Radio core dominance of Fermi/LAT-detected AGNs

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We present a sample of 4388 AGNs with available radio core-dominance parameters—defined as the ratio of the core flux densities to the extended ones, \( R = S_{\text{core}}/S_{\text{ext}} \)—which includes 630 Fermi-detected AGNs from the fourth source catalog (4FGL) of the Fermi Large Area Telescope (Fermi/LAT); the rest are non-Fermi-detected AGNs. In our sample, 584 blazars are Fermi-detected and 1310 are not. The sample also contains other subclasses, such as Seyferts, Fanaro-Riley I/II galaxies, and normal galaxies. We investigate various properties of the Fermi-detected and non-Fermi-detected AGNs by using core-dominance parameters, capitalizing on a previous study which showed that \( R \) is a good indicator of beaming. We then calculate radio spectral indices for the whole sample, and adopt \( \gamma \)-ray-photon indices for the Fermi AGNs from the 4FGL catalog to discuss the properties of different subclasses. We obtain a relation between the core-dominance parameters and the radio spectral indices for both Fermi and non-Fermi sources, assuming a two-component model in the radio band. Our previous study ruled out the assumption that the core-dominance parameters and radio spectral indices are quite different for different AGN subclasses. This holds not only for Fermi sources but also for non-Fermi sources. In particular, \( R \) is, on average, greater for the former AGNs than for the latter. In this study, we enlarge our sample with available values of \( R \) to 4388 AGNs, and the obtained conclusions are consistent with our previous study. We assume that the same two-component model holds for the \( \gamma \)-ray band as for the radio band, and therefore, adopt the same relation between the core-dominance parameters and the \( \gamma \)-ray-photon indices for Fermi AGNs. Our fitting results indicate that the \( \gamma \)-ray emissions of Fermi blazars originate mainly from the jet, and therefore, we conclude that the Fermi blazars are beamed.

active galactic nuclei (AGNs), quasars, \( \gamma \)-rays

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1 Introduction

The approximate structure of an active galactic nucleus (AGN) comprises a supermassive black hole at the center, surrounded by an accretion disk. However, the physical process of energy production—especially the nature of the central region—is still not clear. VLA and VLBI observations of brightness variations and superluminal motions in AGNs support a relativistic-beaming model for the emissions. The VLA and VLBI observations have also enabled investigators to separate the core and the extended components. Thus, the observed radio emissions of AGNs contain two components:
a compact, relativistically beamed core component and an unbeamed lobe (extended) component. Blazars, which comprise the most extreme class of AGNs, are characterized by large amplitudes and rapid variability, contain superluminal motions, are core-dominated \((R > 1)\) and highly polarized, and emit high-energy \(\gamma\)-radiation. All these properties can be explained by relativistic beaming. When the beam points toward the observer, the emissions in the jet are highly boosted along the observer’s line of sight \([1]\). Multiwavelength observational data show that the radio spectra of most blazars are usually flat: \(a_R \approx 0.00\). From emission-line features, blazars can be divided into flat-spectrum radio quasars (FSRQs) and BL Lacerate objects (BL Lacs).

However, there are some obvious problems with this proposal. For example, “Why are some sources \(\gamma\)-ray loud, while others are \(\gamma\)-ray quiet?” \([2,3]\), “Why are some BL Laceratea detected by \textit{Fermi}, but others are not?” \([4]\). The differences between \textit{Fermi} and non-\textit{Fermi} sources have been addressed in many investigations. Blazars detected by \textit{Fermi}/\textit{LAT} are more likely to have higher Doppler factors \([5,6]\) and larger apparent opening angles \([7]\) than those not detected by \textit{Fermi}/\textit{LAT}. Kovalev \([8]\) found that the median brightness temperatures \(T_b\) for the \textit{Fermi}-detected sources are statistically higher than those for the rest. Savolainen’s Group \([7]\) considered 62 objects with apparent velocities obtained from the MOJAVE program and Doppler factors, and compared the sources detected by \textit{Fermi} with those not detected. They found that \textit{Fermi}-detected blazars, on average, have higher Doppler factors than non-\textit{Fermi}-detected blazars. Piner et al. \([9]\) showed that sources detected by \textit{Fermi}/\textit{LAT} have higher apparent speeds than those not detected. Pushkarev and Kovalev \([10]\) found that \textit{Fermi} AGNs have higher brightness temperatures and VLBI core flux densities. Linford et al. \([11]\) showed that \textit{Fermi}-detected BL Lacs have longer jets and are more highly polarized than the others. Xiao et al. \([12]\) compiled a sample of 291 superluminal sources, with 189 detected by \textit{Fermi} (\textit{Fermi}-detected sources: FDSs) and 102 not detected (non-FDSs). They found that, on average, FDSs have higher Doppler factors, apparent velocities, Lorentz factors, and smaller viewing angles than non-FDSs. Kovalev \([8]\) suggested that LAT-detected blazars are brighter and more luminous in the radio domain at parsec scales. Pei et al. \([13]\) showed that the core-dominance parameter log \(R\) is, on average, higher for \textit{Fermi}-detected blazars than for non-\textit{Fermi}-detected blazars, which suggests that the \(\gamma\)-ray sources are more radio-core-dominated and beamed. Xiong et al. \([14]\) found significant differences between \textit{Fermi} and non-\textit{Fermi} blazars: e.g., differing black-hole masses, jet kinetic powers, and broad-line luminosities. However, the differences between their jets and accretion flows are still not clear.

In a relativistic beaming model, the observed total emission, \(S_{\text{ob}}\), is assumed to comprise the sum of a beamed, \(S_{\text{ob}}^{\text{core}}\), and an unbeamed, \(S_{\text{ext}}\), emission component: \(S_{\text{ob}} = S_{\text{ob}}^{\text{core}} + S_{\text{ext}}\), where \(f = S_{\text{ob}}^{\text{core}}/S_{\text{ext}}\). Here \(S_{\text{ob}}^{\text{core}}\) is the de-beamed emission in the co-moving frame, \(\delta\) is a Doppler factor, \(p = \alpha + 2\) \((\text{for a continuous jet})\) or \(p = \alpha + 3\) \((\text{for a moving sphere})\), and \(\alpha\) is the spectral index \((S_{\nu} \propto \nu^{-\alpha})\). The ratio \(R\) of the two components is the core-dominance parameter. Some authors have used the ratio of flux densities for this parameter, while others have used the ratio of luminosities; that is, \(R = S_{\text{core}}/S_{\text{ext}}\), or \(R = L_{\text{core}}/L_{\text{ext}}\). Where \(S_{\text{core}}\) or \(L_{\text{core}}\) indicates the core emission and \(S_{\text{ext}}\) or \(L_{\text{ext}}\) corresponds to the extended emission (see refs. \([13,15,16]\) and references therein).

Doppler boosting is considered an important answer to the following question: “Why are some sources \(\gamma\)-ray loud, while others are \(\gamma\)-ray quiet?” The Doppler factor \(\delta\) is a direct indicator of the jet-beaming effect, so a reliable determination of this factor can provide an important way to study the physical processes associated with the compact emission regions of AGNs. However, the radio Doppler factors are not easy to estimate, although many methods have been proposed. For this reason, we consider the core-dominance parameter in association with the Doppler factor in discussing the beaming effect.

After the launch of the \textit{Fermi} LAT, many astronomical objects were found to be high-energy \(\gamma\)-ray sources. This provides us with a good opportunity to study the \(\gamma\)-ray-emission mechanism. The \textit{Fermi}/\textit{LAT} detects \(\gamma\) rays in the energy range of 20 MeV to more than 1 TeV. Most of the sources in the past \textit{Fermi}/\textit{LAT} \([17-20]\) catalogs are blazars. However, there are far more blazars that are not detected by \textit{Fermi}.

Based on the first eight years of science data from the \textit{Fermi} \(\gamma\)-ray Space Telescope mission, the fourth \textit{Fermi} LAT catalog of high-energy \(\gamma\)-ray sources (4FGL) is the latest catalog to be released. It includes 5098 sources above 4\(\sigma\) in significance in the energy range from 50 MeV to 1 TeV \([21,22]\). Relative to the third LAT source catalog (3FGL), which contains 3033 sources \([19]\), the 4FGL catalog has twice as much exposure as well as several analysis improvements. The data for the 4FGL catalog were taken during the eight-year period from August, 2008, to August, 2016.

A vast majority of 4FGL sources—3009—are AGNs, which include 2938 blazars, 38 radio galaxies, and 33 other AGNs. The blazar sample includes 681 FSRQs, 1102 BL Lacs, and 1152 blazar candidates of uncertain class (BCUs) \([21]\).

Fan et al. \([16]\) collected a sample of 1223 extragalactic radio sources and calculated their core-dominance parameter log \(R\) and radio spectral indices \(\alpha_R\). We compared the values of log \(R\) among the BL Lacs, FSRQs, Seyfert galaxies, Fanaroff-Riley type-I/II galaxies, and other galaxies. In
particular, we found this parameter, on average, to be higher for blazars than for the other subclasses of AGNs. We also probed the correlation between \( \log R \) and \( \alpha_R \) [16].

