X-Ray and GeV-γ-Ray Emission Property of TeV Compact Symmetric Object PKS 1413+135 and Implication for Episodic Jet Activity

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Abstract

PKS 1413+135, a compact symmetric object (CSO) with a two-sided parsec-scale structure in its miniature radio morphology, is spatially associated with 4FGL J1416.1+1320 and recently detected with MAGIC telescopes. We comprehensively analyze its X-ray and gigaelectronvolt γ-ray observation data to reveal its high-energy radiation physics. It is found that the source is in a low-flux stage before MJD 58500 and experiences violent outbursts after MJD 58500 in the gigaelectronvolt band. The flux at 10 GeV varies by ~3 orders of magnitude, and the gigaelectronvolt-flux variation is accompanied by clear spectral variation, which is characterized as a soft log-parabola spectrum in the low-flux state and a hard power-law spectrum in the bright flares. The amplitude of the variability of X-rays is lower than that of γ-rays, and no correlation of variability between γ-rays and X-rays is observed. Fitting the broadband spectral energy distribution during a gigaelectronvolt outburst with a multi-zone leptonic model, we show that the gigaelectronvolt γ-rays are attributed to the external Compton process while the X-rays are a hybrid of several components. The predicted teraelectronvolt γ-ray flux during the gigaelectronvolt outburst is consistent with the detection of MAGIC telescopes. These results, together with its CSO radio morphology, imply that PKS 1413+135 has episodic nuclear jet activities. The weak γ-ray emission before MJD 58500 may be from its sub-parsec-/parsec-scale jet component powered by previous activities, and the violent outbursts with short timescale variability after MJD 58500 could be attributed to the recently restarted jet activity.

Unified Astronomy Thesaurus concepts: Active galactic nuclei (16); Relativistic jets (1390); Gamma-rays (637); Non-thermal radiation sources (1119)

1. Introduction

Compact symmetric objects (CSOs), a subclass of active galactic nuclei (AGNs), are defined as those with a symmetric twin radio jet structure on both sides of their nuclei (e.g., Readhead et al. 1996). They are thought to be a class of misaligned AGNs (Wilkinson et al. 1994; Readhead et al. 1996). Generally, low polarization, low radio variability, low core luminosity, hosted in elliptical galaxies, and lack of the optically thick component at short wavelengths are presented in CSOs (Wilkinson et al. 1994; Readhead et al. 1996). CSOs are characterized by an overall size of less than 1 kpc. The small size of CSOs may result from the frustrated jet due to the dense interstellar medium (O’Dea et al. 1991; Carvalho 1994, 1998). The ages estimated by the advance speed, the lobe supply timescale, and the synchrotron-loss timescale for CSOs are consistent with each other within the uncertainties, indicating that CSOs are young with typical ages of $3 \times 10^7$–$10^8$ yr, almost certainly $<10^7$ yr (Readhead et al. 1996). The non-difference between these compact radio sources and larger radio-loud objects at mid- and far-infrared emission also supports that CSOs are young (Heckman et al. 1994). Thus, CSOs are an important fraction of radio-loud AGNs for understanding the formation and evolution of powerful jets in extragalactic radio sources.

Gamma-ray emission is a critical probe to study the AGN jets. As a new population of γ-ray sources, six CSOs have been detected with Fermi-LAT in the gigaelectronvolt band, i.e., PMN J1603-4904 (Müller et al. 2014, 2015), PKS 1718-649 (Migliori et al. 2016), NGC 3894 (Principe et al. 2020), TXS 0128+554 (Lister et al. 2020), CTD 135 (Gan et al. 2021), and PKS 1413+135 (Principe et al. 2021). It is debated whether the γ-rays of CSOs are from the parsec-scale lobes or the core-jet region. Interestingly, the γ-rays in some CSOs may indicate a characteristic of recently restarted jet activity (Lister et al. 2020; Gan et al. 2021). Recently, PKS 1413+135 was announced to be detected by the Major Atmospheric Gamma-ray Imaging Cherenkov (MAGIC) telescopes on 2022 January 12 (MJD 59591, Blanch et al. 2022). It is the first CSO detected at the very-high-energy (VHE; $E > 100$ GeV) band. It would be a good sample to study the γ-ray emission of young radio sources.

High-resolution observations with the Very Large Array, Very Long Baseline Interferometry (VLBI), and Very Long Baseline Array (VLBA) show no kiloparsec-scale extended structure is present for PKS 1413+135, and there is a minitriple structure with a counter-jet on the parsec scale (Perlman et al. 1994). Using the high-dynamic range VLBA maps at 3.6, 6, 13, and 18 cm, Perlman et al. (1996) revealed a complex, two-sided parsec-scale structure of PKS 1413+135 and no evidence of superluminal motion was obtained, and thus they suggested that PKS 1413+135 likely is a young radio source with an age $\lesssim 10^7$ yr. Intriguingly, the multiband optical images of PKS 1413+135 show a surface brightness profile that can be well fitted by an exponential disk, suggesting that PKS...
1413+135 is hosted in a spiral galaxy (McHardy et al. 1991). A Hubble Space Telescope (HST) observation further revealed that the galaxy contains a previously unresolved dust lane and is very likely an early-type spiral galaxy viewed edge-on (McHardy et al. 1994). In addition, an extremely large column density is needed in the analysis of Einstein X-ray data (Stocke et al. 1992). The enormous extinction, but the lack of the thermal IR emission and strong narrow emission lines, suggests that PKS 1413+135 would not be hosted in this spiral galaxy and be a background source behind the spiral galaxy (Stocke et al. 1992). The redshift of $z = 0.247$ for PKS 1413+135 is derived from redshift H I absorption (Carilli et al. 1992), which should be associated with the spiral galaxy. The U-shaped symmetric achronamic variability from 15–234 GHz of PKS 1413+135 has been proposed to be caused by gravitational lensing of the foreground spiral galaxy (Vedantham et al. 2017). However, no sign of image multiplicity or distortion due to the gravitational lensing is found, in either the optical or radio band (Stocke et al. 1992; Perlman et al. 1996; Vedantham et al. 2017; Readhead et al. 2021). It has thus been argued that PKS 1413+135 should be located at a redshift range of $0.247 < z < 0.5$ (Vedantham et al. 2017; Readhead et al. 2021). Due to the strong obscuring and contamination by the foreground, the high-energy photons, especially $\gamma$-rays at the gigaelectronvolt–teraelectronvolt bands, would be powerful probes for studying the nature of the source.

