A spectral hardening in the Fermi-LAT Data of 1ES 0502+675

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ABSTRACT

The γ-ray spectral feature of the blazar 1ES 0502+675 is investigated by using Fermi Large Area Telescope (Fermi-LAT) Pass 8 data (between 100 MeV and 300 GeV) covering from 2008 August to 2021 April. A significant (~ 4σ) hardening at ~ 1 GeV is found in the γ-ray spectrum during a moderately flaring state (MJD 55050-55350). The photon index below and above the break energy is $\Gamma_1 = 2.36 \pm 0.31$ and $\Gamma_2 = 1.33 \pm 0.11$, respectively. In the rest of the observations, the γ-ray spectrum can be described by a power-law form with the photon index of ≈ 1.6. In the frame of a one-zone synchrotron self-Compton (SSC) model, the spectral hardening is interpreted as the transition between the synchrotron component and the SSC component. This could be the result of a slight increase of the break/maximum Lorentz factor of the electrons.

Key words: gamma-rays: galaxies – galaxies: active – radiation mechanisms: nonthermal

1 INTRODUCTION

Blazars are a subclass of active galactic nuclei (AGN) with their relativistic jets pointing toward us, which makes the jet emission extremely beaming. Blazars are divided into BL Lac Objects (BL Lacs) and flat-spectrum radio quasars (FSRQs) (e.g., Urry & Padovani 1995). FSRQs show broad emission lines in their optical spectra while BL Lacs have spectra with weak or no emission lines. Their radiation is dominated by nonthermal radiation in the jet, covering the entire spectrum band from radio to γ-ray energies (e.g., Ulrich et al. 1997).

The energy distribution (SED) of a blazar contains two characteristic peaks. The first peak appears from radio to X-ray energies, and the other one is in the X-ray to γ-ray ranges. The low-energy peak is considered to be the synchrotron radiation of high-energy electrons. The origin of the high-energy peak is still inconclusive (e.g., Böttcher 2019), and inverse-Compton (IC) scattering of high-energy photons is considered as one of the popular processes for producing the high-energy peak (e.g., Rees 1967; Blumenthal & Gould 1970; Konigl 1981; Maraschi et al. 1992).

After the Fermi Gamma-ray Space Telescope operating in orbit, the Large Area Telescope (LAT) carried on Fermi has advanced the observations of GeV γ-ray emissions from blazars. Generally, GeV emissions from blazars display a power-law (PL) or log-parabola spectrum (Ajello et al. 2020). An interesting case is the significant break in the GeV spectrum of 3C 454.3 (Abdo et al. 2009; Ackermann et al. 2010). This break occurs at 2-3 GeV, and the spectrum becomes softer above the break. The change of photon index below and above the break can be as large as one, which cannot be explained by the cooling of the emitting electrons (Abdo et al. 2009). Several interesting models have been proposed to explain this spectral break (e.g., Poutanen & Stern 2010; Finke & Dermer 2010; Harris et al. 2012; Cerruti et al. 2013; Lei & Wang 2014; Kang et al. 2021).

Another interesting case is the concave GeV spectrum of 1ES 0502+675 (Abdo et al. 2010a). The LAT data collected from 2008 August 4 to 2009 February 1 exhibit a spectral hardening in the GeV spectrum of 1ES 0502+675 at ~ 1 GeV. The photon index changes from $2.68 \pm 0.18$ to $1.47 \pm 0.10$. This unusual concave structure is very rare. If confirmed, it could open interesting questions on the jet physics. Interestingly, this circumpolar blazar (1ES 0502+675) was suggested as one of the best neutrino candidates expected to be associated with high-energy (PeV) cosmic neutrinos detected with IceCube (Righi, Tavecchio, & Guetta 2017).

In this paper, we use the latest Fermi-LAT data to revisit the GeV γ-ray spectrum of 1ES 0502+675 at different time periods. This paper is structured as follows: we give the procedure of data reduction and the γ-ray spectra in Section 2; In Section 3 we show the modelling results for the SEDs; discussion and conclusions are presented in the last section.

