

## Lobe-dominated $\gamma$ -Ray Emission of Compact Symmetric Objects Postprint

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### Abstract

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### Full Text

### Preamble

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## Lobe-dominated $\gamma$ -Ray Emission of Compact Symmetric Objects

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### Abstract

The  $\gamma$ -ray emitting compact symmetric objects (CSOs) PKS 1718-649, NGC 3894, and TXS 0128+554 are lobe-dominated in the radio emission. In order to investigate their  $\gamma$ -ray radiation properties, we analyze the 14 yr Fermi/LAT observation data of the three CSOs. They all show low luminosity ( $10^{41}$ - $10^{43}$  erg s<sup>-1</sup>) and no significant variability in the  $\gamma$ -ray band. Their  $\gamma$ -ray average spectra can be well fitted by a power-law function. These properties are clearly different from the  $\gamma$ -ray emitting CSOs CTD 135 and PKS 1413+135, for which the  $\gamma$ -rays are produced by a restarted aligned jet. In the  $L\gamma - \Gamma\gamma$  plane, the three CSOs are also located in the region occupied by radio galaxies (RGs) while CTD 135 and PKS 1413+135 display features similar to blazars. Together with a similar radio emission property to  $\gamma$ -ray emitting RGs Cen A and Fornax A, we speculate that the  $\gamma$ -rays of the three CSOs stem from their extended mini-lobes. The broadband spectral energy distributions of the three CSOs can be well explained by the two-zone leptonic model, where their  $\gamma$ -rays are produced by the inverse Compton process of relativistic electrons in extended regions. By extrapolating the observed Fermi/LAT spectra to the very high energy band, we find that TXS 0128+554 among the three CSOs may be detected by the Cherenkov Telescope Array in the future.

**Key words:** 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 distinguished by a symmetric and compact radio structure with a projected size of less than one kiloparsec (kpc). Their symmetric radio structure is thought to be due to a misaligned jet with no or weak relativistic effects (Phillips & Mutel 1980; Wilkinson et al. 1994; Readhead et al. 1996). Thus CSOs appear as mini-versions of off-axis observed radio galaxies (RGs). However, some CSOs show obvious flux variation in the radio band, and even significant variability and high luminosity in the  $\gamma$ -ray band, indicating the strong Doppler boosting effect of a relativistic jet (Gan et al. 2021, 2022). Recently, Kiehlmann et al. (2023) reported that in addition to the compact symmetric structure, no significant flux

variation and superluminal motion should be taken as criteria for CSO selection, meaning no relativistic effect.

It is well known that blazars are the main extragalactic  $\gamma$ -ray emitters since a relativistic jet dominates their multi-band radiation, and their  $\gamma$ -rays originate from an aligned pc/sub-pc jet. Generally, it is believed that the  $\gamma$ -rays of RGs are also generated from their pc/sub-pc jets (e.g., Abramowski et al. 2012; Aliu et al. 2012; Grandi et al. 2012; Casadio et al. 2015; Tanaka et al. 2015; Xue et al. 2017). Nevertheless, the detections of  $\gamma$ -rays from the large-scale lobes of RGs Cen A and Fornax A by Fermi/LAT indicate the existence of high-energy particles in these extended regions (Abdo et al. 2010; Ackermann et al. 2016). Until now, five CSOs have been detected in the  $\gamma$ -ray band: 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; Gan et al. 2022). The high luminosity and remarkable variability of CTD 135 and PKS 1413+135 observed by Fermi/LAT, similar to blazars, demonstrate that their  $\gamma$ -rays are dominated by radiation from a recently restarted aligned core-jet (Gan et al. 2021, 2022). Theoretically, the mini-lobes of CSOs can also produce strong  $\gamma$ -ray emission via inverse-Compton (IC) processes (Stawarz et al. 2008; Migliori et al. 2014), thermal bremsstrahlung radiation (Kino et al. 2007, 2009), or even hadronic processes (Kino & Asano 2011), similar to the large-scale lobes of Cen A and Fornax A (Abdo et al. 2010; McKinley et al. 2015).