To reveal the radiation properties of PKS 1413+135, we analyze its data in the X-ray and $\gamma$-ray bands observed by Chandra, XMM-Newton, Swift-XRT, and Fermi-LAT over the past ~15 yr. A description of the data reduction is presented in Section 2. We investigate its temporal and spectral variations in both the X-ray and $\gamma$-ray bands (Sections 3 and 4). Together with the data in the low-energy bands, we compile its broadband spectral energy distributions (SEDs) and study its $\gamma$-ray emission via SED modeling in Section 5. A discussion of the $\gamma$-ray origin of PKS 1413+135 and its AGN type is given in Section 6. A summary is presented in Section 7. Throughout, if not otherwise specified, the results are derived on the basis of $z = 0.247$. $H_0 = 71$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.27$, and $\Omega_{\Lambda} = 0.73$ are adopted in this paper.

2. Observations and Data Reduction

2.1. Gigaelectronvolt $\gamma$-Ray Observations with Fermi-LAT

It has been reported that 4FGL J1416.1+1320 is spatially coincident with PKS 1413+135 in the Fermi-LAT 12 yr Source Catalog (4FGL-DR3; Abdollahi et al. 2022). We download the Pass 8 data from the Fermi Science Support Center. The data are selected within a $15''$ region of interest centered on the radio position of PKS 1413+135 (R.A. = 213$^{3}$995, decl. = 13$^{3}$340; Fey et al. 2015). The temporal coverage of the data is from 2008 August 4 to 2022 March 22 (MJD 54682–59660) of about 15.5 yr. We perform a binned likelihood analysis for the $\gamma$-rays of 4FGL J1416.1+1320 using the publicly available software FermiTools v.2.0.8. Only the $\gamma$-ray photons in the energy range of 0.1–300 GeV and satisfying the standard data quality selection criteria (DATA_QUAL > 0) & (LAT_CONFIG==1) are considered in our analysis. A zenith angle cut of 90° is set to avoid $\gamma$-ray contamination caused by the Earth’s limb. We bin the data with a pixel size of 0.2" in space and 25 logarithmic energy bins. The background models include all $\gamma$-ray sources listed in the 4FGL-DR3 Catalog and the Galactic diffuse component (gll_iem_v07.fits) as well as the isotropic emission (iso_P8R3_SOURCE_V3_v1.txt). The P8R3_SOURCE_V3 set of instrument response functions is used.

The spectrum model of 4FGL J1416.1+1320 reported in the 4FGL-DR3 is a log-parabola function (Abdollahi et al. 2022), i.e.,

$$\frac{dN}{dE} = N_0 \left( \frac{E}{E_0} \right)^{-(\Gamma + \beta \log \left( \frac{E}{E_0} \right)),}$$

where the decimal logarithm is used, $E_0$ is the scale parameter of photon energy, $\Gamma$ is the photon spectral index, and $\beta$ is the curvature parameter (Massaro et al. 2004). So, the model for fitting the spectrum of 4FGL J1416.1+1320 is in priority selected as a log-parabola function in our analysis. If $\beta$ is poorly constrained, we set $\beta = 0$ and the log-parabola function turns into a single power-law function (i.e., $dN/dE = N_0 (E/E_0)^{-\Gamma}$). The spectral parameters of all sources lying within 8° are left free, whereas the parameters of those sources lying beyond 8° are fixed to their 4FGL-DR3 values. Also, the normalization parameters of the standard Galactic and isotropic background templates are set free in the likelihood fit. The significance of the $\gamma$-ray detection is quantified by adopting the maximum likelihood test statistic (TS), which is defined as $TS = 2 (\ln L_1 - \ln L_0)$, where $L_1$ and $L_0$ are the maximum likelihood values for the models with and without the target source, respectively. The results of the analysis of Fermi-LAT observations of PKS 1413+135 are given in Table 1.

2.2. X-ray Observations with Swift-XRT, Chandra, and XMM-Newton

PKS 1413+135 was observed by the Swift-XRT, Chandra, and XMM-Newton in several epochs, as listed in Table 2. It was observed by the Chandra Advanced CCD Imaging Spectrometer S-array (ACIS-S) as a general observer target for an exposure of 20 ks on 2007 March 20. It was also observed several times by Chandra again during 2019 and 2020 as a Director’s Discretionary Time target for exposures of 4 ks. As significant foreground absorption of soft X-rays was found in PKS 1413+135 (Stocke et al. 1992), we first attempt to fit the equivalent neutral hydrogen column density of this absorption using the observation in 2007. The data are reduced using CIAO (version 4.12) and CALDB (version 4.9.2.1). The level-2 event file is created following the standard procedure. We extract source photons from a circle centered on the radio position of PKS 1413+135 with a radius of 6". The background is determined in an annulus region with inner and outer radii of 7" and 14", respectively. There are ~600 net photon counts. The spectrum is grouped to have at least 25 counts per bin and the $\chi^2$ minimization technique is adopted for spectral analysis. The spectrum is fitted by a single power law absorbed by two absorption components, one is absorption at $z = 0$ with the neutral hydrogen column density fixed at Galactic value $N_\text{H}^\text{Gal} = 1.56 \times 10^{20}$ cm$^{-2}$ (HI4PI Collaboration et al. 2016), the other is an extragalactic foreground absorption $N_\text{H}^\text{fgal}$ at a redshift of $z = 0.247$ with column density set free. The model provides a good fit to the spectrum and an extragalactic foreground absorption column density of $N_\text{H}^\text{fgal} = 3.6^{-0.5}_{+0.6} \times 10^{22}$ cm$^{-2}$, which is consistent with the results in Stocke et al. (1992) and Perlman et al. (2002). We generate the Chandra spectra at other epochs following the procedures mentioned above. The single power law with Galactic ($N_\text{H}^\text{Gal}$) and extragalactic ($N_\text{H}^\text{fgal}$) absorption is used to fit...
The spectra. As there are no more than 150 net photon counts for each spectrum, C-statistic minimization is adopted for evaluating the goodness of the fits and \( N^H \) is fixed at \( 3.6 \times 10^{22} \) cm\(^{-2} \) during the fitting.