Basing their work on Fan et al. [16], Pei et al. [13] compiled a list of 1335 blazars with available core-dominance parameters. Of these, 169 blazars have \( \gamma \)-ray emission (from 3FGL), and the averaged values of the core-dominance parameters \( \log R \) for the Fermi blazars and non-Fermi blazars are \( (\log R)_{\text{Fermi}} = 0.99 \pm 0.87 \) and \( (\log R)_{\text{non-Fermi}} = -0.62 \pm 1.15 \), respectively. We also calculated the averaged values of the radio spectral indices \( \alpha_R \) for both samples: \( \langle \alpha_R \rangle_{\text{Fermi}} = 0.06 \pm 0.35 \) and \( \langle \alpha_R \rangle_{\text{non-Fermi}} = 0.57 \pm 0.46 \). For the \( \gamma \)-ray-photon index \( \alpha_{\gamma \text{ph}} \), we obtained \( \langle \alpha_{\gamma \text{ph}} \rangle_{\text{BL Lacs}} = 2.38 \pm 0.21 \) and \( \langle \alpha_{\gamma \text{ph}} \rangle_{\text{Fermi quasars}} = 2.10 \pm 0.21 \) for the Fermi BL Lacs (FBLLs) and Fermi quasars (FQs), respectively. These results show that the core-dominance parameters and radio spectral indices for Fermi blazars are both quite different from the non-Fermi blazars, with \( \log R \) for Fermi blazars being, on average, higher than that for non-Fermi blazars, while \( \alpha_R \) is, on average, smaller than that for non-Fermi blazars.

Pei et al. [23] also collected a larger catalog that includes 2400 radio sources with available core-dominance parameters; those sources were not listed in Fan et al. [16]. We also discussed core-dominated AGNs and other related statistical analyses, and obtained similar conclusions to those of Fan et al. [16].

Following Fan et al. [16] and Pei et al. [23], we have now compiled a new sample of radio sources, which are not included in either of these references. However, 764 AGNs are cross-listed by Pei et al. [24]. We have also calculated core-dominance parameters and radio spectral indices for these sources.

In the present study, based on our previous studies [13, 16, 23, 24], we collected 4388 AGNs with available core-dominance parameters, whose results are presented in sect. 2. We discuss these results in sect. 3, and conclude and summarize our findings in the final two sections. Throughout this paper, without loss of generality, we assume the \( \Lambda \)CDM model, with \( \Omega_M \approx 0.73 \), \( \Omega_M \approx 0.27 \), and \( H_0 \approx 73 \) km s\(^{-1}\) Mpc\(^{-1}\).

2 Sample and results

2.1 Sample and calculations

To obtain the available core-dominance parameters \( \log R \), we adopted the data from Fan et al. [16], Pei et al. [23, 24]. These references include 1224, 2400, and 764 sources, respectively, which constitute our total sample of 4388 AGNs. We obtained the classifications of these objects from the NASA/IPAC EXTRAGALACTIC DATABASE (NED: http://ned.ipac.caltech.edu/forms/byname.html) and the Roma BZCAT database (http://www.asdc.asi.it/bzcat/). The former provides the basic identification, while the latter provides the classifications of BL Lacs and quasars. Furthermore, if a source is identified as “QSO” in NED, we check whether it is identified as a BL Lac, a quasar, or an uncertain type (herein termed “unidentified”) in BZCAT. If a source is identified as “G,” we classify it further as FRI or FRII. We classify a Seyfert galaxy as “Seyfert.” For sources that are not identified as FRI, FRII, or Seyfert, we use the general label “galaxy.” If an object has no identification in NED, we label it as “unidentified.” We then check the sources against the 4FGL catalog, and ultimately, identify 630 AGNs as Fermi/LAT (https://fermi.gsfc.nasa.gov/ssc/data/access/lat/8yr_catalog/). Thus, out of the 4388 AGNs, 630 sources are Fermi-detected AGNs (FAGNs) and the remaining 3758 sources are non-Fermi-detected AGNs.

The 630 FAGNs in our sample include 252 FBLLs, 283 FQs, 49 blazar candidates of uncertain class (FBCUs), and 46 Fermi-detected non-blazars (FNBs). The remaining 3758 sources in our sample are non-Fermi-detected AGNs (NFAGNs), which include 198 BL Lacs (NFBLLs), 1112 quasars (NFQs), 506 Seyfert galaxies (NFSys), 1426 normal galaxies (NFGs), 340 FR type I and II galaxies (NFFRs), and 176 unidentified sources (NFUs). The samples of Fermi-detected and non-Fermi-detected AGNs are shown in Tables 1 and 2, respectively. These two tables are available in their entirety in machine-readable form.

In general, radio observations have been performed at different frequencies by different authors and in different studies. However, most of these data are at 5 GHz, so we converted the data given in the literature at other frequencies to 5 GHz by assuming that [13, 16, 23]

\[
S_{\nu}^{5 \, \text{GHz}} = S_{\nu}^{\text{obs}} \text{core} \quad \text{and} \quad S_{\nu}^{5 \, \text{GHz}} = S_{\nu}^{\text{ext}} \left( \frac{\nu}{5 \, \text{GHz}} \right)^{\alpha_{\text{ext}}}. \tag{1}
\]

The flux densities were then K-corrected, and we finally obtained the core-dominance parameters from the expression

\[
R = \left( \frac{S_{\nu}^{\text{core}}}{S_{\nu}^{\text{ext}}} \right) (1 + z)^{\alpha_{\text{core}} - \alpha_{\text{ext}}}. \tag{2}
\]

For this calculation, we adopt \( \alpha_{\text{ext}} \) (or \( \alpha_{\text{lab}} \)) = 0.75 and \( \alpha_{\text{core}} \) (or \( \alpha_{\text{obs}} \)) = 0.00 [13, 16, 23].

Some data given in the literature are luminosities. If this is not at 5 GHz, we also need to convert its value to the one expected at that frequency. We then calculate the core-dominance parameter as \( \log R = \log (L_{\text{core}}/L_{\text{ext}}) \). From the flux-density data, we also calculated the luminosity using

\[
L_{\nu} = 4\pi d_L^2 S_{\nu},
\]

where \( d_L \) indicates the luminosity distance defined by

\[
d_L = (1 + z) \frac{c}{H_0} \int_{1+z}^{\infty} \frac{1}{\sqrt{\Omega_M x^3 + 1 - \Omega_M}} dx.
\]

The
Table 1  Sample of Fermi AGNs\(^a\)

| 4FGL Name     | IAU Name | Class | \(z\) | Flux (1-100 Gev) | \(\alpha_{\gamma}^{ph}\) | \(\log R\) | \(\log L_{\gamma}\) | \(\sigma_R\) | Ref.       |
|---------------|----------|-------|------|-----------------|-----------------|----------|-----------------|---------|-----------|
| 4FGL J1725.0+1152 | 1722+119 | FBLL  | 0.018 | \(3.62 \times 10^{-9}\) | 1.86            | 0.48     | 47.00           | 0.25    | Pei19(a)  |
| 4FGL J1229.0+0202 | 1226+023 | FQ    | 0.1583 | \(6.26 \times 10^{-9}\) | 2.76            | 0.66     | 45.21           | 0.11    | Fan11     |
| 4FGL J3047.5-2517 | 0045-25  | FNB   | 0.740  | \(7.83 \times 10^{-10}\) | 2.14            | -0.66    | 46.20           | 0.82    | Pei19(a)  |
| 4FGL J0313.0+4119 | 0309+411 | FNB   | 0.134  | \(2.96 \times 10^{-10}\) | 2.56            | 0.54     | 43.76           | -0.08   | Fan11     |
| 4FGL J1114.9-1937 | 1142+198 | FNB   | 0.0217 | \(2.68 \times 10^{-10}\) | 1.89            | -0.93    | 42.40           | 0.95    | Fan11     |
| 4FGL J0708.9+4838 | 0705+486 | FBCU  | 0.019  | \(9.87 \times 10^{-11}\) | 1.91            | -0.31    | 41.83           | 0.59    | Pei19(a)  |

\(\alpha\) for AGNs, without the measured redshifts in our sample.