2 DATA ANALYSIS AND RESULTS

2.1 Data Analysis

The analysis of the data follows the standard criteria for the point-source analysis. We employ the Science Tools package of version v11r05p3 available from Fermi Science Support Center (FSSC). The response function of the instrument is P8R3_SOURCE_V3, and the latest galaxy and isotropic diffusion models gll_iem_v07.fits and gll_iem_v07a.fits.

http://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/Pass8_usage.html

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iso_P8R3_SO URCE_V3_v1.txt are used. The initial γ-ray model file is the LAT ten-year source catalog (4FGL-DR2; Ajello et al. 2020), and the position and spectral shape of all 4FGL-DR2 point sources within 20 degrees of IES 0502+675 are fixed.

Our analysis of IES 0502+675 is based on the Fermi-LAT Pass 8 data observed from August 4, 2008 to April 24, 2021 (MET 239557417-640988613), with energy range from 100 MeV to 300 GeV. A 15 degree radius of interest (ROI) is selected with IES 0502+675 as the center. A 90-degree zenith angle cut is used for the data to avoid contamination from Earth’s limb. The cut of “(DATA_QUAL>0)&&(LAT_CONFIG==1)&&(angsep (RA_target, DEC_target, RA_sun, DEC_sun)>15)” in the Fermi tool gmktime is made to select good time intervals (GTIs) and to suppress the contamination from the Sun’s emission by excluding times when the target is within 15 degrees of the Sun. Fermipy (Wood et al. 2017) is used to facilitate the analysis of data.

2.2 Results

Firstly we use the data and the initial γ-ray model files with parameters mentioned above to perform a standard Fermi-LAT likelihood analysis. The significance of the γ-ray emission is obtained by using the maximum likelihood test statistic (TS). The TS is defined as 2log(L/L0), where L is the maximum likelihood of the model with a point source at the target position, and L0 is the maximum likelihood without the source (Mattox et al. 1996). The parameters for the sources within ROI of 5 degrees are set to be free in the fitting. The spectrum of the target source is modeled by a power-law (PL) function,

$$\frac{dN}{dE}(E) = N_0 \left( \frac{E}{E_0} \right)^{-\Gamma}. \quad \text{(1)}$$

The fitting results in a total TS value of 3220. The average spectrum from August 4, 2008 to April 24, 2021 is showed in Figure 1. It is described well by a single PL function with $\Gamma=1.53\pm0.03$. This γ-ray spectrum is very hard, which is significantly harder than the typical γ-ray spectrum of high-synchrotron-peaked blazars (HSPs) in the Fourth Fermi Catalog of AGN (Ajello et al. 2020)\(^3\).

With the above fitting results, we generate the 100-day bin γ-ray light curve with fixed photon index and free normalization of flux for sources within 3 degrees of ROI. For sources beyond 3 degrees of ROI, both photon index and normalization of flux are fixed. In order to get reliable results, we exclude the time bins with the TS value less than 25. The light curve for the whole time period is showed in Figure 2. Variation can be seen in the first two years observations.

Based on the variation showed in Figure 2, we separate the entire observation into three periods: MJD 54682-55050 (P1), MJD 55051-55350 (P2), and MJD 55351-59329 (P3). The spectra in the three periods are produced (panels a-c in Figure 3). It is found that the spectrum in P2 (panel b in Figure 3) deviates from a single PL form. We then use a broken PL (BPL) function,

$$\frac{dN}{dE}(E) = \begin{cases} N_b \left( \frac{E}{E_b} \right)^{-\Gamma_1}, & \text{if } E < E_b \\ N_b \left( \frac{E}{E_b} \right)^{-\Gamma_2}, & \text{if } E \geq E_b \end{cases} \quad \text{(2)}$$

to perform the fitting again. A likelihood-ratio test of the BPL and PL fit to the spectrum finds that the BPL model is better than the PL model with a test statistic of $\text{TS}_{\text{BPL-PL}} = 16$, which is equal to a significance of $4\sigma$. From the best-fit result with the BPL model, we have $E_b = 1.1 \pm 0.6$ (GeV), $\Gamma_1 = 2.36 \pm 0.31$, and $\Gamma_2 = 1.33 \pm 0.11$. The spectra in P1 (panel a in Figure 3) and P3 (panel c in Figure 3) show a PL form with $\Gamma=1.56\pm0.08$ and $1.55\pm0.03$, respectively. Looking at the spectrum in P3, it is noticed that the energy flux in the first bin has an excess over the modeled PL flux. A further analysis shows that the spectrum during MJD 55350-58950 (P3 in Figure 2) follows a PL form (panel d in Figure 3), and an excess in the first energy bin occurs after MJD 58950 (P4 in Figure 2). The spectrum in P4 is showed in panel e in Figure 3.