The public data of pointing observations on PKS 1413+135 by XMM-Newton are reduced with the XMM-Newton SCIENCE ANALYSIS SYSTEM (version 18) following standard procedures. We generate the spectra using the data from PN CCD arrays since PN has a larger effective area. The source events are extracted from a circle of 32\( ^\circ \) radius centered at the source position while the background events are extracted from a circle of the same radius in a source-free region nearby. The spectrum is binned to contain at least 25 counts per bin required for the \( \chi^2 \) analysis. Again, the single power law with Galactic and extragalactic absorption is used to fit the spectra. The absorption is also fixed as mentioned above during the fitting.

There are 21 observations by the Neil Gehrels Swift Observatory for PKS 1413+135 from 2007–2022. The X-ray telescope (XRT) on board the Swift satellite was operating in the photon counting mode with exposure times of 0.1–10 ks. We collect the XRT data from the Swift archive and reproduce the clean events using the xrtpipeline task. The source photons are extracted from a circle with a radius of 50\( ^\circ \), while the backgrounds are determined in an annulus with an inner and outer radius of 60\( ^\circ \) and 105\( ^\circ \), respectively. There remain 16 observations after excluding those without significant detection for this source. As the statistics are too low for each spectrum, C-statistic minimization is adopted to evaluate the goodness of the fits. \( N_{\text{gd}}^H = 1.56 \times 10^{20} \) cm\(^{-2} \) and \( N_{\text{int}}^H = 3.6 \times 10^{22} \) cm\(^{-2} \) are all fixed, and the photon index is also fixed at \( \Gamma_X = 1.9 \) (the average value shown in Figure 3(b)) during the fitting.

### 3. Temporal Analysis

We perform a likelihood fit for PKS 1413+135 with the \( \sim 13.5 \) yr Fermi-LAT data. PKS 1413+135 is bright in the gigaelectronvolt \( \gamma \)-ray band, with an average flux of \( F_{0.1–300 \text{ GeV}} = (2.28 \pm 0.13) \times 10^{-11} \) erg cm\(^{-2} \) s\(^{-1} \) in the whole interval. Variability is very common for AGNs and its magnitude and timescale are useful to study the properties of the emission region. For estimating the variability of PKS 1413+135 at the gigaelectronvolt band, we follow the definition in 2PGL (Nolan et al. 2012) and derive the variability index \( \Delta S_{\text{var}} \) (see also Abdollahi et al. 2020). We split the full \( \sim 13.5 \) yr interval into 13 intervals of about 1 yr each. The source is considered to be significantly variable if \( \Delta S_{\text{var}} \) exceeds 5.9, where \( \Delta S_{\text{var}} = 5.9 \) corresponds to the 5\( \sigma \) confidence level in a \( \chi^2 \) distribution with 12 degrees of freedom (doF). The \( \Delta S_{\text{var}} \) value of PKS 1413+135 is 2074 and far beyond 5\( \sigma \) confidence level, meaning that its \( \gamma \)-rays are significantly variable. We extract the \( \gamma \)-ray light curve of PKS 1413+135 using an adaptive-binning method based on a criterion of \( \Delta S \geq 9 \) for each time bin, where the minimum bin size is set to be 7 days, as shown in Figure 1(b). We note that before MJD 58500, the \( \gamma \)-ray emission is in a relatively low state, where the \( \gamma \)-ray fluxes are lower than the average flux level for almost all time bins and even lower than the average flux by almost an order of magnitude in some time bins. The \( \gamma \)-ray flux begins to increase from a very low state since \( \sim \)MJD 58200 to the average flux level around MJD 58500. After MJD 58500, the source seems to be in a high state with fluxes higher than the average flux, and almost all the time bins only need the minimum bin size of 7 days to meet \( \Delta S > 9 \). Therefore, the whole \( \gamma \)-ray light curve of PKS 1413+135 seems to present two totally different phases with a boundary of MJD 58500, i.e., a low-flux stage and an outburst stage.

In order to further investigate the short timescale variability of this source, we reanalyze the gigaelectronvolt observation data after MJD 58500 and still extract the light curve using the adaptive-binning method with the criterion of \( \Delta S \geq 9 \) for each time bin, where the minimum time bin is taken as 1 day. The derived flux of each time bin has a large error bar, as illustrated in Figure 1(c). However, many serial time bins only need the minimum bin size of one day to meet \( \Delta S > 9 \), and the variability on a daily timescale for PKS 1413+135 can still be observed.
Note that PKS 1413+135 has been detected at the VHE band with MAGIC telescopes on 2022 January 12 (MJD 59591, Blanch et al. 2022). This source is also in a relatively high state at the gigaelectronvolt band during MJD 59589–59591, as shown in Figure 1(c). Its flux is $F_{0.1-300\,\text{GeV}} \approx 2.25 \times 10^{-10}\,\text{erg cm}^{-2}\,\text{s}^{-1}$ on MJD 59588, rises to $F_{0.1-300\,\text{GeV}} \approx 6.64 \times 10^{-10}\,\text{erg cm}^{-2}\,\text{s}^{-1}$ on MJD 59590, declines to $F_{0.1-300\,\text{GeV}} \approx 2.51 \times 10^{-10}\,\text{erg cm}^{-2}\,\text{s}^{-1}$ on MJD 59592, and then drops to $F_{0.1-300\,\text{GeV}} \approx 3.0 \times 10^{-11}\,\text{erg cm}^{-2}\,\text{s}^{-1}$ after MJD 59593.

We can also observe that there are several time bins with $F_{0.1-300\,\text{GeV}} > 10^{-9}\,\text{erg cm}^{-2}\,\text{s}^{-1}$ between MJD 58700 and 59000, indicating that PKS 1413+135 is in a high-flux state at the gigaelectronvolt band and there may be detectable VHE $\gamma$-rays during that time.