The core-dominance parameter, defined as the luminosity ratio (RCE) of the core to extended regions where  $RCE > 1$  indicates core-dominated and  $RCE < 1$  indicates lobe-dominated, is often used as an indicator of the beaming effect (e.g., Urry & Padovani 1995). We note that Cen A and Fornax A have low RCE values at the radio band compared with other  $\gamma$ -ray emitting RGs. The RCE values at 8 GHz are 0.48, 0.36, and 0.71 for PKS 1718-649, NGC 3894, and TXS 0128+554, respectively. Especially for PKS 1718-649, no clear radio core is resolved (Angioni et al. 2019), resembling a mini-version of Fornax A (which has a very weak radio core; McKinley et al. 2015). In contrast, RCE is 1 for CTD 135 and 1.42 for PKS 1413+135. This seems coincident with the fact that PKS 1413+135 and CTD 135 have been reclassified as blazars rather than CSOs (Readhead et al. 2021; Frey et al. 2022). Different from CTD 135 and PKS 1413+135, PKS 1718-649, NGC 3894, and TXS 0128+554 definitely satisfy the CSO criteria required by Kiehlmann et al. (2023). In this paper, we intend to explore the  $\gamma$ -ray radiation properties of these three lobe-dominated CSOs by comprehensively analyzing their Fermi/LAT observation data. Throughout this paper, we adopt  $H_0 = 71 \text{ km s}^{-1} \text{ Mpc}^{-1}$ ,  $\Omega = 0.27$ , and  $\Omega\Lambda = 0.73$ .

## 2. Lobe-dominated gamma-ray Emitting CSOs

### PKS 1718-649

PKS 1718-649, also named NGC 6328, is located in a compact gas environment with a redshift of  $z = 0.014$  (Fosbury et al. 1977). It is also classified as a GHz-peak spectrum (GPS) source due to a turnover frequency of 3 GHz in its radio spectrum (Tingay et al. 1997). Its morphology at multiple radio bands is characterized by two sub-structures from southeast to northwest (Tingay et al. 1997, 2002), and the total projected size at 8.4 GHz and 22.3 GHz is only 2.5 pc (Angioni et al. 2019). No clear radio core is resolved in multiwavelength observations. However, the spectral index map from 8.4 to 22.3 GHz (Figure 6 in Angioni et al. 2019) reveals that the region between the two sub-structures displays a highly inverted spectrum and may correspond to the core, which cannot be observed at these radio frequencies due to synchrotron-self-absorption (Angioni et al. 2019). The estimated kinematic age is  $70 \pm 30$  yr via the apparent separation speed of  $0.13 \pm 0.06c$  between the two mini-lobes (Angioni et al. 2019; see also Giroletti & Polatidis 2009).

### NGC 3894

NGC 3894 is located in an elliptical galaxy with a redshift of  $z = 0.01075$  (Bilicki et al. 2014). Its radio spectrum peaks at a frequency near 5 GHz (Taylor et al. 1998). The high-resolution Very Long Baseline Array (VLBA) image at 1.4 GHz shows its radio core, two-sided jets, and a southeast radio lobe with a total linear size of 50 mas (Peck & Taylor 1998). Very Long Baseline Interferometry (VLBI) observations at 5 GHz covering 15 yr demonstrate that the two-sided pc-scale jets emerge from the radio core with a mildly relativistic speed of  $0.3c$  (Taylor et al. 1998). Principe et al. (2020) reported that its two-sided jets expand to the southeast and northwest directions with an apparent separation velocity of  $0.202 \pm 0.005c$  between 1995 and 2017, and then estimated its kinematic age to be  $59 \pm 5$  yr.

### TXS 0128+554

TXS 0128+554 is hosted in an elliptical galaxy with a redshift of  $z = 0.0365$  (Huchra et al. 2012). The turnover frequency of its radio spectrum is less than 1 GHz (Lister et al. 2020). Its pc-scale radio structure consists of an unresolved bright core and east-west side cambered lobes, and the overall projected extent of its lobes is similar in multiple-radio-frequency images (Lister et al. 2020). With observations at 2.3 GHz and 5 GHz, faint steep-spectrum emission is revealed for regions at 8.8 pc (eastern lobe) and 7.8 pc (western lobe) from the core (Lister et al. 2020). Lister et al. (2020) reported an apparent advance speed of  $0.32 \pm 0.07c$  for its radio sub-structure and estimated its kinematic age as  $82 \pm 17$  yr under the assumption of constant advance speed in the western lobe.

