Classification of Uncertain-Type Blazar Candidates Based on Effective Spectral Indices[*]

Chen Guangqiang^{1,2} Yan Jianjun^{1,2}

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Abstract

There are approximately 4000 blazars in the Fermi/LAT (Large Area Telescope) source catalog, of which more than 40% are Blazar Candidates of Uncertain type (BCU). Determining the types of BCUs is of great help for better studying the properties of blazars. Taking Fermi blazars as the sample, the effective spectral indices between pairs of radio (R), optical (O), X-ray (X), and γ-ray (γ) bands, $\alpha_{\rm RO}$, $\alpha_{\rm RX}$, $\alpha_{\rm R\gamma}$, $\alpha_{\rm OX}$, $\alpha_{\rm O\gamma}$, and $\alpha_{\rm X\gamma}$, were calculated. A sample of 3387 blazars with two or more effective spectral indices was obtained, including 828 Flat Spectral Radio Quasars (FSRQ), 1382 BL Lacertae objects (BL Lac), and 1177 BCUs. Using the effective spectral indices as characteristic parameters, the GK (Gustafson-Kessel) fuzzy clustering algorithm was applied to perform unsupervised classification of the 1177 BCUs. The results show that among the 1177 BCUs, 904 are FSRQs and 273 are BL Lacs. Among the BCUs whose classification results differ from those in the literature, most are classified as FSRQs in this work, whereas they are classified as BL Lacs in the literature. From the perspective of multiwavelength effective spectral indices, BL Lacs with low synchrotron peak frequencies have radiation properties similar to those of FSRQs across multiple wavebands.

Full Text

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Classification of Uncertain-Type Blazar Candidates Based on Effective Spectral Indices*

Liu Bei1,2 Yang Jianghe1,2,3† Fan Junhui3‡ Yang Wenxin3 Wang Shenghui1,2 Yu Manxian1,2 Bai Hongzi1,2
Chen Guangqiang1,2 Yan Jianjun1,2

1 School of Mathematics, Hunan University of Arts and Science, Changde 415000

2 Hunan Provincial Key Laboratory of Optoelectronic Information Integration and Optical Manufacturing Technology, Changde 415000

3 Center for Astrophysics, Guangzhou University, Guangzhou 510006

Abstract The Fermi/LAT (Large Area Telescope) source catalog contains about 4,000 blazars, of which more than 40% are blazar candidates of uncertain type (Blazar Candidate of Uncertain type, BCU). Determining the types of BCUs is of great help for better studying the properties of blazars. Taking Fermi blazars as the sample, we calculated the effective spectral indices between pairs of the radio (R), optical (O), X-ray (X), and γ-ray (γ) bands, namely $\alpha_{\rm RO}$, $\alpha_{\rm RX}$, $\alpha_{R\gamma}$, $\alpha_{\rm OX}$, $\alpha_{O\gamma}$, and $\alpha_{X\gamma}$. A sample of 3,387 blazars with two or more effective spectral indices was obtained, including 828 flat-spectrum radio quasars (Flat Spectral Radio Quasar, FSRQ), 1,382 BL Lacertae objects (BL

Lac), and 1,177 BCUs. Using the effective spectral indices as feature parameters, the GK (Gustafson–Kessel) fuzzy clustering algorithm was applied to conduct unsupervised classification of the 1,177 BCUs. The results show that among the 1,177 BCUs, 904 are FSRQs and 273 are BL Lacs. Among the BCUs whose classification results differ from those in the literature, most are classified here as FSRQs, whereas the literature classifies them as BL Lacs. From the multi-band effective spectral indices, BL Lacs with low synchrotron peak frequencies and FSRQs have similar radiative properties across multiple bands.