In the X-ray band, there are three XMM-Newton, six Chandra, and 16 Swift-XRT observations from 2007 March to 2022 November 10 Gan et al. 2022 November 10.
Considering the large errors in data points observed by the Swift-XRT, a weighted mean flux $\langle F \rangle$ and its variance $\sigma_{\langle F \rangle}$ were estimated by McLaughlin et al. (1996)

$$\langle F \rangle = \left[ \frac{\sum_{i=1}^{N} F_i}{\sum_{i=1}^{N} \sigma_i^2} \right] \left[ \sum_{i=1}^{N} \frac{1}{\sigma_i^2} \right]^{-1},$$

where $N$ is the number of the data points, and $F_i$ and $\sigma_i$ are the flux and its error for the $i$th data point. We obtain $\langle F \rangle_{2.10\text{ keV}} = (6.97 \pm 0.17) \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$ for the 25 observational data points, which is shown as the horizontal dashed line in Figure 1(a). Interestingly, the last two points shown in Figure 1(a) are obtained with the observations on 2022 January 13–14, just after the ATel of the VHE detection of PKS 1413+135. We find that the X-ray flux declines from $1.3 \times 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$ on 2022 January 13 (MJD 59592) to $5.9 \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$ on 2022 January 14 (MJD 59593), a factor of $\sim 2$ within 1 day. Perlman et al. (2002) reported that the ASCA observations yield a flux of $F_{\gamma} = 9 \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$, which declined by a factor of $\sim 5$ compared to those seen in previous X-ray observations, but the previous X-ray flux obtained from the ROSAT and Einstein observations is almost completely based on the extrapolations. These results indicate that the X-rays of PKS 1413+135 are also variable.

To quantify the variability of X-rays, we calculate $\chi^2 = \sum_{i=1}^{N} \frac{(F_i - \langle F \rangle)^2}{\sigma_i^2}$ and the associated probability $p(\chi^2) = 1 - p(\chi^2)$ (Chen et al. 2022 and references therein) of the light curve. We find that $\chi^2 = 245.9$ (the number of dof $= N - 1 = 24$) with $p \ll 10^{-7}$, indicating that the variability of X-rays is also far beyond the $5\sigma$ confidence level. We also calculate the fractional variability amplitude $F_{\text{var}}$ and its uncertainty for the X-ray light curve via (Chen et al. 2022 and references therein)

$$F_{\text{var}} = \sqrt{\frac{\sum_{i=1}^{N} (F_i - \langle F \rangle)^2 - \sigma_{\langle F \rangle}^2}{N}},$$

$$\sigma_{\text{var}} = \sqrt{\left( \frac{\sigma_{\langle F \rangle}}{\langle F \rangle} \right)^2 + \left( \frac{1}{2N} \sigma_{\langle F \rangle}^2 \right)^2 \left( \langle F \rangle^2 F_{\text{var}} \right)},$$

where $\langle F \rangle$ and $\sigma_{\langle F \rangle}$ are the mean flux and its variance derived with Equations (2) and (3) $F_{\text{var}} = 0.456$ and $\sigma_{\text{var}} = 0.005$ are yielded for the X-ray light curve as shown in Figure 1(a). Furthermore, we estimate the fractional variability amplitude with Equations (2)–(5) for the $\gamma$-ray light curves as shown in Figures 1(b) and (c), and obtain $F_{\text{var}} = 14.990 \pm 0.005$ for the whole $\gamma$-ray light curve and $F_{\text{var}} = 7.472 \pm 0.003$ for the $\gamma$-ray light curve after MJD 58500, respectively. Clearly, the variability in the amplitude of $\gamma$-rays is much larger than that of X-rays. We also investigate the correlation of variability between X-rays and $\gamma$-rays using the observation data shown in Figures 1(a) and (c), as displayed in Figure 2. Considering the large errors in data points, we use a bootstrapping method to estimate the correlation coefficient ($r$) between $F_{2.10\text{ keV}}$ and $F_{0.1-300\text{ GeV}}$, and obtain $r \sim 0.1$. Hence, no correlation of flux variation between the two bands is observed.

In the radio band, significant variations have been widely reported and studied by the community (e.g., Perlman et al. 1996; Vedantham et al. 2017; Readhead et al. 2021; Peirson et al. 2022). In the optical-UV band, the intrinsic optical-UV emission of the source is affected by the foreground edge-on spiral galaxy and is strongly extinct (Stocke et al. 1992; Perlman et al. 2002; Readhead et al. 2021). This source is highly variable in the radio and $\gamma$-ray bands; hence, its intrinsic optical emission may potentially be variable.

4. Spectral Variation

The time-integrated spectrum of the $\sim 13.5$ yr Fermi-LAT observations derived from the likelihood fit is well described with the log-parabola function, as shown in Figure 3(a). The fitting parameters are reported in Table 1. As mentioned above, the $\gamma$-ray emission of PKS 1413+135 can be divided into two stages with a division of MJD 58500. We also extract the time-integrated spectra in the two stages. It is found that the time-integrated spectra of the two stages are also well fitted by the log-parabola function and a smaller curvature parameter value with a harder spectral index is presented in the high-flux stage than in the low-flux stage. The results are also given in Figure 3(a) and Table 1. One can observe that the spectrum in the high-flux stage is harder than that in the low-flux stage.

To further reveal the spectral variation feature, we make a time-resolved spectral analysis for the observational data in the following time slices, MJD 58724–58726, MJD 58796–58798, and MJD 59589–59591, namely, the source being in the high-flux stage. The time slice of MJD 58724–58726 is within the time bin of the highest flux point as shown in Figure 1(b). The VHE observation with MAGIC telescopes is conducted in the time slice of MJD 59589–59591. In the time slice of MJD 58796–58798, Fermi-LAT detects the maximum energy photon ($\sim 236$ GeV) from the source in its $\sim 13.5$ yr observations. The spectral analysis results are given in Figure 3(a) and Table 1. As illustrated in Figure 3(a), the obvious spectral evolution at the gigaelectronvolt band is presented for PKS 1413+135.
First, the flux variation in the high-energy end is more prominent than that in the low-energy end. Above $10^{24}$ Hz, the flux variation is almost three orders of magnitude. Second, the three time-integrated spectra need a curved log-parabola function to fit with a softer photon spectral index, while the three time-resolved spectra of $\gamma$-ray flares can be well modeled by a simple power-law function with a harder photon spectral index. For the power-law function, we can regard it as a log-parabola function with the curvature parameter $\beta = 0$. As listed in Table 1 and shown in Figure 3(a), the spectral curvature decreases and the spectrum becomes hard along with the increase of flux, indicating a harder when brighter behavior in the gigaelectronvolt band of PKS 1413+135.