### 3. Data Analysis and Results

#### 3.1. Data Analysis

We use the public software `fermitools` (ver. 2.0.8, Fermi Science Support Development Team 2019) with the binned likelihood analysis method to analyze the Fermi/LAT Pass 8 data of the three CSOs. The data covering from 2008 August 4 to 2022 May 1 (MJD 54682–59700) are extracted from the Fermi Science Support Center. We set the region of interest as a circle of radius  $15^\circ$  centered on the radio/optical positions of the three CSOs. Photon events in the energy range of 0.1–300 GeV are considered. We filter background  $\gamma$ -ray contamination from the Earth limb by setting the maximum zenith angle to  $90^\circ$ . Good quality photon events are selected using the standard data quality selection criterion “(DATA\_{QUAL}>0)&&(LAT\_{CONFIG}==1)”. The data are binned with a pixel size of  $0.2^\circ$  and 25 logarithmic energy bins. The instrument response function `P8R3_{SOURCE}_{V3}` is used in the data analysis.

The Fermi/LAT 12 yr Source Catalog (4FGL-DR3, Abdollahi et al. 2022), the diffuse Galactic interstellar emission (`gll_{iem}{v07}.fits`), and the isotropic emission (`iso_{P8R3}_{SOURCE}_{V3}_{v1}.txt`) are included as background models. In the data analysis, we use the maximum test statistic (TS) to quantify the significance of  $\gamma$ -ray detection. TS is the logarithmic ratio of the likelihood of a model with the point source to that of a model without the point source, i.e.,  $TS = 2 \log(L/L_0)$  (Mattox et al. 1996). A threshold of  $TS > 25$  is adopted to recognize a point source from the background. By subtracting all background models, we first generate  $3^\circ \times 3^\circ$  residual TS maps to investigate whether there are new  $\gamma$ -ray sources not included in 4FGL-DR3. No excess  $\gamma$ -ray signal with  $TS > 25$  is found in the residual TS maps, indicating that no new additional  $\gamma$ -ray source is detected. We then produce  $2^\circ \times 2^\circ$  TS maps of the three 4FGL point sources: 4FGL J1724.2–6501, 4FGL J1149.0+5924, and 4FGL J0131.2+5547. Using the `gtfindsrc` tool, we also obtain the best-fit positions of the three 4FGL point sources, as shown in Figure 1 [Figure 1: see original paper]. Information on the three CSOs and the three associated 4FGL point sources is also given in Table 1.

During spectral analysis, the normalization of isotropic emission and diffuse Galactic interstellar emission, and the spectral parameters of  $\gamma$ -ray sources listed in 4FGL-DR3 within  $8^\circ$ , remain free, while other parameters are kept fixed. A spectrum should be significantly curved if  $TS_{\text{scurv}} > 9$  (corresponding to a  $3\sigma$  confidence level, Abdollahi et al. 2022), where  $TS_{\text{scurv}} = 2(\log L_{\text{LP}} - \log L_{\text{PL}})$  and  $L_{\text{LP}}$  and  $L_{\text{PL}}$  are the hypothesis likelihoods of Log-Parabola and power-law models, respectively. The  $TS_{\text{scurv}}$  values of the three CSOs are much less than 9; therefore, the power-law spectral model is adopted to fit their photon spectra in our analysis. The average spectra of the three CSOs with power-law fits are presented in Figure 2 [Figure 2: see original paper], and the derived parameters are listed in Table 1. We also generate their long-term light curves with power-law spectral fits, adopting an equal time interval of 180

days, as displayed in Figure 2.

We also calculate the corresponding variability index TSvar, a common method to estimate  $\gamma$ -ray variability (Abdollahi et al. 2022). The definition of TSvar is  $TSvar = 2 \sum [\log L(F_i) - \log L(F_{glob})]$ , where  $F_i$  is the fitting flux for bin  $i$ ,  $L$  is the likelihood corresponding to bin  $i$ ,  $F_{glob}$  is the best-fit flux for the global time assuming a constant flux, and  $N$  is the number of time bins. We keep only the normalization of the target source free to vary and fix other parameters to the best-fit values during calculations.  $TSvar = 53.0$  corresponds to a  $3\sigma$  confidence level in the TSvar distribution with  $N - 1 = 26$  degrees of freedom, where  $N = 27$  is the number of time bins. The  $\gamma$ -ray emission of a source is probably variable when  $TSvar > 53.0$ . The obtained TSvar values are listed in Table 1, and the corresponding confidence levels of variability are also given.