We also produce the spectrum between 2008 August 4 and 2009 February 1 with the Pass 8 data (panel f in Figure 3). No significant spectral hardening is found in this spectrum. The BPL spectrum reported by Abdo et al. (2010a,b) cannot be confirmed.

3 MODELING THE SEDS

We collect the multi-band data through SSDC Sky Explorer\(^4\). Broad-band SEDs covering from infrared wavelengths up to γ-rays energies are constructed (Figure 4). We have the X-ray data obtained from the swift-XRT observations at MJD 54833.00515 and 55155.388232 (grey filled circles). We also show the BeppoSAX data (grey open squares) from Giommi et al. (2002).

We adopt a one-zone synchrotron self-Compton (SSC) model to interpret the broad-band SEDs. In this scenario, the low-energy bump is attributed to synchrotron radiation by relativistic electrons, and the high-energy bump originates from IC scattering off the synchrotron photons by the same electron population. The region responsible for the emission of IES 0502+675 is described as a blob of radius $R'$, containing a tangled magnetic field of strength $B'$, and moving towards us with a Doppler factor $\delta_D$. The blob is assumed to be homogeneously filled with a stationary population of electrons. The distribution of the electrons is assumed to be a BPL which is commonly used in blazar modelling (e.g., Dermer et al. 2009; Ghisellini

\(^3\) The photon index medians and rms for HSPs is $1.88 \pm 0.14$.

\(^4\) https://tools.ssdc.asi.it/
et al. 2010; Yan et al. 2014),
\[ N'_c(y') = \begin{cases} N'_0 \left( \frac{y'}{y'_{\text{br}}} \right)^{-n_1}, & \text{if } y'_{\text{min}} \leq y' \leq y'_{\text{br}} \\ N'_0 \left( \frac{y'}{y'_{\text{br}}} \right)^{-n_2}, & \text{if } y'_{\text{br}} \leq y' \leq y'_{\text{max}} \end{cases} \]  
(3)
where \( N'_0 \) is a normalization constant; \( y'_{\text{min/br/max}} \) is the minimum/break/maximum Lorentz factor of the electrons; and \( n_1 \) and \( n_2 \) are the spectral indices below and above the break Lorentz factor, respectively.

The observed synchrotron spectrum (in units of erg cm\(^{-2}\) s\(^{-1}\)) is calculated by (Finke et al. 2008)
\[ f^{\text{syn}}_{\gamma} = \frac{\delta^4 D^2 \sqrt{3e^4 R^3}}{4\pi h c^2} \epsilon' V'_0 \int_1^{\infty} dy' N'_c(y') R_b(e'/\epsilon'_c), \]  
(4)
where \( e \) is the fundamental charge, \( h \) is Planck’s constant, \( V'_0 = 4\pi R^3 / 3 \) is the intrinsic volume of the blob, \( d_L \) is the luminosity distance of the source at a redshift of \( z \). Here, the function \( R_b(x) \) is the monochromatic emission power averaged over a population of electrons with randomly distributed pitch angle (Crsius & Schlickeiser 1986), and an accurate approximation given by Finke et al. (2008) is adopted in the calculation.

The observed SSC spectrum is given by (e.g., Jones 1968; Blumenthal & Gould 1970; Dermer et al. 2009)
\[ f^{\text{SSC}}_\gamma = \frac{3c \sigma_T V'_b \delta_D^4}{16\pi d_L^2} \epsilon' \int_0^{\infty} e' \frac{d' N'_e(y')}{\gamma'} \int_1^{\infty} dy' N'(y') F_c(x, q), \]  
(5)
where \( \sigma_T \) is the Thomson cross section, the spectral energy density of synchrotron radiation can be calculated through \( \epsilon'_e = \frac{\epsilon' \gamma'^2}{\gamma'^2 + 1} \).
clear spectral hardening is found in a relative high state from 2009 produced with the first seven months observations. Furthermore, a that no significant spectral hardening is found in its spectral feature. We perform the analysis with the Fermi Pass 8 data (2018). hard-TeV BL Lacs (e.g., Tavecchio et al. 2011; Costamante et al. 2018).

