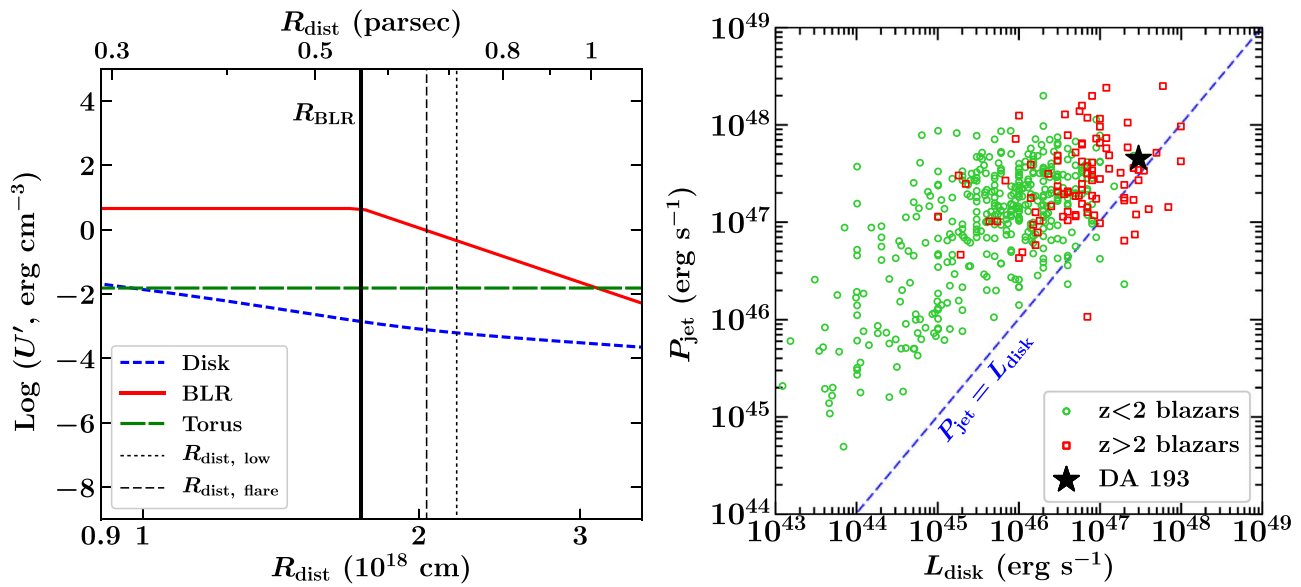


Figure 9. Left: variation of the comoving frame radiative energy densities of various AGN components as a function of the distance from the central black hole as labeled. Vertical black solid line represents the inner boundary of the BLR, whereas dotted and dashed lines denote the locations of the emission region during the low and flaring activity states. Right: the jet power as a function of the accretion disk luminosity for a large sample of blazars studied in Paliya et al. (2017). Blazars beyond $z = 2$ are shown with red squares, while $z < 2$ sources are denoted by lime-green circles. The black star represents DA 193 with the jet power computed during its low-activity state. Blue dashed line corresponds to the equality of the jet power and the accretion luminosity. Note that the jet power of DA 193 is computed assuming a two-sided jet, for equal comparison.

NOT (Figures 4 and 6) supports this finding. Considering the X-ray spectrum taken by *Swift*-XRT alone, we find a hint of softening during the flare (Table 1); however, due to small exposure and hence low photon statistics, a strong claim cannot be made. On the other hand, the photon index derived from the joint *NuSTAR* and *Swift*-XRT spectral fitting is compatible to that noted by Oh et al. (2018) from the *Swift*-BAT observations. Therefore, it can be concluded that there is no significant temporal or spectral evolution in the X-ray band.

