PKS 1413+135: Bright GeV γ-ray Flares with Hard-spectrum and Hints for First Detection of TeV γ-rays from a Compact Symmetric Object

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ABSTRACT

PKS 1413+135, a typical compact symmetric object (CSO) with a two-side pc-scale structure in its miniature radio morphology, is spatially associated with the Fermi-LAT source 4FGL J1416.1+1320 and recently announced to be detected in the TeV γ-ray band with the MAGIC telescopes. We present the analysis of its X-ray and GeV γ-ray observations obtained with Swift-XRT, XMM-Newton, Chandra, and Fermi-LAT for revealing its high energy radiation physics. No significant variation trend is observed in the X-ray band. Its GeV γ-ray light curve derived from the Fermi-LAT 13.5-year observations shows that it is in a low γ-ray flux stage before MJD 58500 and experiences violent outbursts after MJD 58500. The confidence level of the flux variability is much higher than 5σ, and the flux at 10 GeV varies ∼3 orders of magnitude. The flux variation is accompanied by the clearly spectral variation. The spectral shape displays a curvature log-parabola energy spectrum in low-flux state and a hard power-law spectrum with photon spectral index of Γγ ∼ −1.7 in the γ-ray flares. The highest energy of the detected photons by the Fermi-LAT is ∼236 GeV, which is detectable with the MAGIC telescopes. Furthermore, we compile the broadband spectral energy distribution during an GeV γ-ray outburst and fit it with a two-zone leptonic model, in which emission in the radio-optical band is explained by the synchrotron radiation of relativistic electrons and emission in the X-ray-γ-ray band is attributed to the inverse Compton scattering processes. The result shows that the γ-rays of PKS 1413+135 would be detectable with the MAGIC telescopes, whether the source is located at z = 0.247 or z = 0.5. Based on our analysis and its CSO radio morphology, we suspect that the nuclear jet activity of PKS 1413+135 is episodic, the weak γ-ray emission before MJD 58500 may be from its pc-scale jet structures powered by previous activities, and the violent outbursts with short timescale variability after MJD 58500 could be attributed to the recently re-started jet activity.

Keywords: galaxies: active—galaxies: jets—radio continuum: galaxies—gamma rays: galaxies

1. INTRODUCTION

Compact symmetric objects (CSOs), a sub-class of active galactic nuclei (AGNs), are defined as those with 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). In contrast, blazars are believed to be on-axially observed to their jets and an asymmetric one-side aligned jet is usually observed. 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 being 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 the CSOs are consistent with each other within the uncertainties, indicating

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that CSOs are young with typical ages of $3 \times 10^3$ to $10^4$ yr, almost certainly $< 10^5$ yr (Readhead et al. 1996). The non-difference between these compact radio sources and larger radio-loud objects at the 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 $\gamma$-ray sources, six CSOs have been detected with the Fermi-LAT in the GeV 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), PKS 1413+135 (Principe et al. 2021). It is debated whether the $\gamma$-rays of CSOs are from the pc-scale lobes or from the core jet region. Interestingly, the $\gamma$-rays in some CSOs may indicate a characteristic of recently re-started 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 January 12, 2022 (MJD 59591, ATel 15161). It is the first CSO detected at the very high energy (VHE) band. It would be a good sample to study the $\gamma$-ray emission of young radio sources.

The high-resolution observations with the very large array (VLA), US very long baseline interferometry (VLBI) Network, and very long baseline array (VLBA) show no kpc-scale extended structure, and a mini-tripple structure with a counter-jet is presented on pc-scale of PKS 1413+135 (Perelman 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-side pc-scale structure and no evidence of superluminal motion for PKS 1413+135, which are similar to that of CSOs, and thus they suggested that PKS 1413+135 likely is a young radio source with an age $\leq 10^4$ yr. It is intriguing that the multi-band optical images of PKS 1413+135 show a surface brightness profile that can be well fitted by an exponential disk. This suggests that PKS 1413+135 is hosted in a spiral galaxy (McHardy et al. 1991). An unresolved source centered at the galaxy within 0.1 is found in the H-band images (Stroe et al. 1992). The Hubble Space Telescope (HST) observation further reveals that the galaxy contains a previously unresolved dust lane and very likely is 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 (Stroe et al. 1992). These results suggest that PKS 1413+135 would not be hosted in this spiral galaxy and be a background source behind the spiral galaxy. The redshift of $z=0.247$ for PKS 1413+135 is derived from the redshift HI absorption (Carilli et al. 1992), which should be associated with the spiral galaxy. The U-shaped symmetric achromatic variability from 15 to 234 GHz of PKS 1413+135 was proposed to be caused by gravitational lensing of the foreground spiral galaxy (Vedantham et al. 2017). It was 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). However, no sign of image multiplicity or distortion due to the gravitational lensing is found, in either optical or radio bands (Stroe et al. 1992; Perlman et al. 1996; 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 in the GeV–TeV band, would be powerful probes for studying the nature of the source.