### 3.2. Analysis Results

**PKS 1718-649.** By analyzing the 14 yr Fermi/LAT observation data, a  $\gamma$ -ray detection with  $TS = 37$  is yielded for PKS 1718-649. As shown in Figure 1, the radio position of PKS 1718-649 falls within the 68% error circle of the best-fit position of 4FGL J1724.2-6501. Our result is coincident with the previous report that PKS 1718-649 is spatially associated with the  $\gamma$ -ray point source 3FGL J1728.0-6446 (Migliori et al. 2016), where 3FGL J1728.0-6446 is associated with 4FGL J1724.2-6501 in 4FGL-DR3 (Abdollahi et al. 2022). PKS 1718-649 has a steep spectrum at the GeV band with a photon index of  $\Gamma_\gamma = 2.49 \pm 0.16$ . Its 14 yr average spectral luminosity at the GeV band is  $(1.02 \pm 0.19) \times 10^{42}$  erg  $s^{-1}$ . No obvious variability is observed with  $TSvar = 35.6$ ; only four detection points are presented in the whole light curve, and three detection points are obtained with the first 7 yr observations. Using the 7 yr data set, Migliori et al. (2016) found the  $\gamma$ -ray signal of PKS 1718-649 with the same TS value ( $TS = 36$ ) as ours.

**NGC 3894.** A significant  $\gamma$ -ray signal with  $TS = 96.4$  is detected around NGC 3894. The radio position of NGC 3894 is located within the 68% containment of the best-fit position of 4FGL J1149.0+5924, as displayed in Figure 1. Its spectrum at the GeV band is flatter than that of PKS 1718-649, i.e.,  $\Gamma_\gamma = 2.16 \pm 0.11$ , which is slightly steeper than the derived value of  $\Gamma_\gamma = 2.01 \pm 0.10$  with the 10.8 yr observation data in Principe et al. (2020). NGC 3894 has the lowest  $\gamma$ -ray luminosity among the three CSOs, being  $(6.18 \pm 0.89) \times 10^{41}$  erg  $s^{-1}$ . The confidence level of flux variation is less than  $2\sigma$ , also indicating no variability in its  $\gamma$ -ray emission.

**TXS 0128+554.** The analysis with the 14 yr Fermi/LAT observation data yields a significant  $\gamma$ -ray detection with  $TS = 146.5$  for TXS 0128+554. It has the highest  $\gamma$ -ray luminosity of  $(1.62 \pm 0.17) \times 10^{43}$  erg  $s^{-1}$  and the flattest spectrum with  $\Gamma_\gamma = 2.11 \pm 0.08$  among the three CSOs. Same as PKS 1718-649 and NGC 3894, no significant flux variation of  $\gamma$ -rays above the  $2\sigma$  confidence level is observed for TXS 0128+554.

Note that Principe et al. (2021) investigated the  $\gamma$ -ray emission of some young radio sources by analyzing 11 yr Fermi/LAT data. They reported  $TS = 36$  and  $\Gamma_\gamma = 2.60 \pm 0.14$  for PKS 1718-649,  $TS = 95$  and  $\Gamma_\gamma = 2.05 \pm 0.09$  for NGC 3894,  $TS = 178$  and  $\Gamma_\gamma = 2.20 \pm 0.07$  for TXS 0128+554, and found no evidence of significant  $\gamma$ -ray variability for the three CSOs. These results are consistent with our analysis.

### 3.3. The $L_\gamma - \Gamma_\gamma$ Plane

As described above, the  $\gamma$ -ray average spectra of the three CSOs can be well fitted with a power-law function, none displays significant flux variation in the GeV band, and all show low  $\gamma$ -ray luminosity. These are dramatically different from the  $\gamma$ -ray emitting CSOs CTD 135 and PKS 1413+135, both of which show Log-parabola spectra, violent variability, and high luminosity in the GeV band, similar to blazars (Gan et al. 2021, 2022). The diversity of  $\gamma$ -ray emitting CSOs is also displayed in the  $L_\gamma - \Gamma_\gamma$  plane, where  $L_\gamma$  is the  $\gamma$ -ray luminosity in the GeV band, and the data of blazars and RGs are taken from 4FGL-DR3 (Abdollahi et al. 2022). As illustrated in Figure 3 [Figure 3: see original paper], blazars together with CTD 135 and PKS 1413+135 occupy the high-luminosity area of the figure while RGs and the three CSOs studied in this work are located in the low-luminosity region.