A decrease in the dissipation distance, hence an enhanced BLR radiation field in the comoving frame (Figure 9, left panel), explains the detection of a Compton dominated SED during the GeV flare. Though the optical emission originates primarily from the accretion disk, our modeling suggests a substantial synchrotron flux enhancement in the IR band. This is due to a shift in the SED peaks to account for the γ -ray hardening and elevated synchrotron radiation. Finally, as discussed above, a large separation between the synchrotron and EC peaks also indicates the BLR as a primary reservoir of the seed photons for IC scattering.

In the right panel of Figure 9, we show the variation of the total jet power ($P_{\text{jet}} = P_e + P_B + P_p$) as a function of the accretion luminosity for CGRaBS blazars (Healey et al. 2008), whose broadband properties are studied in Paliya et al. (2017). One can immediately notice that high-redshift blazars lie at the highest end of the jet-disk luminosity correlation (see also Ghisellini et al. 2010 for earlier results). This diagram also suggests that DA 193 is among the systems hosting some of the most powerful relativistic jets and accretion disks.

Comparing various jet powers derived from the low-activity state modeling, we find that a major fraction of the total jet power is carried by cold protons in the form of the kinetic power (Table 2). Both magnetic and radiative jet powers are about an order of magnitude lower, which indicates a low magnetization of the emission region (e.g., Zdziarski et al. 2015) and that only a fraction of the kinetic power gets

converted to radiation. During the elevated state, on the other hand, we find the radiative power to be almost equal to the power in protons, which hints a high radiative efficiency of the jet during the flaring episode. Blazars, however, are known to spend only a tiny fraction of time in the high-activity state ($\sim 1\%$, e.g., Tavecchio et al. 2010), therefore such flaring events (with $P_r \sim P_p$) are short-lived.

5. Summary

We have performed a detailed multifrequency study of the high-redshift blazar DA 193. Our findings are summarized below.

1. We report the first-time detection of a significant γ -ray emission from DA 193.
2. Its long time-averaged γ -ray spectrum is soft ($\Gamma_{0.1-300 \text{ GeV}} = 2.9 \pm 0.1$), whereas it exhibits a relatively flat hard X-ray spectrum ($\Gamma_{14-195 \text{ keV}} = 1.5 \pm 0.4$). These observations are aligned with that typically observed from high-redshift blazars.
3. In the first week of 2018, DA 193 underwent an extremely luminous GeV flare ($L_\gamma = (1.3 \pm 0.4) \times 10^{50} \text{ erg s}^{-1}$). The observation of a hard γ -ray spectrum ($\Gamma_{0.1-300 \text{ GeV}} = 1.7 \pm 0.2$) makes this γ -ray outburst a rare phenomenon. Moreover, the multiwavelength light curve covering the flaring period suggests that we were able to follow the source during the decaying phase of the flare.
4. The broadband SED of DA 193, during a low-activity state, is found to be similar to that observed from high-redshift blazars. The optical emission remains accretion disk dominated even during the GeV flare which is further supported from the observation of the low degree of the optical polarization noted from the Steward observatory.

5. A comparison of the near-simultaneous observations both from space and ground telescopes, i.e., *Swift*, *NuSTAR*, and NOT, covering the flaring period, with previous archival measurements, reveals an insignificant flux change in the optical-X-ray energy range. This probably indicates that the source returned back to quiescence even before the beginning of the multiwavelength campaign.
6. A simple one-zone radiation model successfully reproduces the multifrequency observations. According to our analysis, a change in the behavior of the underlying electrons population could be responsible for the observed γ -ray flare.

We conclude that a continuous monitoring of the γ -ray sky by the *Fermi*-LAT is crucial to hunt down the elusive population of the most powerful blazars, similar to DA 193. The *Fermi*-LAT also enables a unique opportunity to study different flavors of the γ -ray flares, which will improve our understanding of the radiative processes powering the relativistic jets of blazars.

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This research has made use of data obtained through the High Energy Astrophysics Science Archive Research Center Online Service, provided by the NASA/Goddard Space Flight Center. This research has made use of the NASA/IPAC Extragalactic Database (NED), which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. Part of this work is based on archival data, software or online services provided by the ASI Data Center (ASDC).

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