For revealing the radiation properties of PKS 1413+135, we analyze its data in the X-ray and $\gamma$-ray bands observed with Fermi-LAT, Chandra, XMM-Newton, and Swift-XRT over the past $\sim 13.5$ yr. Description of the data reduction is presented in Section 2. We investigate its temporal and spectral variations in both X-ray and $\gamma$-ray bands (Section 3 and Section 4). Together with the data in the low-energy bands, we present the possible emission flux at the VHE band in Section 5. Discussion on the type of the source and the physical origin of the $\gamma$-ray outbursts are 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 $\Omega_L = 0.73$ are adopted in this paper.

2. OBSERVATIONS AND DATA REDUCTION

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

It was reported that 4FGL J1416.1+1320 is spatially coincident with PKS 1413+135 in the Fermi-LAT 12-year Source Catalog (4FGL-DR3, Fermi-LAT collaboration et al. 2022). We download the Pass 8 data from the Fermi Science Support Center (FSSC). The data are selected within a 15° region of interest (ROI) centered on the radio position of PKS 1413+135 (R.A. = 213.995°, Decl. = 13.340°; Fey et al. 2015). The temporal coverage of the data is from 2008 August 04 to 2022 March 22 (MJD 54682–59660) of about 13.5 yr. We perform a binned likelihood analysis for the $\gamma$-rays of 4FGL J1416.1+1320 using the publicly available software Fermi tools (ver. 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 the γ-ray contamination causing by the Earth limb. We bin the data with a pixel size of 0.2° in space and 25 logarithmically energy bins. The background model includes all γ-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 (IRFs) is used.

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

\[
\frac{dN}{dE} = N_0 \left(\frac{E}{E_b}\right)^{-\left(\Gamma_0 + \beta \log\left(\frac{E}{E_b}\right)\right)},
\]

where \(E_b\) is the scale parameter of photon energy, \(\Gamma_0\) 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., \(dN/dE = N_0(E/E_b)^{-\Gamma_0}\)). 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 γ-ray detection is quantified by adopting the maximum likelihood test statistic (TS), which is defined as \(TS = 2(\ln \mathcal{L}_1 - \ln \mathcal{L}_0)\), where \(\mathcal{L}_1\) and \(\mathcal{L}_0\) are maximum likelihood values for the models with and without the target source, respectively. The analysis results of the Fermi-LAT observations for 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 March 20, 2007. 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 a significant foreground absorption of soft X-rays was found in PKS 1413+135 (Stocke et al. 1992), firstly we attempt to get 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 centred on the radio position of PKS 1413+135 with radius of 6 arcsec. The background is determined in an annulus region with inner and outer radius of 7 and 14 arcsec, 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 an absorption at \(z = 0\) with neutral hydrogen column density fixed at Galactic value \(N_{\text{H}}^{\text{gal}} = 1.56 \times 10^{20}\) cm\(^{-2}\), the other one is an extragalactic foreground absorption \(N_{\text{H}}^{\text{int}}\) at redshift of \(z = 0.247\) with column density set free. The model gives a well fit to the spectrum and an extragalactic foreground absorption column density of \(N_{\text{H}}^{\text{int}} = 3.6^{+0.6}_{-0.5} \times 10^{22}\) 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 the Galactic \((N_{\text{H}}^{\text{gal}})\) and extragalactic \((N_{\text{H}}^{\text{int}})\) absorption is used to fit the spectra. As there are only no more than 150 net photon counts for each spectrum, \(C\)-statistic minimization is adopted for evaluating the goodness of the fits and \(N_{\text{H}}^{\text{int}}\) is fixed at \(3.6 \times 10^{22}\) cm\(^{-2}\) during the fitting.

The public data of pointing observations on PKS 1413+135 by the 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 arcsec radius centred at 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 \(\chi^2\) analysis. Again, the single power-law with a Galactic and an 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 to 2022. The X-ray telescope (XRT) onboard 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 radius of 50 arcsec, while the backgrounds are determined in an annulus with inner and outer radius of 60 and 105 arcsec, 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. $N_{\text{gal}}^H = 1.56 \times 10^{20}\text{cm}^{-2}$ and $N_{\text{int}}^H = 3.6 \times 10^{22}\text{cm}^{-2}$ are all fixed, and the photon index is also fixed at $\Gamma_X = 1.9$ during the fitting.

3. TEMPORAL ANALYSIS

We perform a likelihood fit for PKS 1413+135 with the ~13.5-year Fermi-LAT data. PKS 1413+135 is bright in the GeV $\gamma$-ray band, with an average luminosity of $L_{\gamma} = (4.13 \pm 0.23) \times 10^{45}\text{erg s}^{-1}$ in the whole interval. Variability is very common for AGNs and its magnitude and timescale are useful to study the property of emission region. For estimating the variability of PKS 1413+135 at the GeV band, we follow the definition in 2FGL (Nolan et al. 2012) and derive the variability index $TS_{\text{var}}$ (see also Abdollahi et al. 2020). We split the full ~13.5-year interval into N=13 intervals of about one year each. The source is considered to be significant variable if $TS_{\text{var}}$ exceeds 53.9, where $TS_{\text{var}} = 53.9$ corresponds to 5σ confidence level in a $\chi^2_{N-1}(TS_{\text{var}})$ distribution with 12 degrees of freedom. The $TS_{\text{var}}$ value of PKS 1413+135 is 2074 and far beyond 5σ 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 $TS \geq 9$ for each time bin, where the minimum time-bin size is set to be seven days, as shown in Figure 1(a). We note that before MJD 58500, the $\gamma$-ray flux is in a relatively low state, where the $\gamma$-rays are lower than the average flux level for almost all time bins and even lower than the average flux by almost one order of magnitude in some time bins. The $\gamma$-ray flux begins to increase from a very low state since ~MJD 58520 to the average flux level around MJD 58500. After MJD 58500 the source seems to be in the high state with fluxes higher than the average flux, and the $TS$ values of almost all the time bins with the minimum binsize of seven days can meet $TS \geq 9$. 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 state and a high state.