In the X-ray band, we generate the Chandra and XMM-Newton spectra at different epochs as described in Section 2.2, and obtain the values of $F_{2-10keV}$ and $\Gamma_X$ for nine observational epochs. We show $F_{2-10keV}$ against $\Gamma_X$ in the $F_{2-10keV}-\Gamma_X$ plane, as displayed in Figure 3(b). Considering the small sample statistics and large errors of data points, we also use the bootstrap method to estimate the correlation coefficient ($r$) of the $F_{2-10keV}-\Gamma_X$ relation and obtain $r = 0.35$, and thus no obvious correlation between $F_{2-10keV}$ and $\Gamma_X$ is found for PKS 1413+135.

5. $\gamma$-ray Emission Property Derived from Broadband SED Modeling

As mentioned above, the gigaelectronvolt $\gamma$-ray emission has a harder when brighter spectral variation behavior, and the maximum energy of the detected photons is up to $\sim 236$ GeV, as listed in Table 1, where the maximum energy of the detected photons is estimated with the gsrsprob tool. We show the sensitivity curves of MAGIC telescopes (50 hr) and Cherenkov Telescope Array (CTA) north array (CTA-N, 50 hr) in Figure 3(a), where the sensitivity curves are obtained from Aleksić et al. (2016) and the CTA webpage,5 respectively. The high-energy end of the time-resolved spectrum during MJD 59589–59591 is over the sensitivity of MAGIC telescopes and the hard spectrum indicates that the gigaelectronvolt spectrum could extend to the VHE band. Interestingly, PKS 1413+135 was detected by the MAGIC telescopes on 2022 January 12 (MJD 59591, Blanch et al. 2022). The high flux with a very hard spectrum ($\Gamma_{\gamma} = 1.63 \pm 0.14$) between MJD 58796 and 58798, especially the detection of the maximum energy photon at $\sim 236$ GeV, clearly implies that the flux of PKS 1413+135 at the VHE band should be detectable by the MAGIC telescopes during that time. As given in Table 1, the maximum energy of the detected photons during MJD 59589–59591 and MJD 58724–58726 for PKS 1413+135 is 25.7 and 55.7 GeV, respectively. Since only one photon with energy of $\sim 55$ GeV was detected during MJD 58724–58726, an upper limit is given for the highest energy bin in the time-resolved spectrum. Although the average flux for the time slice of MJD 58724–58726 is highest among the six time slices in Table 1, the slight soft spectrum, especially, the upper limit for the highest energy bin, may indicate that the simultaneous VHE emission of PKS 1413+135 is below the sensitivity of MAGIC telescopes. We observe that even the time-integrated spectrum of the whole high-flux stage (MJD 58500–59660) is also marginally over the sensitivity of MAGIC telescopes, but the source may not be detectable by MAGIC telescopes at the VHE band when its gigaelectronvolt $\gamma$-ray flux is low.

To further study the $\gamma$-ray emission property of PKS 1413+135, we collect the data at the low-energy band from the NASA/IPAC Extragalactic Database (2019), together with the X-ray and $\gamma$-ray data derived in this paper, and construct its broadband SEDs in the low and high states of $\gamma$-ray emission, respectively, as illustrated in Figure 4. The Fermi-LAT time-resolved spectrum of MJD 59589–59591, corresponding to the first detection of the source at the VHE band, is considered as the data of the high-flux state, and the highest flux point as shown in Figure 1(a) observed by Swift-XRT on 2020 March 26 (MJD 58934) is taken as the upper limit of X-rays. The Fermi-LAT time-integrated spectrum of MJD 54682–58500 and the Chandra observation data on 2019 December 20 (MJD 58837)6 are set as the low-state data. As shown in Figure 4, it seems that there are

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5. https://www.cta-observatory.org/science/cta-performance/

6. It is the data point with the lowest flux as shown in Figure 1(a) and also corresponds to a low-flux state at the gigaelectronvolt band.
two different components at the radio band, a similar feature being observed in some blazars (e.g., Ghisellini et al. 2015). Using a power-law function of $F_{\nu} \propto \nu^{-\alpha}$ to fit to them, we gain $\alpha = 0.66 \pm 0.01$ from 0.08–2.7 GHz and $\alpha = 0.09 \pm 0.06$ from 4.8–375 GHz, respectively; the steep radio spectrum below a few GHz, $\alpha \sim 0.66$, indicates the signature of the optically thin synchrotron emission from the large-scale jet extended regions. The flat radio spectrum from a few gigahertz up to $\sim 10^9$ GHz, $\alpha = 0.09$, is produced by the superposition of the emission from several jet structures located at sub-parsec and parsec scales. The $\gamma$-ray emission region is too compact to produce the observed radio radiations below $\sim 10^9$ GHz on account of the synchrotron-self-absorption (SSA) effect (e.g., Ghisellini et al. 2015).

If the $\gamma$-ray emission region is inside of the broad line region (BLR), there would be absorption (Liu & Bai 2006) and Klein–Nishina (KN; Ghisellini & Tavecchio 2009) effects. Especially for the detection of the high-energy photon at 236 GeV by Fermi-LAT, we propose that the $\gamma$-ray emission region is outside of the BLR. And the torus would provide the seed photons for the EC process. The synchrotron radiation energy density can be estimated by $U_{\text{syn}} = \frac{L_{\text{syn}}}{4\pi R^2 c}$ (Tavecchio et al. 1998), where $L_{\text{syn}} = \left(\frac{E_2}{\alpha_2} - \frac{E_1}{\alpha_1}\right) L_{\alpha}$, $L_{\alpha}$ is taken as the luminosity at $\sim 5 \times 10^{12}$ Hz (z = 0.247), $\alpha_1 = 0.73$ and $\alpha_2 = 1.34$ (the spectral indices at the gigaelectronvolt band shown in Figures 4(a) and (b), respectively), the Doppler boosting factor $\delta \sim 10$ (Peirson et al. 2022). We obtain $U_{\text{syn}} \sim 4.9 \times 10^{-7}$ erg cm$^{-3}$ for $R = 1$ pc and $U_{\text{syn}} \sim 4.9 \times 10^{-3}$ erg cm$^{-3}$ for $R = 0.01$ pc, respectively. The energy density of the torus in the comoving frame is $U_{\text{IR}} \sim 3 \times 10^{-4}$ erg cm$^{-3}$ (e.g., Ghisellini & Tavecchio 2009; Kang et al. 2014), where $\Gamma$ is the bulk Lorentz factor of the emission region. Hence, the contribution of the EC/torus process compared with the synchrotron-self-Compton (SSC) component should be taken into account if the emission region is located at sub-parsec or parsec scale from the core.