\(\alpha\) can be expressed as:

\[ N_0 = \frac{1}{E_{\alpha}} \left( \frac{E_{\gamma} - E_{\alpha}}{E_{\gamma}} \right) \]

\(\alpha_{\gamma}^{ph}\) is the spectral index of the \(\gamma\)-ray photons. The quantity \(N_0\) can be expressed as:

\[ N_0 = \frac{1}{E_{\alpha}} \left( \frac{E_{\gamma} - E_{\alpha}}{E_{\gamma}} \right) \]

\(\alpha_{\gamma}^{ph}\) for \(\alpha = 2\), where \(E_{\alpha}\) and \(E_{\gamma}\) are, respectively, the lower and upper energy limits of the observed \(\gamma\)-ray spectrum. Otherwise,

\[ N_0 = \frac{1}{E_{\alpha}} \left( \frac{E_{\gamma} - E_{\alpha}}{E_{\gamma}} \right) \]

\(\alpha_{\gamma}^{ph}\) is the spectral index of the \(\gamma\)-ray photons. The quantity \(N_0\) can be expressed as:

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\(\alpha_{\gamma}^{ph}\) for \(\alpha = 2\), where \(E_{\alpha}\) and \(E_{\gamma}\) are, respectively, the lower and upper energy limits of the observed \(\gamma\)-ray spectrum. Otherwise,

\[ N_0 = \frac{1}{E_{\alpha}} \left( \frac{E_{\gamma} - E_{\alpha}}{E_{\gamma}} \right) \]

\(\alpha_{\gamma}^{ph}\) is the spectral index of the \(\gamma\)-ray photons. The quantity \(N_0\) can be expressed as:

\[ N_0 = \frac{1}{E_{\alpha}} \left( \frac{E_{\gamma} - E_{\alpha}}{E_{\gamma}} \right) \]

\(\alpha_{\gamma}^{ph}\) for \(\alpha = 2\), where \(E_{\alpha}\) and \(E_{\gamma}\) are, respectively, the lower and upper energy limits of the observed \(\gamma\)-ray spectrum. Otherwise,

\[ N_0 = \frac{1}{E_{\alpha}} \left( \frac{E_{\gamma} - E_{\alpha}}{E_{\gamma}} \right) \]

\(\alpha_{\gamma}^{ph}\) is the spectral index of the \(\gamma\)-ray photons. The quantity \(N_0\) can be expressed as:

\[ N_0 = \frac{1}{E_{\alpha}} \left( \frac{E_{\gamma} - E_{\alpha}}{E_{\gamma}} \right) \]

\(\alpha_{\gamma}^{ph}\) for \(\alpha = 2\), where \(E_{\alpha}\) and \(E_{\gamma}\) are, respectively, the lower and upper energy limits of the observed \(\gamma\)-ray spectrum. Otherwise,

\[ N_0 = \frac{1}{E_{\alpha}} \left( \frac{E_{\gamma} - E_{\alpha}}{E_{\gamma}} \right) \]

\(\alpha_{\gamma}^{ph}\) is the spectral index of the \(\gamma\)-ray photons. The quantity \(N_0\) can be expressed as:

\[ N_0 = \frac{1}{E_{\alpha}} \left( \frac{E_{\gamma} - E_{\alpha}}{E_{\gamma}} \right) \]

\(\alpha_{\gamma}^{ph}\) for \(\alpha = 2\), where \(E_{\alpha}\) and \(E_{\gamma}\) are, respectively, the lower and upper energy limits of the observed \(\gamma\)-ray spectrum. Otherwise,

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\(\alpha_{\gamma}^{ph}\) for \(\alpha = 2\), where \(E_{\alpha}\) and \(E_{\gamma}\) are, respectively, the lower and upper energy limits of the observed \(\gamma\)-ray spectrum. Otherwise,
For all 4388 AGNs, the average value of the core-dominance parameter is \( \langle \log R \rangle_{\text{total}} = -0.293 \pm 1.122 \). Separately, \( \langle \log R \rangle_{\text{FAGNs}} = 0.545 \pm 1.013 \) for the 630 FAGNs and \( \langle \log R \rangle_{\text{NFAGNs}} = -0.434 \pm 1.077 \) for NFAGNs (Table 3).

We find that, on average, the Fermi AGNs have higher core-dominance parameters than the non-Fermi sources. By performing a Kolmogorov-Smirnov test (hereafter, a “K-S test”), we find that the null hypothesis (i.e., the fact that both samples are drawn from the same population) cannot be rejected at the confidence level \( p = 5.132 \times 10^{-81} \) \( (d_{\text{max}} = 0.414) \) for the Fermi AGNs and non-Fermi AGNs. The distribution of the core-dominance parameters \( \log R \) and the cumulative probabilities are shown in Figure 1, and the K-S test results are listed in Table 4.

In the sample of Fermi AGNs, we find that \( \langle \log R \rangle_{\text{FBLL}} = 0.637 \pm 0.950 \) for the 252 FBLLs; \( \langle \log R \rangle_{\text{FQ}} = 0.706 \pm 0.914 \) for the 283 FQs; \( \langle \log R \rangle_{\text{FBBCU}} = 0.119 \pm 1.339 \) for the 49 FBCUs, and \( \langle \log R \rangle_{\text{FNBR}} = -0.493 \pm 0.808 \) for the 46 FNBs. These results are listed in Table 3.

The K-S test indicates that the null hypothesis cannot be rejected at the following confidence levels for the different samples: \( p = 0.144 \) \( (d_{\text{max}} = 0.097) \) for FBLLs and FQs; \( p = 0.061 \) \( (d_{\text{max}} = 0.201) \) FBLLs and FBCUs; \( p = 0.010 \) \( (d_{\text{max}} = 0.248) \) for FQs and FBCUs; and \( p = 3.242 \times 10^{-14} \) \( (d_{\text{max}} = 0.562) \) for Fermi blazars (FBLLs + FQs + FBCUs) and Fermi non-blazars. From the K-S test, we thus find that there is no significant difference between the FBLLs and FQs or between the FBLLs and FBCUs at the significance level \( p = 0.05 \). The average values of \( \langle \log R \rangle \) satisfy the following relation for all subclasses: \( \langle \log R \rangle_{\text{FBLL}} \approx \langle \log R \rangle_{\text{FQ}} > \langle \log R \rangle_{\text{FNBR}} \). The distributions of the core-dominance parameters and the cumulative probabilities are shown in Figure 2, and the K-S test results are listed in Table 4.

Next, we turn to the average values of \( \log R \) for the

![Figure 1](Color online) Distributions of the core-dominance parameters \( \log R \) (upper panel) and the cumulative probabilities (lower panel) for the entire sample. In this plot, the red solid line indicates the FAGNs, while the black dashed line indicates NFAGNs.

**Table 3** Average values for the whole sample

| Sample | \( N \) | \( \langle \log R \rangle \) | \( \langle \sigma_R \rangle \) | \( \langle \sigma_{logR} \rangle \) | \( \langle \log L_r \rangle \) (erg s\(^{-1}\)) |
|--------|--------|-----------------|-----------------|-----------------|-----------------|
| Total  | 4388   | \(-0.293 \pm 1.122\) | \(0.440 \pm 0.575\) | ... | ... |
| FAGN   | 630    | \(0.545 \pm 1.013\) | \(0.125 \pm 0.475\) | 2.269 \pm 0.295 | 45.69 \pm 1.39 |
| NFAGN  | 3758   | \(-0.434 \pm 1.077\) | \(0.500 \pm 0.573\) | ... | ... |
| FBLL   | 252    | \(0.637 \pm 0.950\) | \(0.150 \pm 0.447\) | 2.033 \pm 0.205 | 45.39 \pm 1.14 |
| NFBB   | 198    | \(0.465 \pm 0.947\) | \(0.260 \pm 0.481\) | ... | ... |
| FQ     | 283    | \(0.706 \pm 0.914\) | \(-0.016 \pm 0.433\) | 2.473 \pm 0.181 | 46.40 \pm 0.95 |
| NFQ    | 1112   | \(0.032 \pm 0.871\) | \(0.281 \pm 0.505\) | ... | ... |
| FBCU   | 49     | \(0.119 \pm 1.339\) | \(0.334 \pm 0.519\) | 2.276 \pm 0.283 | 45.05 \pm 1.20 |
| FNB    | 46     | \(-0.493 \pm 0.808\) | \(0.625 \pm 0.383\) | 2.296 \pm 0.343 | 43.61 \pm 1.78 |
| FB     | 584    | \(0.627 \pm 0.982\) | \(0.085 \pm 0.459\) | 2.267 \pm 0.291 | 45.85 \pm 1.19 |
| NFS    | 506    | \(-0.305 \pm 0.909\) | \(0.608 \pm 0.620\) | ... | ... |
| NF2    | 1426   | \(-0.710 \pm 1.002\) | \(0.618 \pm 0.515\) | ... | ... |
| NF3    | 340    | \(-1.643 \pm 0.938\) | \(0.851 \pm 0.455\) | ... | ... |
| NF4    | 176    | \(-0.186 \pm 0.970\) | \(0.280 \pm 0.959\) | ... | ... |
| NF5    | 1310   | \(0.097 \pm 0.896\) | \(0.277 \pm 0.501\) | ... | ... |

a) Col. 1 gives the sample: the representations of all abbreviations are consistent with the previous description; Col. 2 numbers; Col. 3 averaged of core-dominance parameter; Col. 4 averaged of radio spectral index; Col. 5 averaged of γ-ray photon index for Fermi AGNs; Col. 6 averaged of γ-ray luminosity for Fermi AGNs in the unit of erg s\(^{-1}\).
NF AGNs. We find that $\langle \log R \rangle_{\text{NFBL}} = 0.465 \pm 0.947$ for the 198 NFBL; $\langle \log R \rangle_{\text{NFQ}} = 0.032 \pm 0.871$ for the 1112 NFQs; $\langle \log R \rangle_{\text{NF}} = -0.305 \pm 0.909$ for the 506 NFs; $\langle \log R \rangle_{\text{NFAG}} = 0.710 \pm 1.002$ for the 1426 NFAGs; $\langle \log R \rangle_{\text{NFFFR}} = -1.143 \pm 0.938$ for the 340 NFFFRs; and $\langle \log R \rangle_{\text{NFNB}} = -0.186 \pm 0.970$ for the 176 NFNBs. Consequently, we have $\langle \log R \rangle_{\text{NF}} = -0.718 \pm 1.058$ for the 2448 NFNs. The results are also listed in Table 3.