In order to further investigate the short timescale variability of this source, we reanalyze the observation data after MJD 58500 and still extract the light curve using the adaptive-binning method with the criterion of $TS \geq 9$ for each time bin, where the minimum time bin is taken as one day. The derived flux of each time bin has a large error bar, (c) indicates the average flux of the 25 observational data points, i.e., $F_{2-10\text{keV}} = 8.91 \times 10^{-13}\text{erg cm}^{-2}\text{s}^{-1}$. Although the large error bars of the data points, we still can observe the flux variations in some other time bins. We can also observe that there are many time bins with $L_{\gamma} > 10^{47}\text{erg s}^{-1}$ between MJD 58700–59100, indicating that PKS 1413+135 is in a very high GeV flux state and there may be detectable VHE emission during that time.

In the X-ray band, there are 3 XMM-Newton, 6 Chandra, and 16 Swift-XRT observations from March 2007 to January 2022. As shown in Figure 1(c), most of them cluster at the time after January 2020. The horizontal dashed line in Figure 1(c) indicates the average flux of the 25 observational data points, i.e., $F_{2-10\text{keV}} = 8.91 \times 10^{-13}\text{erg cm}^{-2}\text{s}^{-1}$. Although the large error bars of the data points, we still can observe the flux variations at the X-ray band. Interestingly, the last two points in Figure 1(c) are obtained with the observations on January 13–14 2022, just after the ATel of the VHE detection for 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 January 13, 2022 (MJD 59592) to $5.9 \times 10^{-13}\text{erg cm}^{-2}\text{s}^{-1}$ on January 14, 2022 (MJD 59593), a factor of ~2 within one day, when its $\gamma$-rays at the GeV band are also decreasing. Additionally, the $\gamma$-ray emission of PKS 1413+135 is respectively in the low and high states on December 20, 2019 (MJD 58837) and February 03, 2020 (MJD 58882) when the source was observed by the Chandra. We obtain $F_{2-10\text{keV}} = (3.8 \pm 0.5) \times 10^{-13}\text{erg cm}^{-2}\text{s}^{-1}$ with a photon index of $\Gamma_X = 1.83 \pm 0.32$ when $L_{\gamma} \sim 6.5 \times 10^{45}\text{erg s}^{-1}$ on MJD 58837 and $F_{2-10\text{keV}} = 8.4_{-0.7}^{+0.8} \times 10^{-13}\text{erg cm}^{-2}\text{s}^{-1}$ with $\Gamma_X = 1.92 \pm 0.22$ when $L_{\gamma} \sim 1.2 \times 10^{47}\text{erg s}^{-1}$ on MJD 58882. Perlman et al. (2002) reported that the ASCA observations yield a flux of $F_{2-10\text{keV}} = 9 \times 10^{-13}\text{erg cm}^{-2}\text{s}^{-1}$, which declined a factor of ~5 than seen in previous X-ray observations, but the previous X-ray flux obtained from the ROSAT and Einstein observations is based almost completely on the extrapolations. Anyway, these results indicate that PKS 1413+135 is also variable in the hard X-ray band and the high $\gamma$-rays seem to be accompanied by the relatively high X-ray emission. Nevertheless,
the variation amplitude of X-rays is clearly much smaller than that of γ-rays and the correlation of the variations between the two energy bands also needs to be further investigated with more X-ray observations.

In the radio band, the significant variations have been widely reported and studied by the communities (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 emission of the source is affected by the foreground edge-on spiral galaxy and has serious extinction (Stocke et al. 1992; Perlman et al. 2002; Readhead et al. 2021). This source is highly variable in radio and γ-ray bands, hence its intrinsic optical emission may be potentially variable.

4. SPECTRAL VARIATION

The time-integrated spectrum of the ∼13.5-year Fermi-LAT observations derived from the likelihood fit is well described with the log-parabola function, as shown in Figure 2(a). The fitting parameters are reported in Table 1. As mentioned above, the source seems in the stages of low and high γ-ray flux divided 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 2(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 also make 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 stages. The time slice of MJD 58724–58726 is within the time bin of the highest flux point in Figure 1(a). The VHE observation with the MAGIC telescopes is conducted in the time slice of MJD 59589–59591. In the time slice of MJD 58796–58798, Fermi-LAT detects the highest energy photon (∼236 GeV) from the source in its ∼13.5-year observations. The spectral analysis results are presented in Figure 2(a) and reported in Table 1. As illustrated in Figure 2(a), the obviously spectral evolution at the GeV band is presented for PKS 1413+135. Firstly, 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. Secondly, the three time-integrated spectra need a curved log-parabola function to model with a softer photon spectral index, while the three time-resolved spectra of the γ-ray flares can be well fitted 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 β = 0. As listed in Table 1 and shown in Figure 2(a), the spectral curvature decreases and the spectrum becomes hard along with the increase of luminosity, indicating a “harder when brighter” behavior in the GeV band for 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_{2–10 keV} and Γ_x for the nine observational epochs. We show F_{2–10 keV} against Γ_x in the F_{2–10 keV} − Γ_x plane, as displayed in Figure 2(b). Considering the large error bars, we cannot obtain the definite evidence of spectral variability at the hard X-ray band. A tendency of “softer when brighter” is presented in the F_{2–10 keV} − Γ_x plane, which is different from the behavior in the GeV band.