The electron distribution in the radiation region is taken as a power law or broken power law. It is characterized by an electron density parameter $N_0$, a break energy $\gamma_b$, and indices ($p_1$ and $p_2$) in the range of $\gamma_e \in [\gamma_{\text{min}}, \gamma_{\text{max}}]$, where $\gamma_e$ is the Lorentz factor of electrons. The radiation region is assumed as a sphere with radius $R$, magnetic field strength $B$, the Doppler boosting factor $\delta$, where $\delta = 1/(\Gamma - \sqrt{\Gamma^2 - 1 \cos \theta})$, $\Gamma$ and $\theta$ are the bulk Lorentz factor and viewing angle of the emission region. The synchrotron ($\gamma$), SSC, and EC processes of the relativistic electrons are considered to fit the broadband SEDs of PKS 1413+135. The spectrum from near-infrared to optical-UV bands is seriously extinct due to an edge-on intervening Seyfert 2 galaxy between PKS 1413+135 and Earth (Stocke et al. 1992; Perlman et al. 1994), and thus we do not consider these data during the SED modeling. The KN effect and the absorption of high-energy $\gamma$-ray photons by extragalactic background light (EBL; Franceschini et al. 2008) are taken into account during the SED modeling.

The radio spectrum below several gigahertz in the broadband SED of PKS 1413+135 is thought to be produced by the emission of jet-extended regions. The overall size of PKS 1413+135 at the radio band is $\sim$110 mas (Readhead et al. 2021), which corresponds to the projection distance of $\sim$422 pc for $z = 0.247$. As reported by Stawarz et al. (2008), the external photon field is still dominated by the dusty torus at this scale and its energy density ($U_{\text{IR}}$) can be estimated by Equation (21) in Stawarz et al. (2008). We obtain $U_{\text{IR}} \sim 9 \times 10^{-5}$ erg cm$^{-3}$.

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**Figure 4.** Observed SEDs with model fitting for PKS 1413+135 in the low-flux (panel (a)) and high-flux (panel (b)) states of $\gamma$-rays. The $\gamma$-ray spectra in the two panels are the time-integrated spectrum before MJD 58500 (panel (a)) and the time-resolved spectrum during MJD 59589–59591 (panel (b)), respectively. The data in radio-optical bands, the gray solid and opened squares, are taken from NED. The green solid and magenta opened stars indicate the data of the radio core and knot-D, which are observed in some blazars. The green dotted–dashed line, 50 hr and CTA-N (blue dotted–dashed line, 50 hr) are also presented. Panel (a): the black solid line is the sum of each component emission for the source located at $z = 0.247$, synchrotron radiation (red lines), SSC process (magenta lines), and external Compton (EC) process (cyan lines), where the solid and dashed lines, respectively, represent the radiations from the sub-parsec-scale jet component and the large-scale jet extended region. An insert in the upper left of panel (a) shows the fitting results for the spectra from 0.08–2.7 GHz and from 4.8–375 GHz with the power-law function of $F_{\nu} \propto \nu^{-\alpha}$, and $\alpha = 0.66$ (orange solid line) and $\alpha = 0.09$ (yellow solid line) are obtained, respectively. Panel (b): the dark-yellow dashed line is the same line as the black solid line in panel (a). The colored solid lines represent the different radiation components of the compact $\gamma$-ray emission region, synchrotron radiation (red line), SSC process (magenta line), and EC process (cyan line), where the cyan line at the VHE band indicates the intrinsic flux of the source without considering the extragalactic background light (EBL) absorption. The black solid line is the sum of the dark-yellow dashed line and three colored solid lines after considering the EBL absorption for the source located at $z = 0.247$. The green dotted–dashed line represents the fitting result when the source is located at $z = 0.5$.
which is much higher than the energy density of cosmic microwave background light at $z = 0.247$. Hence, the syn +SSC+EC/torus model under the equipartition condition ($U_B = U_e$) is taken to reproduce the emission of the large-scale jet extended region, where $U_B$ and $U_e$ are the energy densities of the magnetic fields and electrons. $R$ is taken as $R = 211$ pc, corresponding to half of the overall size of the radio band. The relativistic effect is not considered, i.e., $\delta = 1$. Considering the limited observation data of the large-scale jet extended region at the radio band, the electron distribution is taken as a power law. $p_1$ is derived by the radio spectral index ($\alpha \sim 0.66$) below several gigahertz and is fixed as $p_1 = 2.32$. $\gamma_{\text{min}} = 1$ is also fixed during the modeling. We adjust the values of $\gamma_{\text{max}}$ and $N_0$ to fit the radio spectrum below several gigahertz in the broadband SED and obtain $\gamma_{\text{max}} = 2000$ and $N_0 = 0.036$ cm$^{-3}$. And then we fix the reproduced spectrum component of the large-scale jet extended region in the following SED modeling for the low-flux and high-flux states.