The K-S test results show that the chance probability is $p = 1.173 \times 10^{-7}$ ($d_{\text{max}} = 0.221$) for non-Fermi BL Lacs versus non-Fermi quasars and that $\langle \log R \rangle_{\text{NFBL}} > \langle \log R \rangle_{\text{NF}} > \langle \log R \rangle_{\text{NFNB}}$. The distributions of the core-dominance parameters and cumulative probabilities for NFAGNs are shown in Figure 3 (also see Table 4).

If we consider only the blazars, we find that $\langle \log R \rangle_{\text{FB}} = 0.627 \pm 0.982$ for 584 FBs and $\langle \log R \rangle_{\text{FB}} = 0.097 \pm 0.896$ for 1310 FBs, indicating that the Fermi blazars have core-dominance parameters that are, on average, higher ($\langle \log R \rangle_{\text{FB}} = 0.627$) than the non-Fermi blazars ($\langle \log R \rangle_{\text{FB}} = 0.097$). The K-S test yields $p = 3.428 \times 10^{-31}$ ($d_{\text{max}} = 0.295$) for these two samples. The distributions of the core-dominance parameters and the cumulative probabilities are shown in Figure 4 (also see Table 4).

Through the K-S test, we find that the log $R$ distributions for FAGNs and NFAGNs are significantly different (with chance probability $p = 5.132 \times 10^{-81}$). For the subclasses, the K-S test also shows the FQs and NFQs to be significantly different, with a chance probability of $6.486 \times 10^{-30}$ ($d_{\text{max}} = 0.387$). However, for the FBLs and NFBLs, the K-S test shows that the chance probability is $p = 0.009$ ($d_{\text{max}} = 0.154$). We thus conclude that some objects in the NFBL sample may also be $\gamma$-ray sources but that they have not yet been detected during the Fermi/LAT mission.

2.2.2 Radio spectral index $\alpha_R$

We obtain $\langle \alpha_R \rangle_{\text{Total}} = 0.440 \pm 0.575$ for our entire sample of 3809 AGNs with the adopted available radio spectral indices $\alpha_R (S_\nu \propto \nu^{-\alpha_R})$. In addition, $\langle \alpha_R \rangle_{\text{FAGN}} = 0.125 \pm 0.475$ for

![Figure 2](image-url) (Color online) Distributions of the core-dominance parameters $\log R$ (upper panel) and the cumulative probabilities (lower panel) for the Fermi-detected AGNs. In this plot, the magenta solid line indicates the FBLs, the red dashed line indicates the FQs, the orange dotted line for the FBCUs, and the blue dash-dotted line indicates the FNBs.
614 Fermi AGNs and $\langle \alpha_R \rangle_{\text{NFAGN}} = 0.500 \pm 0.573$ for 3195 non-Fermi AGNs (Table 3).

From these results, we find that, on average, Fermi AGNs have smaller radio spectral indices than non-Fermi AGNs. The K-S test shows that $p = 4.518 \times 10^{-56} (d_{\text{max}} = 0.383)$. The distributions of the radio spectral indices $\alpha_R$ and the cumulative probabilities are shown in Figure 5.

For the various subclasses of the Fermi sources, we have $\langle \alpha_R \rangle_{\text{FBLL}} = 0.150 \pm 0.447$ for the 243 Fermi BL Lacs; $\langle \alpha_R \rangle_{\text{FQ}} = -0.016 \pm 0.433$ for the 277 Fermi quasars; $\langle \alpha_R \rangle_{\text{FBCU}} = 0.334 \pm 0.519$ for the 49 Fermi BCUs; and $\langle \alpha_R \rangle_{\text{FNB}} = 0.625 \pm 0.383$ for the 45 Fermi non-blazars.

The K-S test indicates that the chance probabilities for the entire sample are $p = 6.466 \times 10^{-5} (d_{\text{max}} = 0.197)$ for the FBLLs and FQs, $p = 0.006 (d_{\text{max}} = 0.260)$ for the FBCUs and FBCUs, and $p = 3.684 \times 10^{-5} (d_{\text{max}} = 0.357)$ for the FQs and FBCUs. Therefore, we have $\langle \alpha_R \rangle_{\text{FNB}} > \langle \alpha_R \rangle_{\text{FBLL}} > \langle \alpha_R \rangle_{\text{FQ}}$.

For the subclasses of the NFAGNs, we find $\langle \alpha_R \rangle_{\text{NFAGN}} = 0.260 \pm 0.481$ for the 182 NFAGNs; $\langle \alpha_R \rangle_{\text{NFQ}} = 0.281 \pm 0.505$ for the 1018 non-Fermi quasars; $\langle \alpha_R \rangle_{\text{NFBCU}} = 0.608 \pm 0.620$ for the 451 non-Fermi Seyfert galaxies; $\langle \alpha_R \rangle_{\text{NFSG}} = 0.618 \pm 0.515$ for the 1156 non-Fermi normal galaxies; $\langle \alpha_R \rangle_{\text{NFFR}} = 0.851 \pm 0.455$ for the 294 non-Fermi FR-type galaxies; and $\langle \alpha_R \rangle_{\text{NFU}} = 0.280 \pm 0.959$ for the 94 non-Fermi unidentified sources. Thus, we have $\langle \alpha_R \rangle_{\text{NFNB}} = 0.634 \pm 0.572$ for the 1995 non-Fermi non-blazars (also see Table 3).

Thus, we find $\langle \alpha_R \rangle_{\text{NFNB}} > \langle \alpha_R \rangle_{\text{NFU}} > \langle \alpha_R \rangle_{\text{NFAGN}}$. The distributions of the radio spectral indices and the cumulative probabilities for all BL Lacs (FBLLs+NFAGNs) and quasars (FQs+NFQs) are shown in Figure 6.
For the 569 Fermi blazars, we have \( \langle \alpha_R \rangle_{\text{FB}} = 0.085 \pm 0.459 \), and \( \langle \alpha_R \rangle_{\text{NFB}} = 0.277 \pm 0.501 \) for the 1200 non-Fermi blazars, which shows that the radio spectral indices, on average are smaller for the Fermi blazars than for the non-Fermi ones. The distributions of \( \alpha_R \) and the cumulative probabilities for all blazars (FBs+NFBs) and non-blazars (FNBs+FNFBs) are shown in Figure 7.

For the radio spectral index \( \alpha_R \), the K-S test indicates that the chance probability for FBLLs and FQs is \( p = 0.02 \) (\( d_{\text{max}} = 0.146 \)) for the Fermi BL Lacs and non-Fermi BL Lacs, \( p = 7.144 \times 10^{-19} \) (\( d_{\text{max}} = 0.311 \)) for the Fermi quasars and non-Fermi quasars, and \( p = 2.942 \times 10^{-17} \) (\( d_{\text{max}} = 0.223 \)) for the Fermi blazars and non-Fermi blazars.

### 2.2.3 Gamma-ray-photon spectral index \( \alpha_{\gamma}^{ph} \)

For all Fermi AGNs, we find that \( \langle \alpha_{\gamma}^{ph} \rangle_{\text{FAGN}} = 2.269 \pm 0.295 \). For the different subclasses, we have \( \langle \alpha_{\gamma}^{ph} \rangle_{\text{FBLL}} = 2.033 \pm 0.205 \) for FBLLs; \( \langle \alpha_{\gamma}^{ph} \rangle_{\text{FQ}} = 2.473 \pm 0.181 \) for FQs; \( \langle \alpha_{\gamma}^{ph} \rangle_{\text{FBCU}} = 2.276 \pm 0.283 \) for FBCUs; \( \langle \alpha_{\gamma}^{ph} \rangle_{\text{FNB}} = 2.296 \pm 0.343 \) for FNBs; and \( \langle \alpha_{\gamma}^{ph} \rangle_{\text{FB}} = 2.267 \pm 0.291 \) for FBs. All gamma-ray-photon spectral indices we have compiled in our sample thus satisfy the relation \( \langle \alpha_{\gamma}^{ph} \rangle_{\text{FBLL}} > \langle \alpha_{\gamma}^{ph} \rangle_{\text{FQ}} \).

The distributions of \( \alpha_{\gamma}^{ph} \) and the cumulative probabilities are shown in Figure 8. The K-S test shows that the chance probability for FBLLs and FQs is \( p = 1.974 \times 10^{-70} \) (\( d_{\text{max}} = 0.775 \)); \( p = 1.035 \times 10^{-7} \) (\( d_{\text{max}} = 0.447 \)) for FBLLs and FB-CUs; \( p = 3.762 \times 10^{-5} \) (\( d_{\text{max}} = 0.356 \)) for FQs and FBCUs; and \( p = 0.849 \) (\( d_{\text{max}} = 0.094 \)) for FBs and FNBs (Table 4).