5. HINTS FOR THE DETECTION OF TEV GAMMA-RAYS

As mentioned above, the GeV γ-ray emission has a “harder when brighter” spectral variation behavior, and the highest energy of the detected photons is up to ∼236 GeV, as listed in Table 1. The highest energy of the detected photons is estimate with the gtsrecprob tool. Interestingly, PKS 1413+135 was announced to be detected by the MAGIC telescopes on January 12 2022 ((MJD 59591, ATel 15161). We also show the observational thresholds of the MAGIC telescopes (72 hours) and Cherenkov Telescope Array (CTA) North array (CTA-N, 50 hours) in Figure 2(a). The high energy end of the time-resolved spectrum during MJD 59589–59591 is marginally over the observational threshold of the MAGIC telescopes and the hard spectrum indicates that the GeV spectrum would extend to the VHE band. This is consistent with the announcement that PKS 1413+135 was detected by the MAGIC telescopes. We observe that even the time-integrated spectrum of the high-flux stage (MJD 58500–59660) is also marginally over the observational threshold of the MAGIC telescopes. The high luminosity with a very hard spectrum (Γ_γ = 1.63 ± 0.14) between MJD 58796–58798, especially the detection of the highest energy photon at ∼236 GeV, clearly implies the detectable flux of PKS 1413+135 at the VHE band 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 GeV and 55.7 GeV, respectively. Since only one photon with energy of ∼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
luminosity for the time slice of MJD 58724–58726 is highest among the six time slices, as listed in Table 1, the slightly soft spectrum, especially, only an upper-limit for the highest energy-bin, may make the extrapolated VHE flux to be out of the observational threshold of the MAGIC telescopes. These results demonstrate that PKS 1413+135 is indeed detectable by the MAGIC telescopes when its GeV emission is in the high-flux state with a hard spectrum, and it is also undoubtedly detectable by the CAT-N in the future, as displayed in Figure 2(a).

To further study the γ-ray emission properties at GeV and TeV bands for PKS 1413+135, we collect the data at low-energy band from the NASA/IPAC Extragalactic Database (NED), together with the X-ray and γ-ray data derived in this paper, and construct its broadband spectral energy distributions (SEDs) in the low and high states, respectively, as illustrated in Figure 3. The Fermi-LAT time-resolved spectrum of MJD 59589–59591, corresponding to the VHE detection time of the source, and the Chandra observation data on February 03, 2020 (MJD 58882) are taken as the high-state data, while the Fermi-LAT time-integrated spectrum of MJD 54682–58500 and the Chandra observation data on December 20, 2019 (MJD 58837) are set as the low-state data.

As shown in Figure 3, it seems that there are two different components at the radio band. Using a power-law function of $F_\nu \propto \nu^{-\alpha}$ to fit them, we gain $\alpha = 0.66 \pm 0.01$ from 80 MHz to 2.7 GHz and $\alpha = 0.09 \pm 0.06$ from 4.8 GHz to 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 extended regions. The flat radio spectrum from a few GHz up to $\sim 10^3$ GHz, $\alpha = 0.09$, is produced by the superposition of the emission from several larger parts of the jet. The emission region of γ-rays is too compact to produce the observed radio radiations below $\sim 10^2$ GHz on account of the synchrotron-self-absorption (SSA) effect (e.g., Ghisellini et al. 2015). As displayed in Figure 3(a), the second bump from X-ray to GeV band in the SED is very broad with a peak above $10^{25}$ Hz. A single radiation process is difficult to represent such broad emission component, namely, the single synchrotron-self-Compton (SSC) radiation process cannot reproduce such broadband spectral component of PKS 1413+135. So the synchrotron, SSC, and external Compton (EC) scattering of the relativistic electrons in both the core and extended region are considered to fit the broadband SEDs of PKS 1413+135, as done in other γ-ray emitting compact radio sources (Zhang et al. 2020; Gan et al. 2021; Gu et al. 2022).

The electron distributions in both the core and extended region are taken as a 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 $\gamma_e$ to $[\gamma_{\text{min}}, \gamma_{\text{max}}]$, 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 Lovrentz factor and viewing angle of the emitting region. The spectrum from near-infrared to optical-UV bands is serious extinction due to an edge-on intervening Seyfert 2 galaxy between PKS 1413+135 and the Earth (Stocke et al. 1992; Perlman et al. 1994), and thus we would not consider these data during the SED modeling. The Klein–Nishina effect and the absorption of high-energy γ-ray photons by extragalactic background light (EBL, Franceschini et al. 2008) are taken into account during the SED modeling.