Keywords galaxies: active; galaxies: nuclei; quasars: general; BL Lacertae objects: general; methods: statistical
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1 Introduction

Active Galactic Nuclei (AGN) are a class of extragalactic objects with bright and compact nuclear regions, accompanied by intense nuclear activity. As a subclass of AGN, blazars have become one of the hot research fields because of their extreme observational properties[1–14]. According to observational properties or certain characteristic parameters, blazars have several classifications. According to emission-line characteristics, blazars are divided into flat-spectrum radio quasars (Flat Spectral Radio Quasar, FSRQ) with strong emission lines and BL Lacertae objects (BL Lac object) without emission lines. The spectral energy distribution (Spectral Energy Distribution, SED) of blazars from the radio band to the gamma-ray (γ-ray) band has two very prominent peaks[15–17]. The first peak is produced by synchrotron radiation and is called the synchrotron peak; the second is mainly produced by inverse Comp–

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† yjh2019@huas.edu.cn
‡ fjh@gzhu.edu.cn

The peak produced by Compton scattering is called the inverse Compton peak. For the inverse Compton peaks of some BL Lac objects, the hadronic model can provide a good explanation [18, 19]. Some authors have studied the SEDs of the synchrotron-radiation component using different blazar samples [15–17, 20–26]. According to the synchrotron peak frequency, Refs. [15–17, 23] classified blazars into three classes: low-, intermediate-, and high-synchrotron-peak-frequency blazars, denoted respectively as LSP (Low Synchrotron Peak), ISP (Intermediate Synchrotron Peak), and HSP (High Synchrotron Peak). Correspondingly, BL Lacs were divided into low-synchrotron-peak BL Lacs (Low synchrotron peak BL Lac, LBL), intermediate-synchrotron-peak BL Lacs (Intermediate synchrotron peak BL Lac, IBL), and high-synchrotron-peak BL Lacs (High synchrotron peak BL Lac, HBL). Ref. [27] studied the SEDs of the inverse Compton component of blazars in 4FGL-DR3 (The 4th Fermi Gamma-ray Large Area Telescope (LAT)-Data Release 3) [28], derived relevant parameters for the inverse Compton peaks of 3,743 blazars, and classified blazars into low- and high-inverse-Compton-peak-frequency blazars, denoted as LCP (Low Inverse Compton Peak frequency) and HCP (High Inverse Compton Peak frequency). Ref. [28] used the γ-ray variability index (Variability Index, I_{V}) to classify blazars into variable sources and quiescent sources. Celestial objects in the same class indicate that all or part of their physical properties are identical or similar, whereas different classes indicate that there are certain differences in their physical properties. The above classifications of blazars provide important help for our understanding and study of blazars.

Since the Fermi Large Area Telescope (Fermi/LAT (Large Area Telescope)) began operating, it has released a large amount of γ-ray observational data for blazars, greatly advancing blazar research. During the first 14 yr of observations, Fermi/LAT released eight source catalogs based on observations over 3 months and over 1, 2, 4, 8, 10, 12, and 14 yr; these are 0FGL [29], 1FGL [30], 2FGL [31], 3FGL [32], 4FGL [33], 4FGL-DR2 [34], 4FGL-DR3 [28], and 4FGL-DR4 [35], respectively. There are many identical blazars in the eight source catalogs, meaning that these blazars have multiple observational results. For these blazars observed multiple times, because the observation times differ, the results of each observation differ, and the source names and classifications are not entirely the same. This has made it inconvenient for us to study the properties of blazars comprehensively and systematically. To study the properties of Fermi blazars more comprehensively and effectively, we merged the blazars in the eight source catalogs. The results show that the eight source catalogs contain 3,993 non-repeated blazars, including 840 FSRQs, 1,495 BL Lacs, and 1,658 BCUs (Blazar Candidate of Uncertain type [28]).