It is widely known that blazars demonstrate frequent and violent variabilities, especially in the  $\gamma$ -ray band, favoring a compact emission region with significant Doppler boosting effect. Similarly, the high-luminosity  $\gamma$ -ray emission of CTD 135 and PKS 1413+135 is due to episodic nuclear jet activities and is generated from a newborn aligned core-jet (Gan et al. 2021, 2022). In contrast, RGs normally have low luminosity and weak variability, and are thought to be the parent populations of blazars with large viewing angles and small Doppler factors (Urry & Padovani 1995). Accordingly, it remains an open question whether the  $\gamma$ -rays of RGs originate from the jet with a large inclination angle or from large-scale jet extended regions. In the LAT band, Fornax A shows no significant variability while Cen A only displays some flux variation at a  $3.5\sigma$  confidence level in the low-energy band (Brown et al. 2017; Abdollahi et al. 2022). In particular, Fermi/LAT observations definitively demonstrate that the  $\gamma$ -rays from the large-scale lobes of Cen A and Fornax A account for more than 50% and 86% of the total  $\gamma$ -ray flux, respectively (Abdo et al. 2010; Ackermann et al. 2016). Thereby, the  $\gamma$ -rays of Cen A and Fornax A are lobe-dominated. Recently, the  $\gamma$ -ray emission from FR II RG IGR J18249-3243 was also found to be lobe-dominated (Bruni et al. 2022). In view of no obvious  $\gamma$ -ray variability and the lobe-dominated radio emission for TXS 0128+554, PKS 1718-649, and NGC 3894, similar to these RGs, we speculate that their  $\gamma$ -rays stem from the extended mini-lobes.

## 4. Discussion

### 4.1. Broadband SED Modeling and $\gamma$ -ray Origin

In order to further explore the  $\gamma$ -ray emission properties of the three CSOs, we collect low-energy band data from literature and the NASA/IPAC Extragalactic Database (NED) as well as the ASI Science Data Center (ASDC) and construct their broadband spectral energy distributions (SEDs), as displayed in Figure 4 [Figure 4: see original paper]. A detailed description of the data is provided in the caption of Figure 4. Considering the similar radiation properties of the three CSOs to RGs Cen A and Fornax A, the lobe-dominated emission in the radio band, and no significant variability in the GeV band, we infer that the  $\gamma$ -rays of the three CSOs are also dominated by the extended region. Due to the broad second bump in the broadband SEDs of the three CSOs, we represent their SEDs with the two-zone leptonic model, similar to that used in other  $\gamma$ -ray emitting compact radio sources (e.g., Zhang et al. 2020; Gan et al. 2021, 2022; Gu et al. 2022). The synchrotron (syn), synchrotron-self-Compton (SSC), and external Compton (EC) scattering of relativistic electrons in both the core and extended regions are considered. The synchrotron-self-absorption (SSA) effect at low energies, the Klein-Nishina effect at high energies, and the absorption of high-energy  $\gamma$ -ray photons by extragalactic background light (EBL; Franceschini et al. 2008) are also taken into account during SED modeling.

The electron distributions in both the core and extended regions are assumed to be broken power-laws, characterized by a density parameter  $N_0$ , a break energy  $\gamma_b$ , and indices  $p_1$  and  $p_2$  in the energy range  $[\gamma\{min\}, \gamma\{max\}]$ . The radiation region is assumed to be a sphere with radius  $R$ , magnetic field  $B$ , and Doppler factor  $\delta$ . Since mildly relativistic motions have been observed and reported for NGC 3894 (Principe et al. 2020) and TXS 0128+554 (Lister et al. 2020), we take their relativistic effects into account for both the core and extended regions:  $\delta = 1.3$  and  $\Gamma = 1.04$  for NGC 3894 (Principe et al. 2020), and  $\delta = 1.2$  and  $\Gamma = 1.06$  for TXS 0128+554 (corresponding to a viewing angle of  $\theta = 52^\circ$ ; Lister et al. 2020), where  $\Gamma$  is the bulk Lorentz factor. The jet is accelerated and collimated reaching up to sub-pc/pc scale (see Boccardi et al. 2017 for a review). After the acceleration phase, the jet assumes a conical shape and initiates deceleration as a logarithmic function of distance ( $r$ ) from the black hole (see Potter & Cotter 2013; Wang et al. 2022). We assume the same value of  $\Gamma$  for both the core and extended regions because the total projected size of NGC 3894 and TXS 0128+554 is less than 20 pc. Assuming the same advance speed for the two-sided mini-lobes, an apparent advance velocity of only  $0.06c$  is observed for PKS 1718-649 (Angioni et al. 2019); we thus take  $\Gamma = \delta = 1$  for both the core and extended regions during SED modeling.