#### 2.2.4 Gamma-ray luminosity \( \log L_{\gamma} \)

For all Fermi AGNs, we can calculate the gamma-ray luminosities \( \log L_{\gamma} \), and find \( \langle \log L_{\gamma} \rangle_{\text{FAGN}} = 45.69 \pm 1.39 \) (erg s\(^{-1}\)). For separate subclasses, we have \( \langle \log L_{\gamma} \rangle_{\text{FBLL}} = 45.39 \pm 1.14 \) (erg s\(^{-1}\)) for FBLLs; \( \langle \log L_{\gamma} \rangle_{\text{FQ}} = 46.40 \pm 0.95 \) (erg s\(^{-1}\)) for FQs; and \( \langle \log L_{\gamma} \rangle_{\text{FBCU}} = 45.05 \pm 1.20 \) (erg s\(^{-1}\)) for FBCUs (also see Table 3). Therefore, for the FBs, we have \( \langle \log L_{\gamma} \rangle_{\text{FB}} = 45.85 \pm 1.19 \) (erg s\(^{-1}\)) and \( \langle \log L_{\gamma} \rangle_{\text{FNB}} = 43.61 \pm 1.78 \) (erg s\(^{-1}\)) for the FNBs.

The distributions and cumulative probabilities are shown in Figure 9. The K-S test indicates that the chance probability for FBLLs and FQs is \( p = 1.271 \times 10^{-20} \) (\( d_{\text{max}} = 0.415 \)); \( p = 0.084 \) (\( d_{\text{max}} = 0.192 \)) for FBLLs and FBCUs; \( p = 1.188 \times 10^{-11} \) (\( d_{\text{max}} = 0.552 \)) for FQs and FBCUs; and \( p = 2.460 \times 10^{-14} \) (\( d_{\text{max}} = 0.565 \)) for FBs and FNBs.

The statistical average values for our whole sample are summarized in Table 3, and the K-S test results of different distributions are shown in Table 4.

### 2.3 Correlation analysis

In the following discussions of our correlation analyses, we determine the regressions by minimizing \( \Sigma \left[ \log(A/B) \right]^2 \), where \( A \) and \( B \) refer to two different quantities.
2.3.1 Correlation between redshift and core-dominance parameter

Observations of distant AGNs indicate that these sources are strong radiation emitters. Theoretical work indicates that such sources have relativistic jets pointing toward us, and thus, have large core-dominance parameters. We, therefore, expect the core-dominance parameter to be positively correlated with distance (or redshift $z$).
We find the correlation between the core-dominance parameter $\log R$ and redshift $\log z$ to be given by $\log R = (0.21\pm0.08)\log z+(0.62\pm0.05)$, with a correlation coefficient $r = 0.11$ and a chance probability of $p < 10^{-12}$ for Fermi AGNs. We also find $\log R = (0.12\pm0.03)\log z-(0.38\pm0.02)$, with $r = 0.07$ and $p = 4.763\times10^{-5}$, for non-Fermi AGNs (see Figure 10).

These correlations may actually originate from a selection effect: AGNs with large redshifts and strong beaming are easier to observe, and therefore, more likely to be selected by us, thus resulting in a larger value of $\log R$ for a higher redshift $z$.

### 2.3.2 Correlation between core-dominance parameter and gamma-ray luminosity

We find the correlation between the gamma-ray luminosity $\log L_\gamma$ and the core-dominance parameter $\log R$ to be given by $\log L_\gamma = (0.22\pm0.05)\log R+(45.57\pm0.06)$, with $r = 0.16$ and $p = 3.598 \times 10^{-5}$, for the entire sample of Fermi AGNs (Figure 11). This shows that the gamma-ray luminosity increases with $\log R$ for Fermi sources, indicating that the gamma-ray emission is associated with the relativistic beaming of the jet. Thus, $\log R$ can act as an indicator of the beaming effect.

As shown in Figure 12, we obtain an anti-correlation between the gamma-ray-photon index $\alpha_{\gamma}^{\text{ph}}$ and the radio spectral index $\alpha_{\text{R}}$ for the Fermi BL Lacs: $\alpha_{\gamma}^{\text{ph}} = -(0.06 \pm 0.03)\alpha_{\text{R}} + (2.05 \pm 0.01)$, with the correlation coefficient $r = -0.10$ and a chance probability $p = 0.01$. However, we find no significant correlation between the Fermi quasars and Fermi BCUs. In this plot, the magenta solid line represents the best fit to the Fermi BL Lacs.

### 3 Discussion

Photons are conventional messengers for astronomical studies, and are currently the best indicators for multi-messenger astronomy. The most energetic photons, i.e., gamma-rays, are electromagnetic radiation in the high-energy (HE) range (from a few Mev to around 30 GeV) and the very-high-energy (VHE) range ($\geq$ 30 GeV). There are two scenarios for the
origin of the $\gamma$-rays: bottom-up models and top-down models. For the typical radiation characteristic of AGNs, we term the former leptonic or hadronic emission if the parent population that emits the $\gamma$-rays consists of leptons or hadrons, respectively. For leptonic emission, we can determine the relation between the electron and photon energies for a given population of electrons [27]:

$$E_\gamma = 6.5 \left( \frac{E_e}{1 \text{ TeV}} \right) \left( \frac{\epsilon}{\text{meV}} \right) \text{GeV},$$  

(9)

where $E_\gamma$ and $E_e$ denote the photon energy and electron energy, and $\epsilon$ is the soft-photon energy of a given blackbody population. For hadronic emission, the $\gamma$-rays originate from accelerated proton-proton interactions ($pp$ interactions) or from hadron-nucleon collisions [28, 29]. Another way to produce $\gamma$-rays is from the interaction between protons and the photons stemming from synchrotron radiation or bremsstrahlung from accelerated electrons. This is termed photoproduction:

$$p + \gamma \rightarrow \pi^+ + n \text{ and } p + \gamma \rightarrow \pi^0 + p.$$  

(10)

The cross-sections for these two processes are quite small, so in this case, the target photon density must be much higher than the matter density [27].

Blazars and some other AGNs show extreme observational properties that are associated with relativistic beaming. All these extreme properties indicate that blazars are the most active extragalactic sources in the Universe. BL Lac objects are usually identified as "lineless" active galactic nuclei, while quasars show strong, broad emission lines. Many methods have been proposed to estimate the boost factor due to beaming [13, 30-34]. As noted above, the core-dominance parameter $R$ can be used as an indicator of the orientation of the jet, which is also correlated with polarization [35, 36].

In this study, we compiled 252 FBLLs and 198 NFBLLs, as well as 283 FQs and 1112 NFQs. When we probe the correlation between $\log R$ and $\alpha_R$, we find that there are significant differences between FQs and NFQs from the K-S test ($p = 6.486 \times 10^{-30}$ for $\log R$ and $p = 7.144 \times 10^{-19}$ for $\alpha_R$). However, our K-S results also demonstrate that there is no dramatic difference between FBLLs and NFBLLs ($p = 0.009$ for $\log R$ and $p = 0.020$ for $\alpha_R$). Linford et al. [3, 11] previously indicated that FBLLs tend to be similar to NFBLLs. For instance, FBLLs and NFBLLs have nearly identical core brightness-temperature distributions. In addition, there are no differences in the fraction of polarized BL Lac objects or polarization distribution. Therefore, our conclusion supports that of Linford et al. [3, 11].

### 3.1 Correlation between core-dominance parameter $\log R$ and radio spectral index $\alpha_R$

Fan et al. [37] obtained a theoretical correlation between the total radio spectral index $\alpha_{\text{Total}}$ and the core-dominance parameter $\log R$ (see also refs. [13, 16, 23]):

$$\alpha_{\text{Total}} = \frac{R}{1 + R} \alpha_{\text{core}} + \frac{1}{1 + R} \alpha_{\text{ext}}.$$  

(11)

We adopt this relation for the present sample and obtain fits for $\alpha_{\text{core}}$ and $\alpha_{\text{ext}}$.

The plot in Figure 13 shows that we cannot use a simple curve of the form given in eq. (11) to fit all data points, although there is a clear trend for $\alpha_R$ to be associated with $\log R$. Even though the total radio spectral index $\alpha_{\text{Total}}$ can be divided into a core component $\alpha_{\text{core}}$ and an extended one $\alpha_{\text{ext}}$, they are likely to be different for different sources. Thus, one possible explanation for the scatter in Figure 13 is that the flux densities used to calculate the spectral index may not be the same as those used to calculate the core-dominance ratio [13, 16, 23]. For this reason, we estimated the spectral indices $\alpha_{\text{core}}$ and $\alpha_{\text{ext}}$ for the whole sample by minimizing $
abla \sum(\alpha_{\text{Total}} - \alpha_{\text{core}}R/(1 + R) + \alpha_{\text{ext}}(1 + R))^2$.