Among the blazars observed by Fermi/LAT, more than 40% are BCUs. Therefore, better blazar studies require larger samples, and determining the types of BCUs is an urgent problem to be solved. A large body of literature has used different methods and different parameters to estimate the types of BCUs [36–41]. For example, Ref. [38] used a support vector machine (Support Vector Machine, SVM) classifier to classify BCUs in 4FGL-DR3; Refs. [39–40] used random forest (Random Forest, RF), SVM, artificial neural network (Artificial Neural Network, ANN), and extreme gradient boosting (eXtreme Gradient Boosting, XGBoost) classifiers, respectively, to classify BCUs; Ref. [41] used five different supervised machine-learning algorithms—RF, logistic regression (Logistic Regression, LR), XGBoost, categorical features + gradient boosting (Categorical Features + Gradient Boosting, CatBoost), and ANN—to classify BCUs. The algorithms used in these studies are all supervised machine-learning algorithms, which require manually predefined labels, have a certain degree of subjectivity, and cannot complete classification in real time.

Refs. [42–43] discussed the relationships among the effective spectral indices between the radio, optical, X-ray, and γ-ray bands for Fermi 3FGL blazars. Refs. [15–17] discussed the relationship between the effective spectral indices α_{RO} and α_{OX}. From Refs. [15–17, 42–43], it can be seen that, in the relationships among effective spectral indices, different subclasses of blazars show obvious clustering phenomena. In this paper, the multi-band effective spectral indices of blazars observed by Fermi/LAT will be calculated. Based on the clustering properties of blazar subclasses in the relationships among multi-band effective spectral indices, and using effective spectral indices as characteristic parameters, the GK fuzzy clustering algorithm is adopted to perform unsupervised identification of the types of BCUs in Fermi/LAT.

2 Blazar samples and calculation of effective spectral indices

We merged the blazars in the eight source catalogs released by Fermi/LAT during 14 yr of observations and found a total of 3,993 non-repeated blazars. Taking these 3,993 blazars as the sample, and following the methods of Refs. [42–43], we obtained and processed the radio (R), optical (O), and X-ray (X) data and calculated the flux density at 1 GeV in γ-rays (γ). The effective spectral indices between each pair of the four bands were calculated: α_{RO}, α_{RX}, $\alpha_{\mathrm{R}\gamma}$, α_{OX}, $\alpha_{\mathrm{O}\gamma}$, and $\alpha_{\mathrm{X}\gamma}$. The formula for calculating the effective spectral index [15] is

$$\alpha_{\mathrm{ab}} = -\frac{\lg\left(f_b/f_a\right)}{\lg\left(\nu_b/\nu_a\right)},$$

where α_{ab} is the effective spectral index from band a to

the effective spectral index between bands a and b; f_a and f_b are the processed flux densities at the band frequencies ν_a and ν_b, respectively.

Using this method, a total of 3,387 blazars with effective spectral indices in two or more different wavebands were obtained, including 828 FSRQs, 1,382 BL Lacs, and 1,177 BCUs.

3 GK Fuzzy-Clustering Classification Method for BCUs

GK (Gustafson–Kessel) fuzzy clustering is an improved fuzzy-clustering algorithm. Its characteristic is that it adopts a dynamically adjusted distance metric. By constructing an adaptive distance-measure criterion through covariance matrices, this algorithm can better handle clustering distributions of different shapes. For a given data set $X = \{x_1, x_2, \cdots, x_n\}$, clustering analysis requires optimization of a specific objective function,

$$J(X, V, U) = \sum_{i=1}^{c} \sum_{j=1}^{n} (u_{ij})^{\theta} D_{ij}^2. \tag{1}$$

In Eq. (1), X is the given data set; V is the cluster center; U is the membership matrix; c is the number of cluster centers; n is the sample size; u_{ij} is the membership degree of the j-th element in the i-th class; D_{ij}^2 is the Mahalanobis distance; and θ is the fuzziness index. Its selection is of crucial importance, since an excessively large θ value may lead to blurred class boundaries.