For the extended region, the cosmic microwave background (CMB) is taken as the seed photon field of the inverse Compton (IC) process. Hence the syn+SSC+IC/CMB model under the equipartition condition ($U_B = U_e$) is taken into reproduce the emission of the extended region, where $U_B$ and $U_e$ are the energy densities of the magnetic fields and electrons. $R$ is roughly derived by the angular size of 110 mas (Readhead et al. 2021) at the radio band. The relativistic effect is not considered, i.e., $\delta = \Gamma = 1$. $p_1$ is derived by the radio spectral index ($\alpha \sim 0.66$) below several GHz and is fixed as $p_1 = 2.32$, $p_2 = 4$, $\gamma_{\text{min}} = 100$, $\gamma_{\text{max}} = 50 * \gamma_b$ are taken and fixed during the modeling as in other literature (e.g., Zhang et al. 2020). We adjust the values of $\gamma_b$ and $N_0$ to fit the radio spectrum below several GHz in the broadband SED of PKS 1413+135. And then we fix the reproduced spectrum component of the extended region during the SED modeling of the core region in both the high and low states.

For the core region, the radius of radiation region is taken as $R = \delta c \Delta t / (1 + z)$. The obvious variability is observed in both low and high states of γ-rays. $\Delta t = 1$ day and $\Delta t = 7$ days are taken for high and low states, respectively, corresponding to the minimum time bin to derive the light curve in high and low states. Since the viewing angle of jet is debated and PKS 1413+135 was also classified as a BL Lac (Bregman et al. 1981; Beichman et al. 1981) with an aligned core jet, we take $\delta = \Gamma$ during SED modeling, namely, the viewing angle ($\theta$) being equal to the opening angle ($1/\Gamma$) of jet (e.g., Chen & Zhang 2021). As shown in Figure 3(a), the second bump is very broad and should be peaked above $10^{25}$ Hz, the seed photon field with high-energy photons is needed, and thus we consider the broad line regions (BLRs) to provide the seed photons of the IC process (IC/BLR). Since only some weak emission lines are observed in PKS 1413+135 (Vedantham et al. 2017), a lower energy density of BLRs than the typical value in flat-spectrum radio
quasars (FSRQs) is used during the SED modeling, i.e., $U_{\text{BLR}} = 3 \times 10^{-3}$ erg cm$^{-3}$. $p_1$ and $p_2$ are constrained by the derived GeV spectra in the high and low states, respectively, and they are fixed as $p_1 = 2.32$ and $p_2 = 4.5$ in both states. $\gamma_{\text{min}} = 10$ is fixed since the smaller values would not fit the X-ray spectrum well. $\gamma_{\text{max}}$ is poorly constrained and taken as $10^6$. We then adjust the values of $B$, $\delta$, and $N_0$ to fit the SEDs in both high and low states.

The modeling parameters are listed in Table 3. As shown in Figure 3, the spectrum between several GHz to $\sim$100 GHz cannot be explained well since it should be the superposition of the SSA frequencies from some pc/sub-pc-scale jet components. The derived X-ray spectra with the Chandra observations are flat ($T_x \simeq 2$), which suggests a transition between the synchrotron and IC components (e.g., Ghisellini et al. 1998). This is coincident with our results. The X-rays are dominated by the SSC component of the core region, but have some contributions from the IC processes. The $\gamma$-rays are absolutely produced by the EC process of the core. The complex origins of the X-rays may cause its smaller amplitude of flux variation than that of $\gamma$-rays.

The $\gamma$-ray spectrum in Figure 3(a) is the Fermi-LAT time-resolved spectrum of MJD 59589–59591, corresponding to the time when PKS 1413+135 was announced to be detected firstly at the VHE $\gamma$-ray band by the MAGIC telescopes. We find that the predicted flux by the model at the VHE band indeed exceeds the observational threshold of the MAGIC telescopes, whether considering the EBL absorption or not. The integral flux of the model prediction over the MAGIC observational threshold is $\sim 1.5 \times 10^{-10}$ erg cm$^{-2}$ s$^{-1}$ after considering the EBL absorption. Note that no observation data above the peaks of synchrotron, SSC, and EC components in Figure 3(a), we thus use the $\gamma$-ray spectral index of the low state to constrain the slope ($p_2$) above the peaks, i.e., the $\gamma$-ray slope in Figure 3(b). $p_2 = 4.5$ indicates a very steep spectrum above the EC peak. Hence, there may be a higher observational VHE flux for PKS 1413+135 than the model prediction in Figure 3(a). However, PKS 1413+135 would not be detectable at the VHE band when its GeV emission is in the low state, as illustrated in Figure 3(b).

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 3(a), the predicted flux by the model after considering the EBL absorption is still over the threshold of the MAGIC telescopes if PKS 1413+135 is located at $z=0.5$. Therefore, whether located at $z=0.247$ or $z=0.5$, the VHE emission of PKS 1413+135 is indeed detectable for the MAGIC telescopes. And PKS 1413+135 is definitely detectable with the CTA-N.