For the core region, we take  $R = \delta c \Delta t / (1 + z)$  and  $\Delta t = 180$  days. Due to the absence of apparent variability in the  $\gamma$ -ray light curves, the time-bin value of the light curves is adopted, similar to other compact radio sources emitting  $\gamma$ -rays (Zhang et al. 2020). In this case,  $R > 0.1$  pc, the energy dissipation region

should be located at  $10 \times R$  from the black hole and outside of the broad-line regions, and the photon field of the torus provides the dominant seed photons for the EC process (see Ghisellini & Tavecchio 2009). The overall projected size is less than 20 pc. The seed photon field of the EC process is still dominated by photons from the torus within this scale (Ghisellini & Tavecchio 2009; see also Stawarz et al. 2008). We thus only consider the external photon field of the torus to calculate the EC process for both the core and extended regions. The typical energy density of the torus photon field,  $U_{\text{IR}} = 3 \times 10^{-4} \text{ erg cm}^{-3}$  (Cleary et al. 2007; Kang et al. 2014), is taken for the core region, whereas the values of  $U_{\text{IR}}$  for the extended regions are estimated according to Equation (21) in Stawarz et al. (2008) and are given in Table 4.

For the core region,  $\gamma_{\text{min}}$  is set to  $1.0 \times 10^4$ .  $p_1$  is roughly estimated by the spectral index of the X-ray observation data while  $p_2 = 4$  is fixed.  $\gamma_b$ ,  $N_0$ , and  $B$  are free parameters. For the extended region,  $R$  is equal to the total projected size of the radio morphology, as listed in Table 2.  $\gamma_{\text{min}}$  is taken as 300 or 500 to match the observation data at the radio band and  $\gamma_{\text{max}}$  is set as  $2.5 \times 10^6$  (roughly constrained by the last upper-limit data point in the Fermi/LAT spectrum).  $p_1$  and  $p_2$  are constrained by the radio and  $\gamma$ -ray spectral indices, respectively.  $\gamma_b$ ,  $N_0$ , and  $B$  are also free parameters. As shown in Figure 4, observational data at the near-IR-optical band are dominated by starlight from the host galaxy. The data of the soft X-ray band (0.5–1.5 keV) for NGC 3894 are not corrected for absorption (Balasubramaniam et al. 2021). We thus do not take these data into account during SED modeling. Due to limited observational data, we cannot constrain the fitting parameters precisely, and we only obtain a set of model parameters that provide an acceptable fit. We also plot a cartoon illustration of the radiation model, as depicted in Figure 5 [Figure 5: see original paper].

The fitting results are presented in Figure 4 and the modeling parameters are given in Table 2. The broadband SEDs of the three CSOs can be well explained by the two-zone leptonic radiation model. Under this scenario, the  $\gamma$ -rays are produced by the IC process of relativistic electrons in the extended region and the X-rays are dominated by radiation from the core region. As listed in Table 2, the derived  $B$  values of core regions are higher than those of extended regions while  $\gamma_b$  of the core is smaller than that of the extended region. We find that the magnetic field strengths between the core region ( $B_1$ ) and the extended region ( $B_2$ ) for the three CSOs basically satisfy the relation  $B_1/B_2 = r_2/r_1$ , where  $r_1$  and  $r_2$  are the distances from the core and extended regions to the black hole, respectively. This result is consistent with VLBA observations of some AGN jets (O’ Sullivan & Gabuzda 2009). The derived  $B$  values of extended regions are several mG, in agreement with typical values measured in CSOs (Oriente et al. 2006; Lister et al. 2020). As listed in Table 2,  $\gamma_{\text{max}} > 10^6$  is required to account for the  $\gamma$ -ray emission originating from these extended regions of CSOs. The detection of GeV  $\gamma$ -rays in the large-scale lobes of RGs Cen A and Fornax A (Abdo et al. 2010; Ackermann et al. 2016) provides compelling evidence for the acceleration of ultrarelativistic electrons in the extended regions of AGN jets,

particularly highlighted by the very high-energy detection along the jet of Cen A (H.E.S.S. Collaboration et al. 2020). The leptonic radiation model employed to explain the observed  $\gamma$ -ray flux from these extended regions of AGN jets requires electron Lorentz factors on the order of  $10^6$  (Persic & Rephaeli 2019), or even higher ( $10^7$ – $10^8$ ; H.E.S.S. Collaboration et al. 2020).