When we adopt this correlation across the whole sample of Fermi and non-Fermi AGNs (see Figure 13), we obtain $\alpha_{\text{core}} = -0.021 \pm 0.016$ and $\alpha_{\text{ext}} = 0.785 \pm 0.013$, with $\chi^2 = 0.257, R^2 = 0.220$, and a chance probability $p < 10^{-22}$. These fitting results are consistent with the general consensus that $\alpha_{\text{core}} = 0.00$ and $\alpha_{\text{ext}} = 0.75$ [13, 16, 23].

For the Fermi AGNs alone, we obtain $\alpha_{\text{core}} = -0.012 \pm 0.029$ and $\alpha_{\text{ext}} = 0.402 \pm 0.048$, with $\chi^2 = 0.213, R^2 = 0.059$ and a chance probability $p = 1.867 \times 10^{-10}$, for the entire Fermi AGN sample. On the other hand, for the non-Fermi AGNs, we have $\alpha_{\text{core}} = 0.006 \pm 0.019$ and $\alpha_{\text{ext}} = 0.805 \pm 0.014$, with $\chi^2 = 0.260, R^2 = 0.200$, and a chance probability $p < 10^{-20}$ (see Figure 14).

For all blazars in our sample, we obtain the following correlations. We find $\alpha_{\text{core}} = 0.108$ and $\alpha_{\text{ext}} = 0.247$, with $\chi^2 = 0.199, R^2 = 0.002$, and a chance probability $p = 1.731 \times 10^{-4}$.
for the Fermi BL Lacs: \( \alpha_{\text{core}} = 0.118 \) and \( \alpha_{\text{ext}} = 0.504 \), with \( \chi^2 = 0.220, R^2 = 0.049 \) and a chance probability \( p = 3.879 \times 10^{-8} \) for the non-Fermi BL Lacs; \( \alpha_{\text{core}} = -0.031 \) and \( \alpha_{\text{ext}} = 0.022 \), with \( \chi^2 = 0.188, R^2 = 0.003 \), and a chance probability \( p = 0.569 \) for the Fermi quasars; and \( \alpha_{\text{core}} = -0.108 \) and \( \alpha_{\text{ext}} = 0.710 \), with \( \chi^2 = 0.196, R^2 = 0.230 \), and a chance probability \( p < 10^{-20} \) for the non-Fermi quasars (Figure 15).

### 3.2 Correlation between the core-dominance parameter log \( R \) and the \( \gamma \)-ray-photon index \( \alpha_{\gamma}^{\text{ph}} \) for Fermi AGNs

Now, we turn to investigating the correlation between the \( \gamma \)-ray-photon spectral index \( \alpha_{\gamma}^{\text{ph}} \) and the core-dominance parameter \( R \). However, we do not have core-dominance parameters in the gamma-ray band. If we assume that there is a correlation similar to that given in eq. (11) between \( \alpha_{\gamma}^{\text{ph}} \) and \( R \), we can use that equation to investigate the correlation between the gamma-ray spectral index and the core-dominance parameter. In this sense, \( \alpha_{\gamma}^{\text{ph, Total}}, \alpha_{\gamma}^{\text{ph, core}}, \) and \( \alpha_{\gamma}^{\text{ph, ext}} \) represent the \( \gamma \)-ray-photon spectral indices for the total, core, and extended components, respectively:

\[
\alpha_{\gamma, \text{Total}}^{\text{ph}} = \frac{R}{1 + R} \alpha_{\gamma, \text{core}}^{\text{ph}} + \frac{1}{1 + R} \alpha_{\gamma, \text{ext}}^{\text{ph}}.
\]  

(12)
When we plot all points from our entire sample, as in Figure 16, we obtain a curve for the correlation between the gamma-ray spectral index and the core-dominance parameter, which is similar to that found above for $\alpha_R$ vs. $\log R$. For all Fermi AGNs, we obtain $\alpha_{\gamma,\text{core}} = 2.279 \pm 0.018$ and $\alpha_{\gamma,\text{ext}} = 2.049 \pm 0.030$, with $\chi^2 = 0.087, R^2 = 0.016$, and a chance probability $p < 10^{-4}$ (see Figure 16). For the various subclasses, we have $\alpha_{\gamma,\text{core}} = 2.039 \pm 0.020$ and $\alpha_{\gamma,\text{ext}} = 1.821 \pm 0.038$, with $\chi^2 = 0.042, R^2 = 0.040$, and a chance probability $p < 10^{-3}$ for the Fermi BL Lacs; $\alpha_{\gamma,\text{core}} = 2.482 \pm 0.016$ and $\alpha_{\gamma,\text{ext}} = 2.249 \pm 0.033$, with $\chi^2 = 0.033, R^2 < 10^{-3}$, and a chance probability $p < 10^{-3}$ for the Fermi quasars; $\alpha_{\gamma,\text{core}} = 2.266 \pm 0.069$ and $\alpha_{\gamma,\text{ext}} = 2.488 \pm 0.084$, with $\chi^2 = 0.082, R^2 = 0.020$, and a chance probability $p < 10^{-3}$ for the Fermi blazar candidates of uncertain class; and $\alpha_{\gamma,\text{core}} = 2.227 \pm 0.133$ and $\alpha_{\gamma,\text{ext}} = 2.329 \pm 0.077$, with $\chi^2 = 0.120, R^2 = 0.015$, and a chance probability $p < 10^{-4}$ for the Fermi non-blazars (see Figure 17 and Table 5).

Some previous studies have indicated that, in the radio band, fluctuations in the core dominate the observed variability in the total flux density for core-dominated sources but that the fluctuations can be suppressed by the radio jets in jet-dominated sources. This suggests that the spectrum is softer for high-variability sources, and thus, the spectral index is larger. If we assume that the variability comes from the AGN jets, then for high-variability sources—e.g., Fermi blazars—the gamma-ray spectral index is dominated by the core component. In this paper, for all Fermi AGNs, we obtained $\alpha_{\gamma,\text{core/FAGN}} = 2.279 \pm 0.018$, while the statistical-average value for those FAGNs is $2.269 \pm 0.295$. These two values are very close. Similarly, we also obtained approximate values for $\alpha_{\gamma,\text{core}}$ and for the statistical averages for FBLLs, FQs, FBCCUs, and FNBs (Table 5). Our analysis shows that the derived core component of the gamma-ray photon index $\alpha_{\gamma,\text{core}}$ is approximately equal to the statistical-average value of the photon index $\langle \alpha_{\gamma,\text{ph}} \rangle$ relative to the extended component $\alpha_{\gamma,\text{ext}}$. Therefore, if we adopt eq. (12) to represent the correlation between $R$ and $\alpha_{\gamma,\text{ph}}$, in terms of the two-component model for gamma-ray emission, then the gamma-ray emissions originate mainly from the core component.

3.3 Correlation between the core-dominance parameter $\log R$ and the gamma-ray luminosity $L_{\gamma}$ for Fermi AGNs

Wu et al. [38] found that the ratio of gamma-ray luminosity to the extended radio luminosity, $\log (L_{\gamma}/L_{\text{ext}})$, is correlated with $\log R$ for 124 Fermi blazars, with a positive linear regression, and asked, “Does that mean that the gamma-ray luminosity consists of two components, as do the radio bands?” However, our Figure 11 does not show a clear positive correlation between the gamma-ray luminosity and $\log R$. We thus consider the two-component model for the gamma-ray emissions to be the same as in the radio band, namely $L_{\text{total}} = L_{\text{core}} + L_{\text{ext}} = R \cdot L_{\text{ext}} + L_{\text{ext}} = (1 + R) L_{\text{ext}}$. In contrast, we do obtain a clear positive correlation between the gamma-ray luminosity to the extended radio luminosity, $\log (L_{\gamma}/L_{\text{ext}})$, and $\log (R + 1)$: $\log (L_{\gamma}/L_{\text{ext}}) = (0.92 \pm 0.05) \log (R + 1) + (2.68 \pm 0.06)$, with a correlation coefficient $r = 0.56$ and a chance probability of $p < 10^{-20}$ (see Figure 18). Thus, if we exclude the effect of extended radio luminosity from gamma-ray luminosity, we obtain a clear positive relation between $\log (L_{\gamma}/L_{\text{ext}})$ and the core-dominance parameter.

Thus, if we consider a two-component model for the gamma-ray emission that is composed of a core (beamed) component and an extended (unbeamed) one, we conclude that the gamma-ray emissions from blazars originate mainly from the core (jet) component (see also ref. [13]).

Previous studies have shown that the core-dominance parameter $R$ can also serve as an indicator of the beaming effect (see refs. [1, 39]):

$$R(\theta) = \frac{f_{\text{in}}}{f_{\text{in}}(1 - \beta \cos \phi)^{-n+\alpha} + (1 + \beta \cos \phi)^{-n+\alpha}},$$

(13)

where $f_{\text{in}}$ is the intrinsic ratio, defined as the ratio of intrinsic flux density in the jet to the extended flux density in the comoving frame, $f_{\text{in}} = S_{\text{core}}^{\text{in}}/S_{\text{ext}}^{\text{in}}$ [15], $\theta$ is the viewing angle, $\gamma = (1 - \beta^2)^{-1/2}$ is the Lorentz factor, $\alpha$ is the radio spectral index, and $n$ depends on the shape of the emitted spectrum and the physical details of the jet, with $n = 2$ for a continuous jet and $n = 3$ for blobs.