The gigaelectronvoltage emission of the low-flux and high-flux states may have different origins, and we return to this point in Section 6.1. For the low-flux state of gigaelectronvoltage emission, we propose that the emission is dominated by the sub-parsec-/parsec-scale jet structures. The radius of the radiation region is taken as $R = 0.6$ pc, corresponding to half of the projection distance between the radio core and component-D8 (0.16 mas; Peirson et al. 2022) for $z = 0.247$. Considering the relativistic effect, $\delta = 1$ is assumed during SED modeling, namely, the viewing angle ($\theta$) being equal to the opening angle ($1/\Gamma$) of the jet (e.g., Chen & Zhang 2021). The electron distribution of a broken power law is used here. $\gamma_{\text{min}} = 1$ and $\gamma_{\text{max}} = 10^5$ are fixed. $p_2 = 3.84$ is fixed and constrained by the spectral index in the gigaelectronvoltage band. We adjust the values of $B$, $\delta$, $p_1$, $\gamma_b$, and $N_0$ to fit the SED of the low-flux state as shown in Figure 4(a), and then obtain $B = 0.45$ G, $\delta = 2.2$, $p_1 = 1.8$, $\gamma_b = 2609$, and $N_0 = 2.81$ cm$^{-3}$. For the high-flux state at the gigaelectronvoltage band, we speculate that the outbursts after MJD 58500 as shown in Figure 1(b) are due to the restarted activity of the central engine and originate from the region closer to the black hole. The radius of the radiation region is taken as $R = 6\times10^5$ cm$^{\Delta t/(1+z)}$, where $\Delta t = 1$ day is taken since the variability on a daily timescale is presented in Figure 1(c). As shown in Figure 4(b), the peak of the second bump is above $10^{25}$ Hz, which needs an electron population with higher energy than that produces the low-flux emission. We thus consider the syn+SSC+EC processes of another electron population to reproduce the emission of the gigaelectronvoltage outburst on the basis of the fitting result of the low-flux state. The distribution of the new electron population is also taken as a broken power law. $p_1 = 2.46$, $p_2 = 3.84$, and $\gamma_{\text{max}} = 10^6$ are fixed, where $p_1$ is derived by the spectral index in the gigaelectronvoltage outburst while $p_2$ is taken the same value as the low-energy electron population.$^8$ $\gamma_{\text{min}} = 50$ is roughly constrained by the upper limit of the X-ray flux. We adjust the values of $B$, $\delta$, $\gamma_b$, and $N_0$ to fit the spectrum during the $\gamma$-ray outburst on the basis of the fitting result of the low-flux state. No observational data at the optical-UV band are available, and the highest flux point as shown in Figure 1(a) observed by the Swift-XRT is taken as the upper limit to roughly constrain the fitting parameters. We obtain $B = 0.8$ G, $\delta = 20$, $\gamma_b = 1.45 \times 10^4$, and $N_0 = 631.8$ cm$^{-3}$. The fitting results are shown in Figure 4 and the modeling parameters are listed in Table 3. Note that $B$ and $\delta$ are degenerate (e.g., Zhang et al. 2012), and the model parameters cannot be totally constrained with the current observational data.

As displayed in Figure 4, the $\gamma$-rays are absolutely produced by the EC process while the X-rays are a hybrid of several components. The observed spectral indices at the X-ray band cluster at $1.8 < \Gamma_X < 2.2$, as shown in Figure 3(b), suggesting a transition between the synchrotron radiation and inverse-Compton component (e.g., Ghisellini et al. 1998). The complex origins of X-rays may result in a smaller amplitude of flux variation than that of $\gamma$-rays. No significant correlation of variability between X-rays and $\gamma$-rays, as shown in Figure 2, also demonstrates that the X-rays are of different origin than $\gamma$-rays.

The observation time of the $\gamma$-ray spectrum shown in Figure 4(b) corresponds to the time when PKS 1413+135 was first detected at the VHE band by the MAGIC telescopes. The predicted flux by the SED modeling at the VHE band exceeds the sensitivity of MAGIC telescopes, whether considering the EBL absorption or not. The integral flux of the model prediction over the MAGIC sensitivity is $\sim 1.4 \times 10^{-10}$ erg cm$^{-2}$ s$^{-1}$ after considering the EBL absorption. Recently, Malik et al. (2022) reported that the attenuation of VHE photons due to the EBL absorption may be overestimated, especially for the highly redshift sources. Hence, there may be a higher observational VHE flux for PKS 1413+135 than the model prediction. We also observe that PKS 1413+135 is not detectable at the VHE band when its gigaelectronvoltage emission is in the low-flux state, as illustrated in Figure 4(a).

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$^8$ Although no observational data are available to constrain the $p_2$ value, a broken power-law (not a power-law) distribution of electrons is generally needed to explain the broadband SEDs of $\gamma$-ray emitting AGNs (Tavecchio et al. 1998; Aleksić et al. 2014; Ghisellini et al. 2015), we thus still consider a broken power-law distribution for the higher energy electron population.

### Table 3

SED Fitting Parameters of PKS 1413+135

| State$^a$ | $R$ (pc) | $R_{\text{dist}}$ (pc) | $B$ (mG) | $\delta$ | $\Gamma$ | $\gamma_{\text{min}}$ | $\gamma_b$ | $\gamma_{\text{max}}$ | $N_0$ (cm$^{-3}$) | $p_1$ | $p_2$ |
|-----------|--------|-----------------|--------|--------|--------|----------------|--------|----------------|----------------|--------|--------|
| E         | 211    | 400             | 1.25   | 1      | 1      | 1              | 1      | 2000           | 0.036          | 2.32   | ...   |
| L         | 0.6    | 1               | 450    | 2.2    | 2.2    | 1              | 2609   | 10$^5$         | 2.81           | 1.8    | 3.84   |
| H         | $4.15 \times 10^{36}$ | $4.15 \times 10^{37}$ | 800    | 20     | 20     | 50             | 14,513 | 10$^6$       | 631.8          | 2.46   | 3.84   |

Notes.

$^a$ “E”, “L”, and “H” represent the parameters for the large-scale jet extended region, the sub-parsec-/parsec-scale jet component, and the compact radiation region close to the black hole, respectively. The parameter values correspond to the result for the source located at $z = 0.247$.

$^b$ $R_{\text{dist}}$ is the distance of the radiation region from the black hole, which is roughly estimated. For the large-scale jet extended region, $R_{\text{dist}}$ corresponds to the overall projection size of the radio morphology. For the sub-parsec-/parsec-scale jet component, $R_{\text{dist}}$ is roughly the projection distance of component-D8. For the compact radiation region, $R_{\text{dist}} \sim 10 \times R$ (see also Ghisellini & Tavecchio 2009).
The host galaxy and redshift of PKS 1413+135 are also still debated. PKS 1413+135 may be a background source of the spiral galaxy and is located at a higher redshift of $0.247 < z < 0.5$ (Readhead et al. 2021). As displayed in Figure 4(b), the predicted flux by the SED modeling after considering the EBL absorption is still over the sensitivity of MAGIC telescopes if PKS 1413+135 is located at $z = 0.5$. Hence, we cannot give a more accurate constraint on its redshift with SED modeling.