6. DISCUSSION

PKS 1413+135 was classified as either a BL Lac or a “red quasar” on account 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 ± 3)% (Bregman et al. 1981; Stocke et al. 1992). We find that PKS 1413+135 also displays the significant flux variation in the GeV band accompanied by the obvious spectral evolution. As shown in Figure 1(a), the variation of $L_{\gamma}$ for PKS 1413+135 exceeds two orders of magnitude, indicating the typical relativistic jet effect, similar to balzars. Especially, the report of the VHE detection for 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. We plot $\Gamma_\gamma$ against $L_{\gamma}$ for the six different time-slice spectra of PKS 1413+135 in Figure 4, and the Fermi blazars are also shown in the $L_{\gamma} - \Gamma_\gamma$ plane, where the blazar data are taken from Ackermann et al. (2015). The temporal and spectral variations of PKS 1413+135 at the GeV band are remarkable. In the $L_{\gamma} - \Gamma_\gamma$ plane, PKS 1413+135 is more similar to BL Lacs and located in the BL Lac distribution region. In high-flux state, PKS 1413+135 shows the harder spectrum than those BL Lacs that have the same luminosity. On the contrary, it displays the softer spectrum in low-flux state than those BL Lacs that have the same luminosity. Generally, the broadband SEDs of BL Lacs can be reproduced with the single-zone syn+SSC model (e.g., Zhang et al. 2012; Yan et al. 2014). This model is not suitable for PKS 1413+135 since the broad second bump in its broadband SED. We thus added a EC component during the SED modeling similar to done in FSRQs and other compact radio sources (Zhang et al. 2020; Gan et al. 2021).

Different from blazars, no significant superluminal motions on pc-scale jet of PKS 1413+135 were reported. The maximum value is $1.72 \pm 0.11$ c, i.e., $110\pm\delta$ mas/yr (Lister et al. 2019), which corresponds to the component-D3 (in Figure 2 of Peirson et al. 2022) located at $\sim 7$ mas away from the core. The closest component to the core is the component-D8 located at 0.32 mas away (Peirson et al. 2022) and its separation speed apart from the core is $9.2\pm2.2$ mas/yr ($0.144\pm0.034$ c, Lister et al. 2019). We suppose that this component emerges from the core recently (see also Peirson et al. 2022). The long-term light curve of PKS 1413+135 at 14.5 GHz taken from the University of Michigan Radio Astronomical Observatory (UMRAO, Readhead et al. 2021) show three outbursts around in 1982, 1988, and
1992. Maybe the emerging of component-D8 is connected with one of the three outbursts. On account of the miniature radio morphology with two-side pc-scale structure, PKS 1413+135 was suggested to be a CSO (Perlman et al. 1996). The counter-jet of PKS 1413+135 is also a strong radio source (Perlman et al. 1996; Peirson et al. 2022), which is very rare for a blazar. The lack of the relativistic speed for the counter-jet to separate from the core is owing to the interaction between the counter-jet and the surrounding medium (Readhead et al. 2021), which may be also the reason of the bent in the counter-jet, a fairly dense nuclear medium (Perlman et al. 1996). Using the observation data of the outer component-A in the counter-jet, Perlman et al. (1996) estimated the age of PKS 1413+135 to be \( \leq 10^4 \) yr and suggested that it represents the earliest stages in a double radio source active lifespan.

As displayed in Figure 1(a), the GeV \( \gamma \)-rays of PKS 1413+135 are in a low-flux stage before MJD 58500, then undergo the obvious outbursts, and always stay in a high-flux stage after MJD 58500. We can also observe that the GeV spectral features are different for the high-flux and low-flux states, as displayed in Figure 2(a). The curvature log-parabola energy spectrum with a softer spectral index is shown in the low-flux state while the spectrum 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 for PKS 1413+135 may reflect the differently dominant acceleration mechanisms or acceleration regions of radiation electrons. In the radio band, the emission above 5 GHz is totally dominated by the core (Table 2 in Perlman et al. 1996; Figure 4 in Peirson et al. 2022). Except the core and component-D, its other jet structures show the steep spectra, which should originate from the optical thin synchrotron radiations. The inverted spectrum of the core is due to the SSA effect while the flat spectral index (\( \alpha \sim 0 \)) of the component-D may indicate a reacceleration and/or recollimation region (Perlman et al. 1996). We thus speculate that the \( \gamma \)-rays of PKS 1413+135 may have two origins; one is from the pc-scale jet components, including components D3, D4, D6, D7 and D8, which contribute the low-flux \( \gamma \)-rays in Figure 1(a) and the flat radio spectral component in Figure 3. Another is connected with the outbursts of \( \gamma \)-rays, which may be due to the ejection of a new component from the radio 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).

An explanation of the size below 1 kpc for the compact radio sources is that they are transient or episodic sources (O’Dea et al. 2021 for a review). For instance, the lack of compact, inverted spectrum hotspots and an emission gap between the bright inner jet and outer radio lobe structure indicate the episodic jet activity of the \( \gamma \)-ray emitting CSO TXS 0128+554 (Lister et al. 2020). The episodic nuclear jet activity may generate a blazar-like core jet and the symmetric radio structure for CSO CTD 135 (Gan et al. 2021). The formation of the prominent component (namely C3) at the jet tip in the \( \gamma \)-ray emitting radio galaxy 3C 84 is also due to the re-started jet activity (Nagai et al. 2016). One of the most striking evidence of episodic nuclear jet activity is that two or more pairs of distinct radio components are observed on opposite sides of the core (O’Dea et al. 2021). The episodic nuclear jet activity may exist in the center of PKS 1413+135 too. The axis of the recently re-started jet is aligned within a few degree to the line of sight and is different from the direction of the pre-existing components, similar to the typical radio galaxy 3C 84 (Nagai et al. 2016). The re-started jet may result in a new component ejected from the core, which would interact with the surrounding material (or the pre-existing components) and then accelerate particles to produce the strong radiations and variability. The jet outer components and counter-jet of PKS 1413+135, which are far away from the core, such as the components A, F and G (Perlman et al. 1996), may be the remnants of nuclear jet activity long-ago. The recent \( \gamma \)-ray outbursts of PKS 1413+135 may be connected with the re-started nuclear jet activity. And the ejected new component would be resolved out with the VLBI observations in the future.