The association between the spectral index $\alpha_R$ and the core-dominance parameter $R$ in radio sources is a subject of continuing study. Fan et al. [16] calculated the core-dominance parameter and radio spectral index for the entire sample, and obtained a relation between $\alpha_R$ and $\log R$. We
suggest that relativistic beaming can also produce an association between the spectral index and core-dominance parameter for radio emission from extragalactic sources (see also ref. [23]). In the two-component beaming model, the prominence of the core relative to the extended emission is defined by the ratio of core-to-extended-flux density measured in the rest frame of the source. Thus, log $R$ has become a suitable statistical measure of beaming and orientation. The use of log $R$ as a beaming indicator and an indicator of radio source orientation is predicated on Doppler beaming effects in the radio core, which is an unresolved base of the relativistic jet.

### 3.4 Correlation between radio core luminosity log $L_{\text{core}}$ and $\gamma$-ray luminosity log $L_{\gamma}$

With an increasing development of radio surveys, an increasing number of low-luminosity, core-dominated sources are being discovered. However, they have not yet been detected by Fermi because they are too faint. Some studies have proposed that low-luminosity, core-dominated radio galaxies may contribute prominently to the unresolved extragalactic $\gamma$-ray background [40]. The radio core emission is directly associated with the power produced by non-thermal processes in the central engine of the AGN. We, thus, consider the core luminosities of the radio sources, rather than their total luminosities.

For $\gamma$-ray radio galaxies, Di Mauro et al. [41], Hooper et al. [42], and Stecker et al. [40] found a strong relation between the radio core luminosity at 5 GHz and $\gamma$-ray luminosity. Using our large sample of Fermi sources, we can study the correlations among the 5 GHz radio core luminosity, log $L_{\text{core}}$, and $\gamma$-ray luminosity, log $L_{\gamma}$, for the Fermi
AGNs.

For all Fermi sources, we obtain the fit $\log L_{\gamma} = (0.70 \pm 0.02) \log L_{\text{core}} + (15.68 \pm 0.89)$, with $r = 0.80$ and $p < 10^{-20}$. Our result is shown in Figure 19, where the lines are the best fits for Fermi BL Lacs—$\log L_{\gamma} = (0.68 \pm 0.04) \log L_{\text{core}} + (16.71 \pm 1.72)$, with $r = 0.73$ and $p < 10^{-12}$—and $\log L_{\gamma} = (0.76 \pm 0.04) \log L_{\text{core}} + (13.21 \pm 1.74)$, with $r = 0.75$ and $p < 10^{-22}$, for Fermi quasars. Our results demonstrate that the sources with high $\gamma$-ray luminosities are indeed strongly core-dominated.

Synchrotron self-Compton (SSC) and external-radiation-Compton scattering are two typical models for the $\gamma$-radiation mechanism of blazars, the latter scenario being based on inverse Compton (IC) scattering. Previous studies of high-energy $\gamma$-ray emission assumed that the SSC $\gamma$-rays originate from jets of more than a parsec from the central engine and that the IC $\gamma$-rays are produced comparatively close to the center (i.e., within a parsec distance) [43]. Our results from Figure 19 suggest that the $\gamma$-rays originate co-spatially within the arcsecond-scale radio core emission, indicating that the $\gamma$-rays are produced by the SSC process (see also ref. [43]).

3.5 Doppler variability factor $\delta_{\text{var}}$ and the beaming effect

Blazars are a subclass of AGNs with extreme observational properties, which are explained by relativistic beaming. Owing to Fermi/LAT, the $\gamma$-ray-loud blazars detected in the high-energy bands provide us with a good opportunity to investigate the emission mechanism and beaming effects.

According to relativistic beaming, emissions from the jet are strongly boosted in the observer’s frame; that is, $S_{\text{ob}} = \delta^2 S_{\text{eq}}$, where $S_{\text{eq}}$ represents the intrinsic emission in the source frame and $S_{\text{ob}}$ is the observed luminosity, with $\delta$ being the Doppler-boost factor. The value of $p$ depends on the shape of the emitted spectrum and the physical properties of the jet, with $p = 3 + \alpha$ for a moving compact source and $p = 2 + \alpha$ for a continuous jet, where $\alpha$ is the spectral index.

The Doppler factor $\delta$ is quite important for probing the beaming effect and the high-energy emission mechanism. Some methods have been proposed for calculating $\delta$ from the variability brightness temperature $T_{\text{var}}$ [34,44-46] in the radio band:

$$T_{\text{var}} = 1.47 \times 10^{13} \frac{d^2 \Delta S_{\text{ab}}(\nu)}{y^2 T_{\text{var}}(1+z)^4} K,$$

where $\Delta S_{\text{ab}}(\nu)$ is the amplitude of a flare in Jy, $\nu$ is the observed frequency in GHz, $t_{\text{var}}$ is the rise time of a flare in days (see ref. [44]), $z$ is the redshift, and $d_l$ is the luminosity distance in Mpc. We can then calculate the Doppler-variability factor as:

$$\delta_{\text{var}} = (1+z) \frac{T_{\text{var}}}{T_{\text{eq}}},$$

where $T_{\text{eq}}$ is the equipartition brightness temperature, $T_{\text{eq}} = 2.78 \times 10^{11} K$ [34].

The plot of the Doppler-variability factor $\log \delta_{\text{var}}$ against the core-dominance parameter $\log R$ for Fermi AGNs in Figure 20 demonstrates a positive association between $\log \delta_{\text{var}}$ and $\log R$, with a correlation coefficient $r = 0.37$ and a chance probability of $p < 10^{-9}$. We adopted the Doppler-variability factors from Liodakis et al. [34], which gives the largest catalog of blazars with the estimated Doppler-variability factors. We, thus, obtained 65 Fermi BL Lacs and 191 Fermi quasars with available core-dominance parameters. This correlation shows that $R$ is a good indicator of the beaming effect.

From the distribution shown in Figure 20, we find that the average values of $\log \delta_{\text{var}}$ for Fermi BL Lacs and Fermi
The γ-ray variability index is associated with the core-dominance parameter \( \log R \) (e.g., ref. [37]). Fermi quasars are generally higher than those for the Fermi AGNs. The solid line in the lower panel shows the best linear fit, with a correlation coefficient \( r = 0.37 \) and chance probability \( p < 10^{-6} \).

Some previous studies have indicated that \( \gamma \)-ray luminosity is associated with the core-dominance parameter (e.g., ref. [37]). The \( \gamma \)-ray variability index is correlated with that in the radio band [47] and is associated with the core-dominance parameter [13], and there is a real correlation between \( \gamma \)-ray luminosity and the Doppler factor [26]. In this paper, we confirm these findings, all of which suggest beaming of \( \gamma \)-ray emissions.

### 3.6 Unified scheme for the dichotomy between BL Lacs/radio quasars and FRI/II-type galaxies

Following the scheme originally proposed by Fanaroff & Riley [48] in terms of edge-darkened and edge-brightened objects, radio galaxies are classified into two morphological subclasses, namely FR type one (FRI) and FR type two (FRII). FRI objects are more powerful than FRI radio galaxies. For FRIs, the jets are thought to decelerate and become subrelativistic on scales of hundreds of pc to kpc. On the contrary, the jets in FRIIs are moderately relativistic and supersonic all the way from the core to the hotspots. FRIs appear to have large jet-inclination angles, and correspondingly, small core-dominance parameters, which can be observed only if they have sufficiently large radio flux densities. Because the source flux becomes weaker as the distance increases, \( \log R \) decreases with distance. However, there are no FRIIs observed at large angles to the jet axis, as reflected by their small core-dominance parameters, and therefore, they have not been detected by Fermi/LAT. In our sample of FR radio galaxies, we obtain from the redshift distribution \( \langle z \rangle_{\text{FRI}} = 0.11 \pm 0.043 \) and \( \langle z \rangle_{\text{FRII}} = 0.66 \pm 0.58 \). However, we suspect that the differences in the redshift distributions of FRIs and FRIIs may be a selection effect.

In our sample of Fermi AGNs, we found only two FRIs—4FGL J0319.8+4130 and 4FGL J1630.6+8234—and two FRIIs—4FGL J0436.9+2915 and 4FGL J1443.1+5201. In contrast, we have 122 FRIs and 218 FRIIs among non-Fermi AGNs. We denote all these sources as FRIs and FRIIs, irrespective of whether or not they have been detected by Fermi. For the core-dominance parameters, we thus obtain \( \langle \log R \rangle_{\text{FRI}} = -1.178 \pm 0.042 \), with a median of \(-1.193\), in the range of \(-3.420\) to 1.270 for the 124 FRIs, and find \( \langle \log R \rangle_{\text{FRII}} = -1.858 \pm 0.057 \), with a median of \(-1.800\), in the range of \(-3.420\) to 1.270 for the 220 FRIIs.

Circumstantial evidence for this unified model includes the fact that the power and morphology of the extended (supposedly unbeamed) radio emissions of the BL Lac are similar to those of the FRI sources (e.g., refs. [49, 50]).