6. Discussion

6.1. Origin of $\gamma$-Ray Emission of PKS 1413+135

As displayed in Figure 1(b), the gigaelectronvolt $\gamma$-rays of PKS 1413+135 are in a low-flux stage before MJD 58500, then undergo obvious outbursts, and always stay in a high-flux stage after MJD 58500. We can also observe that the gigaelectronvolt spectral features are quite different for the high-flux and low-flux states, as displayed in Figure 3(a). The curvature log-parabola energy spectrum with a softer spectral index is shown in the low-flux state while the spectra in the outbursts of $\gamma$-rays can be well fitted by a power-law function with a harder spectral index. The different spectral features in the two states of PKS 1413+135 may reflect the differently dominant acceleration mechanisms or acceleration regions of relativistic electrons. In the radio band, the emission above 5 GHz is totally dominated by the radio core (Table 2 in Perlman et al. 1996; Figure 4 in Peirson et al. 2022). Except for the radio core and knot-D, the other jet structures show steep spectra, which should originate from the optical thin synchrotron radiations, as illustrated by the red dashed line in Figure 4(a). The inverted spectrum of the radio core is due to the SSA effect while the flat spectrum ($\alpha \sim 0$) of knot-D may indicate a reacceleration and/or recollimation region (Perlman et al. 1996). Component-D8 is the closest component to the radio core located at 0.32 mas away (Peirson et al. 2022) and is also the brightest component except for the radio core in the MOJAVE images (Lister et al. 2019). We speculate that the reacceleration spectral feature of knot-D is due to the emergence of a new component-D8 from the radio core, and the component-D8 interacts with other jet structures to reaccelerate the electrons in knot-D. Peirson et al. (2022) reported that component-D8 displayed rapid variability between 1995 and 1998. The long-term light curve of PKS 1413+135 at 14.5 GHz taken from the University of Michigan Radio Astronomical Observatory (Readhead et al. 2021) shows three outbursts around 1982, 1988, and 1992. Maybe the emergence of component-D8 is connected with one of the three outbursts, and this is roughly coincident with the derived result using the separation speed $(9.2 \pm 2.2)$ $\mu$as yr$^{-1}$, Lister et al. 2019) and distance of component-D8 from the radio core. We thus suggest that the $\gamma$-rays of PKS 1413+135 may have two origins: one is from the sub-parsec-/parsec-scale jet components, which contributes to the low-flux $\gamma$-rays shown in Figure 1(b) and the flat radio spectral component shown in Figure 4(a). Another is connected to the outbursts of $\gamma$-rays, which may be due to the ejection of a new component recently from the core, similar to many blazars (e.g., Marscher et al. 2010; Jorstad et al. 2013; Lisakov et al. 2017; Rani et al. 2018; Lee et al. 2019; Zhang et al. 2020), namely, the restarted nuclear jet activity of PKS 1413+135.

The $\gamma$-ray luminosity of the source during outbursts is up to $\sim 10^{43}$ erg s$^{-1}$ ($z = 0.247$), as listed in Table 1, together with the significant variability at the $\gamma$-ray band, implying the strong Doppler boosting effect of the $\gamma$-ray emission region. We assume $\delta = \Gamma$ during the SED fitting, the viewing angle ($\theta$) is equal to the opening angle (1/$\Gamma$) of the jet (e.g., Chen & Zhang 2021), and thus it is $\theta \sim 3^\circ$. This conflicts with the two-sided parsec-scale structure in the radio morphology of PKS 1413+135 since the symmetric radio structure of CSOs is thought to be due to a misaligned jet to the observers (Phillips & Mutel 1980; Wilkinson et al. 1994; Readhead et al. 1996). Recently, episodic nuclear jet activity in $\gamma$-ray emitting CSOs, TXS 0128+554 (Lister et al. 2020) and CTD 135 (Gan et al. 2021) was reported. We thus propose that there are episodic nuclear jet activities in the center of PKS 1413+135. The axis of the recently restarted jet is aligned within a few degrees to the line of sight and is different from the direction of the preexisting components, similar to the typical radio galaxy 3C 84 (Nagai et al. 2016). The restarted jet may result in a new component ejected from the core, which would interact with the surrounding materials (or the preexisting components) and then accelerate particles to produce a significant $\gamma$-ray outburst and variability. One of the most striking pieces of evidence of episodic nuclear jet activity is that two or more pairs of distinct radio components are observed on opposite sides of the radio core (O’Dea & Saikia 2021). The outer components of the jet and counter-jet of PKS 1413+135, which are faraway from the radio core, such as the components A, F, and G (Perlman et al. 1996), may be the remnants of the nuclear jet activity long ago.

The overall size of the radio morphology of PKS 1413+135 is $\sim 422$ pc (projection size, $z = 0.247$, Readhead et al. 2021), and an explanation of the size below 1 kpc for compact radio sources is that they are transient or episodic sources (O’Dea & Saikia 2021 for a review), which cannot provide enough energy for the jet to propagate to large scale. On the other hand, a fairly dense nuclear medium (Perlman et al. 1996) may also frustrate the jet propagation of PKS 1413+135. And the interaction between the jet and surrounding medium may change the jet direction and result in a bend in the extended jet structures. As given in Table 3, the derived values of $\delta$ by the SED modeling are 2.2 and 20 for low-flux and high-flux states, respectively, implying that the jet of PKS 1413+135 is decelerated effectively at the sub-parsec scale. If the scenario described above is true, the recent $\gamma$-ray outbursts of PKS 1413+135 should be connected with the restarted nuclear jet activity. And the ejected new component from the central engine could be resolved out with VLBI observations in the future.

6.2. PKS 1413+135: A CSO or a Blazar

PKS 1413+135 was classified as either a BL Lac or a red quasar because of the inverted and rapidly variable radio spectrum, the absence of optical emission lines, its extremely steep near-IR slope, and an IR $K$-band polarization of $(16 \pm 3)$% (Bregman et al. 1981; Stocke et al. 1992). We find that PKS 1413+135 also displays significant flux variation in the GeV band accompanied by obvious spectral evolution. As shown in Figure 1(b), the variation of the $\gamma$-ray flux of PKS 1413+135 exceeds two orders of magnitude, indicating the typical relativistic jet effect, similar to blazars. Especially, the report of the VHE detection of PKS 1413+135 by the MAGIC telescopes further supports that it may be a BL Lac since most of the confirmed extragalactic VHE emission sources are BL Lacs. Generally, the broadband SEDs of BL Lacs can be reproduced with the
bands, we proposed that the $\gamma$-ray outbursts after MJD 58500 of PKS 1413+135 may be connected to the recently restarted nuclear jet activity of the central engine and are produced in an aligned core-jet component. The sub-parsec-scale jet components, which may be produced by the previous nuclear jet activities, contribute to the low-flux $\gamma$-ray emission. This scenario can be checked by future VLBI observations.

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