7. SUMMARY

The miniature radio morphology with two-side pc-scale structure makes PKS 1413+135 to be classified as a CSO. Interestingly, it has been detected with the MAGIC telescopes and would be the first CSO detected at the VHE band. In this paper, we comprehensively analyzed the 13.5-year Fermi-LAT observation data of PKS 1413+135, together with its archive X-ray data observed with Swift-XRT, Chandra, and XMM-Newton, to investigate its high energy radiation properties. No significantly temporal and spectral variation trend is observed in the X-ray band. The significant variabilities are presented in the long-term GeV \( \gamma \)-ray light curve with a confidence level far beyond 5\( \sigma \). And the whole \( \gamma \)-ray light curve shows two distinct stages, a low-flux stage before MJD 58500 and a high-flux stage with violent outbursts after MJD 58500. The clearly spectral variations accompanying the \( \gamma \)-ray flux variations are observed, namely, the curvature log-parabola energy spectrum with a softer spectral index in the low-flux state and the power-law spectrum with a harder spectral index in the \( \gamma \)-ray outbursts, indicating a “harder when brighter” behavior at the GeV band. The highest energy of the detected photons by the Fermi-LAT is \( \sim 236 \) GeV, which is detectable...
with the MAGIC telescopes. Attributing the broadband SEDs of PKS 1413+135 to the radiations from the core and extended region, we showed that the SED can be represented by a two-zone leptonic model. Its $\gamma$-rays are contributed by the core region. The model predicted flux at the VHE band would be detectable by the MAGIC telescopes when PKS 1413+135 is in a high-flux state at the GeV band, whether it is located at $z = 0.247$ or $z = 0.5$. Considering the features of the temporal and spectral variations at the GeV band together with observations in other bands, we proposed that the $\gamma$-ray flares of PKS 1413+135 may be connected with the recently re-started nuclear jet activity and are produced in an aligned core-jet component, while other pc-scale jet components, which may be produced by the previous nuclear jet activities, contribute the low $\gamma$-ray emission. This scenario can be checked by the future VLBI observations.

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Figure 1. Light curves of PKS 1413+135 in X-ray and γ-ray bands. Panel-(a): the ∼13.5-year γ-ray light curve derived with an adaptive-binning method based on a criterion of TS ≥ 9 for each time-bin, where the minimum time-bin step is 7 days. The horizontal blue solid line indicates the 13.5-year average luminosity of $4.13 \times 10^{45}$ erg s$^{-1}$. The horizontal green short-dashed line is the observational threshold of the Fermi-LAT, which is obtained and derived from the link of https://www.slac.stanford.edu/exp/glast/groups/canda/lat_Performance.htm. Panel-(b): the γ-ray light curve after MJD 58500 obtained also with the adaptive-binning method and the criterion of TS ≥ 9 for each time-bin, where the minimum time-bin step is one day. The horizontal red dashed line indicates the average luminosity of $1.41 \times 10^{46}$ erg s$^{-1}$ while the horizontal blue solid line is the same as in Panel-(a). Panel-(c): the X-ray light curve obtained by the observations of Swift-XRT (black squares), Chandra (red circles), and XMM-Newton (blue stars), where the horizontal red dashed line represents the average flux of all the data points.
together with the time-integrated spectra before (MJD 5468–58500, cyan symbols) and after (MJD 58500–59660, orange symbols) MJD 58500, the time-resolved spectra of MJD 58724–58726 (green symbols), MJD 58796–58798 (blue symbols), and MJD 59589–59591 (red symbols). The corresponding colored solid lines represent the fitting results. The observational thresholds of the MAGIC (pink dotted-dashed line, 72 hr) telescopes and CTA-N (blue dotted-dashed line, 50 hr) are also given in the figure. Panel-(b): $\Gamma_X$ against $F_{2-10keV}$, where $\Gamma_X$ and $F_{2-10keV}$ are the photon spectral index and flux in the $2–10$ keV band. They are obtained with the observations of Chandra (red circles) and XMM-Newton (blue stars).