It should be noted that we used a phenomenological electron spectrum—a broken power-law spectrum—to model the SEDs here. Although a power-law electron spectrum with an exponential cutoff would be more naturally motivated by particle acceleration theory, a broken power-law electron spectrum can better represent the symmetric peaks in the observed SEDs (e.g., Aharonian et al. 2009; Ghisellini & Tavecchio 2009; Chen et al. 2012; Zhang et al. 2012; Aleksić et al. 2014). It is unclear whether the electron distribution has a low-energy cutoff with  $\gamma_{\min} > 1$  in theory; generally,  $\gamma_{\min} = 1$  is fixed (e.g., Ghisellini & Tavecchio 2009; Zhang et al. 2012). Sometimes  $\gamma_{\min}$  can be roughly constrained with X-ray data (e.g., Tavecchio et al. 2000; Zhang et al. 2014), or a low-energy cutoff in the electron spectrum is required to explain the radio spectra of some large-scale jet substructures, with  $\gamma_{\min}$  being several hundreds (Harris et al. 2000; Hardcastle et al. 2001; Lazio et al. 2006; Godfrey et al. 2009). During SED modeling,  $\gamma_{\max}$  is normally constrained by the last observation point in the  $\gamma$ -ray band. The theoretical upper limit of the maximum electron energy can be determined by  $t_{\text{acc}} = \min(t_{\text{esc}}, t_{\text{cool}})$ , where  $t_{\text{acc}}$ ,  $t_{\text{esc}}$ , and  $t_{\text{cool}}$  are the timescales of acceleration, escape, and cooling, respectively. We estimated the three theoretical timescales using equations from Wang et al. (2022) and found that the derived values of  $\gamma_{\max}$  from SED modeling are much smaller than the theoretical upper limit. In addition,  $\gamma_b$  derived from SED modeling is not exactly the same as the cooling break since  $\gamma_b$  results from complex physical processes including adiabatic losses, particle escape, and cooling (e.g., Ghisellini & Tavecchio 2009).

The energy densities of non-thermal electrons ( $U_e$ ) and magnetic fields ( $U_B$ ) of extended regions are also listed in Table 4. The ratio  $U_e/U_B$  for the three CSOs is close to that of the lobes in Cen A and Fornax A, which are also derived by SED modeling (Persic & Rephaeli 2019), and is also in agreement with values in the radio lobes of some RGs obtained by X-ray measurements (e.g., Croston et al. 2005; Kataoka & Stawarz 2005; Isobe et al. 2011).

Based on the SED fitting parameters, we estimate the jet powers ( $P_{e\pm}$ ) of the core and extended regions in the case of electron-positron pair jets. The powers of non-thermal electrons ( $P_e$ ) and magnetic fields ( $P_B$ ) are calculated with  $P_i = \pi R^2 \Gamma^2 c U_i$ , where  $U_i$  can be  $U_e$  or  $U_B$ . The radiation power of jets is estimated by  $P_r = \pi R^2 \Gamma^2 c U_r = L_{\text{bol}} \Gamma^2 / 4\delta^4$ , where  $L_{\text{bol}}$  is the total luminosity of non-thermal radiation from a radiation region.  $P_{e\pm}$  is the sum of  $P_e$ ,  $P_B$ , and  $P_r$ . As given in Tables 3 and 4,  $P_{e\pm}$  of the core is within  $3 \times 10^{42}$ – $10^{44}$  erg s $^{-1}$  while  $P_{e\pm}$  of extended regions are in the range of  $10^{43}$ – $10^{44}$  erg s $^{-1}$ . We find that the jet powers of the core and extended regions for the three CSOs are roughly of the same order, and similar results

have been reported for the  $\gamma$ -ray-emitting RG 3C 120 (Zargaryan et al. 2017) and the blazar 4C +49.22 (Zhang et al. 2018). We also estimate the kinetic power ( $P_{\text{kin}}$ ) of the three CSOs using the radio luminosity at 1.4 GHz of extended regions and Equation (1) in Cavagnolo et al. (2010), obtaining  $1.4 \times 10^{44} \text{ erg s}^{-1}$ ,  $3.0 \times 10^{42} \text{ erg s}^{-1}$ , and  $7.3 \times 10^{43} \text{ erg s}^{-1}$  for PKS 1718-649, NGC 3894, and TXS 0128+554, respectively.  $P_{\text{kin}}$  is also roughly of the same order as  $P_{\text{e}\pm}$  for the core and extended regions.