In the framework of this unified model for active galactic nuclei, the low-luminosity FRI radio galaxies are identified as the parent population of BL Lac objects. Some studies have proposed that BL Lacs and quasars are distributed differently, and thus, their parent populations must be different as well, which would require two separate unified schemes. Based on the unbeamed characteristics of FRI-type galaxies and the idea that BL Lacs are relativistically beamed, Xie et al. [51] indicated that their observed apparent magnitudes must be corrected for the Doppler effect, and found that BL Lacs ~ FRIs and quasars ~ FRIIs follow the same Hubble relation. Capetti et al. [52] used ROSAT and HST observations to isolate the emission originating from the nuclei of FRI sources, with the aim of studying their spectral-energy distributions (SEDs), and found that the SEDs of FRIs are qualitatively (but probably not quantitatively) similar to those of BL Lac...
objects, supporting the identification of these sources as their misoriented counterparts. Furthermore, Capetti and Celotti [53] found that, for a subsample of (only) five FRIs, the optical core luminosity decreases with an increase in the angle of the jet axis with respect to the line of sight, which agrees with the unified scheme.

In this paper, we find that the differences in the luminosities of BL Lacs and FRIs can be explained with a single amplification factor over the extended luminosity range in the radio band. This clearly provides further support for the unified BL Lac/FRI scheme and for the interpretation that in all cases, we are seeing synchrotron emission from a relativistic jet. According to the unified model, the beam and unbeam populations must cover the range of extended luminosity, as this is considered isotropic. On the contrary, emission from the core is affected by beaming. Radio galaxies have a fainter central component, whose intensity depends on the Doppler factor $\delta = \Gamma(1 - \beta \cos \theta)^{-1}$, where $\Gamma = (1 - \beta^2)^{-1/2}$, $\beta c$ is the bulk velocity of the emitting plasma, and $\theta$ is the angle between the direction of the jet and the line of sight. The transformation law for the specific flux density is, in fact, $F_\nu = \delta^{\gamma-\alpha} F'_\nu$, where the primed quantity refers to the co-moving frame, $\alpha$ is the local spectral index, and $p = 2$ or 3 for the case of a continuous jet or a moving sphere.

In a previous study, we probed this unified model by adopting the extended radio luminosity $L_{\text{ext}}$, associated with BL Lacs $\sim$ FRIs and quasars $\sim$ FRIs, and confirmed the current unification scheme (see refs. [16, 23]). Because we have already compiled a larger sample of blazars and FR radio galaxies, we can use it to study the unified model further.

For the 450 BL Lacs (FBLLs+NFBLs) in our current sample, we obtain $\langle \log L_{\text{ext}} \rangle_{\text{BL}} = 24.83 \pm 1.31$ (W Hz$^{-1}$) in the range of 19.41 to 29.47; for the 1395 quasars (FQs+NFQs), $\langle \log L_{\text{ext}} \rangle_{\text{Q}} = 26.07 \pm 1.12$ (W Hz$^{-1}$) in the range of 21.47 to 29.76; for the 124 FR type-I galaxies, $\langle \log L_{\text{ext}} \rangle_{\text{FRI}} = 24.76 \pm 1.27$ (W Hz$^{-1}$) in the range of 21.02 to 27.81; and for the 220 FR type II galaxies, $\langle \log L_{\text{ext}} \rangle_{\text{FRII}} = 25.91 \pm 1.14$ (W Hz$^{-1}$) in the range of 19.45-28.00 (see Figure 21).

When we performed the K-S test, we obtained $p = 66.73\%$ ($d_{\text{max}} = 0.07$) for BL Lacs and FR I galaxies; $p = 5.63\%$ ($d_{\text{max}} = 0.14$) for quasars and FR II galaxies; $p = 2.81 \times 10^{-47}$ ($d_{\text{max}} = 0.39$) for BL Lacs and quasars; $p = 6.27 \times 10^{-27}$ ($d_{\text{max}} = 0.45$) for FBL Lacs and FR I galaxies; $p = 5.48 \times 10^{-20}$ ($d_{\text{max}} = 0.44$) for quasars and FR II galaxies; and $p = 7.12 \times 10^{-14}$ ($d_{\text{max}} = 0.44$) for FRI and FR II galaxies.

We, therefore, conclude that BL Lacs and FRIs, as well as quasars and FRIs, originate from the same parent population. When we probe the correlation between $\log L_{\text{ext}}$ and $R$ for our sample of BL Lacs $\sim$ FRIs and quasars $\sim$ FRIs, we find a negative trend for BL Lacs $\sim$ FRIs $\log L_{\text{ext}} = -(0.21 \pm 0.05) \log R + (24.86 \pm 0.05)$, with a correlation coefficient of $r = -0.19$ and a chance probability of $p = 3.50 \times 10^{-6}$ (see Figure 22). Conversely, we do not obtain a clear correlation for quasars $\sim$ FRIs (see also Figure 22).

4 Conclusion

The Fermi-LAT has revealed many new discoveries from the $\gamma$-ray sky. The latest catalog, 4FGL, includes 5065 sources based on the first 8 years of data. AGNs constitute a vast majority of sources in the catalog, 98% of which are blazars [21, 22]. Fermi-LAT has, thus, pioneered a new era for the exploration of high-energy astrophysics, which has provided us with a good opportunity to study the $\gamma$-ray mechanisms, high-energy phenomena, and extreme properties of extragalactic sources, such as blazars.

Standard beaming models indicate that the more core-dominated sources should be more beamed, and consequently, have larger Doppler-boost factors. This paper indicates that objects that are more core-dominated are indeed also more boosted.

Figure 21 (Color online) Distributions of the extended luminosities at 5 GHz $\log L_{\text{ext}}$ in units of W Hz$^{-1}$ (upper panel) and the cumulative probabilities (lower panel) for the whole sample. In this plot, the magenta solid line stands for BL Lacs, the red dashed line for quasars, the blue dotted line for FR I galaxies, and the green dash-dotted line for FR II galaxies.
From our discussions, given the core-dominance parameter \( \log R \) and the radio spectral index \( \alpha_R \), we can obtain \( \alpha_{\text{core}} \) and \( \alpha_{\text{ext}} \). When we adopt the same type of relation for the \( \gamma \)-ray-photon index \( \alpha_{\gamma} \), we can also obtain \( \alpha_{\gamma,\text{core}} \) and \( \alpha_{\gamma,\text{ext}} \). In this paper, we have compiled 4388 AGNs with available values of \( \log R \), which include 630 Fermi-detected AGNs and 3758 non-Fermi-detected AGNs. This sample is still not large enough, but we believe that it is adequate for the statistical analyses reported herein. From these analyses, we draw the following conclusions:

(1) The core-dominance parameters \( \log R \) and radio spectral indices \( \alpha_R \) are quite different for different subclasses of both Fermi AGNs and non-Fermi AGNs. In particular, Fermi AGNs, on average, have higher values of \( \log R \) than non-Fermi AGNs, and the former have smaller values of \( \alpha_R \) than the latter. For \( \log R \), we obtain the following sequence for Fermi AGNs: \( \langle \log R \rangle_{\text{Fermi BL Lacs}} \approx \langle \log R \rangle_{\text{Fermi quasars}} > \langle \log R \rangle_{\text{Fermi non-blazars}} \). We also obtain \( \langle \log R \rangle_{\text{non-Fermi BL Lacs}} > \langle \log R \rangle_{\text{non-Fermi quasars}} > \langle \log R \rangle_{\text{non-Fermi non-blazars}} \) for the non-Fermi AGNs.

(2) We have obtained theoretical correlation fits between the radio spectral indices \( \alpha_R \) and the core-dominance parameters \( \log R \) for both Fermi sources and non-Fermi sources. We have also obtained similar fits for all subclasses, which means that the spectral index depends on the core-dominance parameter, probably due to relativistic beaming.

(3) There is a trend that larger values of \( \log R \) are also correlated with larger \( \gamma \)-ray luminosities \( L_{\gamma} \).

(4) When we adopt the correlation obtained from a two-component model for the \( \gamma \)-ray-photon spectral indices \( \alpha_{\gamma} \) and the core-dominance parameters \( \log R \) for the Fermi sources, we find that the spectral index for the core component is close to that for the total emission. This suggests that the gamma-ray emissions originate mainly from the core (jet) component.

(5) We also conclude that BL Lac objects can be unified with FR type I radio galaxies and that quasars can be unified with FRII galaxies.

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**Figure 22** (Color online) Plot of \( \log L_{\text{ext}} \) against \( \log R \) for BL Lacs ~ FRI (upper panel) and quasars ~ FRII (lower panel). We obtain a negative correlation \( \log L_{\text{ext}} = -0.21 \pm 0.05 \log R + 24.86 \pm 0.05 \) for BL Lacs ~ FRI, but there is no clear correlation for quasars ~ FRII. In this plot, a magenta \( \circ \) stands for a BL Lac, a red \( \square \) for a quasar, a blue \( \triangle \) for an FRI, and a green \( \Delta \) line for an FRII galaxy.