Figure 3. Observed SEDs with model fitting for PKS 1413+135 in the high (Panel-(a)) and low (Panel-(b)) $\gamma$-ray states. The $\gamma$-ray spectra are the time-resolved spectrum during MJD 59589–59591 (Panel-(a)) and the time-integrated spectrum before MJD 58500 (Panel-(b)) in the whole light curve. The X-ray data are obtained with the Chandra observations on December 20 2019 (in Panel-(b)) and February 03 2020 (Panel-(a)) when the $\gamma$-rays of PKS 1413+135 are in the low and high states, respectively. Other data are taken from the NED. The green stars represent the fluxes of the radio core. The black solid lines are the sum of each component emission for the source located at $z=0.247$: synchrotron radiation (red lines), SSC process (magenta lines), and EC process (cyan lines), where the solid lines and dashed lines respectively represent the radiation from the core and extended region. The cyan lines at the VHE band indicate the intrinsic flux of the source without considering the EBL absorption. The short dashed gray line in the Panel-(a) represents the fitting result when the source is located at $z=0.5$. The observational thresholds of the MAGIC (pink dotted-dashed lines, 72 hr) telescopes and CTA-N (blue dotted-dashed line, 50 hr) are also presented. The orange and purple solid lines indicate the fitting results for the spectrum from 80 MHz to 2.7 GHz and from 4.8 GHz to 375 GHz with the power-law function of $F_{\nu} \propto \nu^{-\alpha}$, and $\alpha \sim 0.66$ and $\alpha \sim 0.09$ are obtained, respectively.
Figure 4. $\Gamma_\gamma$ as a function of $L_\gamma$ for PKS 1413+135 in the selected time slices as shown in Figure 2(a) in comparison with samples of blazars taken from Ackermann et al. (2015).
Table 1. *Fermi*-LAT Analysis Results for PKS 1413+135

| Obs-date      | Model$^a$ | $\Gamma_\gamma$ | $\beta$ | $F_\gamma$ (erg cm$^{-2}$ s$^{-1}$) | $L_\gamma$ (erg s$^{-1}$) | TS | $E_{\text{max}}$ (GeV) | Det-time$^b$ (MJD) |
|--------------|-----------|----------------|--------|-----------------------------------|---------------------------|----|-----------------|-----------------|
| 54682–59660  | LP        | 2.02 ± 0.03    | 0.03 ± 0.01 | (2.28 ± 0.13) $\times 10^{-11}$ | (4.13 ± 0.23) $\times 10^{45}$ | 355 | 235.9          | 58798           |
| 54682–58500  | LP        | 2.34 ± 0.08    | 0.08 ± 0.05 | (5.74 ± 0.61) $\times 10^{-12}$ | (1.04 ± 0.11) $\times 10^{45}$ | 300 | 20.6           | 57959           |
| 58500–59660  | LP        | 1.90 ± 0.03    | 0.04 ± 0.01 | (7.74 ± 0.48) $\times 10^{-11}$ | (1.41 ± 0.09) $\times 10^{46}$ | 4704 | 235.9         | 58798           |
| 58724–58726  | PL        | 1.75 ± 0.11    | 0.00 (fixed) | (1.07 ± 0.39) $\times 10^{-09}$ | (1.94 ± 0.71) $\times 10^{47}$ | 200 | 55.7           | 58726           |
| 58796–58798  | PL        | 1.63 ± 0.14    | 0.00 (fixed) | (8.59 ± 4.02) $\times 10^{-10}$ | (1.56 ± 0.73) $\times 10^{47}$ | 102 | 235.9         | 58798           |
| 59589–59591  | PL        | 1.73 ± 0.13    | 0.00 (fixed) | (7.95 ± 3.43) $\times 10^{-10}$ | (1.44 ± 0.62) $\times 10^{47}$ | 137 | 25.7           | 59590           |

$^a$“LP” and “PL” represent the spectra are fitted by the Log-Parabola (LP) and Power-Law (PL) functions, respectively.

$^b$The detected time of the maximum energy photon by the *Fermi*-LAT.

Table 2. Public X-ray observations of PKS 1413+135

| Obs-date      | Mission    | Exp. (s) |
|--------------|------------|----------|
| (1)          | (2)        | (3)      |
| 2007-03-20   | Chandra    | 20180    |
| 2019-12-20   | Chandra    | 4060     |
| 2019-12-29   | XMM-Newton | 13000    |
| 2020-02-03   | Chandra    | 4060     |
| 2020-02-05   | XMM-Newton | 17000    |
| 2020-03-22   | Chandra    | 4060     |
| 2020-05-04   | Chandra    | 4060     |
| 2020-06-18   | Chandra    | 4060     |
| 2020-07-04   | XMM-Newton | 15000    |
| 2007 to 2022 | Swift      | $10^2$ to $10^4$ |
Table 3. SED Fitting Parameters of PKS 1413+135

| State | R (cm) | B (G) | δ | Γ | γ_{min} | γ_{max} | N_0 (cm^{-3}) | p_1 | p_2 | R (cm) | B (G) | γ_{min} | γ_{max} | N_0 (cm^{-3}) | p_1 | p_2 |
|-------|--------|-------|---|---|--------|--------|---------------|----|----|--------|-------|--------|--------|---------------|----|----|
| H     | 2.7E16 | 1.1   | 13| 10| 3070   | 1E6    | 12811         | 2.32| 4.5| 110    | 475   | 100    | 1E4    | 5E5          | 0.019| 2.32| 4 |
| L     | 7.6E16 | 2.6   | 5.2| 10| 999    | 1E6    | 4204          | 2.32| 4.5| 110    | 475   | 100    | 1E4    | 5E5          | 0.019| 2.32| 4 |

a “H” and “L” represent the SEDs in Figure 3(a) and Figure 3(b), respectively.
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