#### 4.2. Possible VHE Emission

Recently, the CSO PKS 1413+135 was detected at very high energy (VHE) band by the MAGIC telescope (Blanch et al. 2022; Gan et al. 2022). Although the  $\gamma$ -rays of PKS 1413+135 should be dominated by aligned jet emission and may be totally different from the three lobe-dominated CSOs, we still wonder whether the three CSOs could be detected at VHE band. In particular, the H.E.S.S. Collaboration reported that Cen A has VHE emission along its large-scale jet, providing direct evidence for the presence of high-energy electrons in the extended regions of AGN jets (H.E.S.S. Collaboration et al. 2020).

Extrapolating the Fermi/LAT  $\gamma$ -ray spectrum to the VHE band is a common method to estimate the intrinsic VHE spectrum of sources (Paiano et al. 2021; Zhu et al. 2021; Malik et al. 2022). As described in Section 3.2, the spectra observed by Fermi/LAT for the three CSOs are well represented by a power-law function, and no evidence of variability has been found in their long-term  $\gamma$ -ray light curves. We therefore directly extend the power-law spectra at the GeV band to the VHE band for the three CSOs, as illustrated in Figure 4. The sensitivity curves of Cherenkov Telescope Array south and north (CTA-S and CTA-N, 50 hr) are also presented in Figure 4, where the sensitivity curves are obtained from the CTA webpage. We find that the extrapolated flux at VHE band for PKS 1718-649 and NGC 3894 is below the sensitivity curve of CTA. Especially for PKS 1718-649, together with its steep spectrum at the GeV band, it would be difficult to detect with CTA in the future. The extrapolated intrinsic VHE spectrum of TXS 0128+554 clearly surpasses the sensitivity curve of CTA; however, when considering EBL absorption, it only marginally intersects with CTA's sensitivity curve, as depicted in Figure 4.

Nevertheless, theoretical suggestions have proposed episodic jet activity for compact radio sources (e.g., Reynolds & Begelman 1997; Czerny et al. 2009), and episodic nuclear jet activity has been reported for TXS 0128+554 (Lister et al. 2020). The reactivation of TXS 0128+554 could position it as a potential candidate for VHE emission, making it detectable by CTA.

### 5. Summary

We comprehensively analyzed the 14 yr Fermi/LAT observation data of three radio-lobe-dominated CSOs (PKS 1718-649, NGC 3894, TXS 0128+554) to explore their  $\gamma$ -ray emission properties. They are all characterized by low  $\gamma$ -ray

luminosity ( $10^{41}$ – $10^{43}$  erg s $^{-1}$ ), their average spectra in 0.1–300 GeV can be well fitted by a power-law function, and no significant variability is observed in their long-term  $\gamma$ -ray light curves. These  $\gamma$ -ray features are prominently different from those of the  $\gamma$ -ray emitting CSOs PKS 1413+135 and CTD 135. In the  $L\gamma - \Gamma\gamma$  plane, the three CSOs are located in the region occupied by RGs, also distinctly different from PKS 1413+135 and CTD 135, which are similar to blazars. Considering the similar radiation properties between the three CSOs and  $\gamma$ -ray emitting RGs, specifically similar to RGs Cen A and Fornax A, together with no significant variability in the  $\gamma$ -ray band and no superluminal motion in the radio band, we speculate that their  $\gamma$ -rays stem from lobe-dominated radiation, different from CTD 135 and PKS 1413+135 (Gan et al. 2021, 2022). Their broadband SEDs can be represented by the two-zone leptonic model where  $\gamma$ -rays are produced by IC processes of relativistic electrons in extended regions and X-rays are dominated by radiation from the core region. This radiation model can be tested by studying whether flux variations in X-ray and  $\gamma$ -ray bands are correlated. Based on the derived fitting parameters, we calculated the jet powers of the core and extended regions assuming electron-positron pair jets and found that the jet powers of the core and extended regions for the three CSOs are roughly of the same order. TXS 0128+554 may be a VHE emission candidate and could be detected by CTA in the future.

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