This kind of spectrum is usually considered as evidence of two-component model (e.g., Abdo et al. 2010a,b; Katarzyński 2012). The disadvantage of the two-component model is that there are a large number of free parameters. Intensive multiwavelength observations are required to constrain model parameters (e.g., Acciari et al. 2020). Here, we interpret the SED with a one-zone SSC model. The historical infrared, optical, and X-ray data are used to put a general constraint on our model. In this model, the γ-ray emission below 1 GeV is the tail of the synchrotron component, and the emission above 1 GeV is produced by SSC process. An increase of the will produce such a result. The excess in the first energy bin occurs after MJD 58950 indicates a slight increase of the . The spectrum above 1 GeV of IES 0502+675 is very hard, similar to the GeV spectra of the hard-TeV BL Lacs. To produce such a hard spectrum, the extreme model parameters ( and ) are needed, which is also found in previous works (e.g., Lefa et al. 2011; Tavecchio et al. 2011; Costamante et al. 2018). Recently, Zhou et al. (2021) fitted the average SED of IES 0502+675 with a one-zone SSC mode by assuming a log-parabolic electron distribution. The γ-ray data considered in Zhou et al. (2021) are the results in Nolan et al. (2012) and Ackermann et al. (2016), which cover the energy range between 2 GeV and 1 TeV. The values of and derived by Zhou et al. (2021) are close to the values we obtained in P1.

Brown et al. (2017) reported a significant (> 5σ) hardening in the Fermi-LAT spectrum of the radio galaxy Centaurus A (Cen A). This spectral hardening occurs at ~2.6 GeV, and the photon index varies from ~2.7 to 2.3. The change of the photon index below and above the break energy is smaller than that of IES 0502+675. The smaller break energy in the spectrum of IES 0502+675 prevents us obtaining a higher significance for the spectral hardening. As far as we know, the spectral hardening of IES 0502+675 is the first case for blazars and the second case for AGNs.

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DATA AVAILABILITY

Data available on request.

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Table 1. Values of the model parameters.

| Model | P1     | P2     | P3     | P4     |
|-------|--------|--------|--------|--------|
| $t_{\text{var}}$ (days) | 60     | 60     | 60     | 60     |
| $\nu_{\text{ph}}$ (Hz)  | $10^{12}$ | $10^{12}$ | $10^{17}$ | $10^{17}$ |
| $\nu_{\text{F}}$ (Hz)  | $2.3 \times 10^{-11}$ | $2.3 \times 10^{-11}$ | $2.3 \times 10^{-11}$ | $2.3 \times 10^{-11}$ |
| $B^\prime$ (G)         | $5.0 \times 10^{-4}$ | $5.0 \times 10^{-4}$ | $9.5 \times 10^{-4}$ | $1.2 \times 10^{-3}$ |
| $\alpha_{\text{p}}$    | 17.5   | 17.5   | 17.5   | 17.5   |
| $n_{1}$                | 2.4    | 2.4    | 2.4    | 2.4    |
| $n_{2}$                | 3.3    | 3.3    | 3.3    | 3.3    |
| $\gamma_{\text{min}}$  | $6.0 \times 10^{4}$ | $6.0 \times 10^{4}$ | $4.0 \times 10^{4}$ | $4.0 \times 10^{4}$ |
| $\gamma_{\text{max}}$  | $1.8 \times 10^{9}$ | $2.5 \times 10^{9}$ | $5.0 \times 10^{8}$ | $1.0 \times 10^{9}$ |
| $R^\prime$ (cm)        | $2.03 \times 10^{18}$ | $2.03 \times 10^{18}$ | $2.03 \times 10^{18}$ | $2.03 \times 10^{18}$ |
| $\gamma_{\text{S}}$    | $2.02 \times 10^{6}$ | $2.02 \times 10^{6}$ | $1.47 \times 10^{6}$ | $1.31 \times 10^{6}$ |
| $N_0^\prime$ (cm$^{-3}$) | $2.47 \times 10^{-12}$ | $2.47 \times 10^{-12}$ | $1.79 \times 10^{-12}$ | $1.59 \times 10^{-12}$ |

Figure 4. SSC modelling of the SEDs. The grey data are historical infrared, optical and X-ray data obtained from SSDC Sky Explorer. LAT data are for the periods P1-P4.
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