The Mahalanobis distance is adopted as the distance measure between a sample and a class center. Its formula is

$$D_{ij}^2 = (x_j - v_i)^{\mathrm{T}} Z_i (x_j - v_i). \tag{2}$$

In Eq. (2), $v_i (i = 1, 2, \cdots, c)$ is the i-th cluster center; Z_i is a positive definite symmetric matrix, which can be obtained from

$$Z_i = \det(F_i)^{1/n} F_i^{-1} \tag{3}$$

where F_i is the covariance matrix. In GK fuzzy clustering, the cluster centers $V = (v_1, v_2, \cdots, v_c)^{\mathrm{T}}$ and the membership matrix $U = [u_{ij}]_{c \times n}$ can be obtained by minimizing the objective function, satisfying the constraint

$$\sum_{i=1}^{c} u_{ij} = 1, \quad u_{ij} \in [0, 1], \quad 1 \le i \le c, \quad 1 \le j \le n.$$

Thus, the optimization problem of the objective function can be solved by the Lagrange multiplier method. By constructing the Lagrange function and taking derivatives, the extremal constraint conditions are obtained, and the membership equation and cluster centers are then updated iteratively:

$$u_{ij} = 1 \Bigg/ \sum_{z=1}^{c} \left(\frac{D_{ij}}{D_{zj}} \right)^{2/(\theta-1)}; \tag{4}$$

$$v_i = \sum_{j=1}^{n} \left[(u_{ij})^{\theta} x_j \right] \Bigg/ \sum_{j=1}^{n} (u_{ij})^{\theta}. \tag{5}$$

The implementation procedure of the GK fuzzy-clustering algorithm includes the following key steps:

(1) Determine the number of clusters c (the two classes BL Lac and FSRQ) and set the fuzziness index θ (usually taken as $1.5 \sim 2.5$). According to Eq. (4), randomly initialize the membership matrix U, and then calculate the cluster center v_i using Eq. (5).

(2) Calculate the covariance matrix F_i for each class:

$$F_i = \sum_{j=1}^{n} \left[(u_{ij})^m (x_j - v_i)(x_j - v_i)^{\mathrm{T}}\right] \Big/ \sum_{j=1}^{n} (u_{ij})^m.$$

Based on the covariance matrix F_i, construct the positive definite symmetric matrix Z_i, and then calculate the Mahalanobis distance D_{ij}^2 according to Eq. (2). Using the obtained Mahalanobis distance D_{ij}^2, recalculate the membership matrix U using Eq. (4). If the change in the membership matrix does not satisfy $\|u^{(L+1)} - u^{(L)}\| < \eta$, increase the iteration number L; here η is the convergence threshold. If the condition is satisfied, terminate the iteration.

In this paper, based on the Euclidean closeness degree and the nearest-selection principle, the BL Lac and FSRQ types among BCUs can be effectively distinguished. Here, the closeness value is positively correlated with the similarity between samples. For data sets A and B, the Euclidean closeness is calculated as

$$E(A, B) = 1 - \frac{1}{\sqrt{n}} \sqrt{\sum_{i=1}^{n} \left[u_A(u_i) - u_B(u_i)\right]^2}. \tag{6}$$

In the formula, $u_A(u_i)$ and $u_B(u_i)$ are respectively the membership functions of data u_i with respect to data sets A and B; n is the number of data to be classified. According to the nearest-selection principle, type identification is achieved by comparing the Euclidean closeness values between each sample and the two standard cluster centers: when a BCU sample has a higher closeness to the BL Lac class center, it is assigned to BL Lac; if its closeness to the FSRQ class center is more pronounced, it is classified as FSRQ. Finally, the BCU classification results under different parameter models are compared, yielding the type-tendency results for the BCUs.

4 GK Fuzzy-Clustering Model for Known-Type blazars

There are 15 combinations of the six effective spectral indices between pairs of the Radio, Optical, X-ray, and γ-ray bands (α_{RO}, α_{RX}, $\alpha_{\mathrm{R}\gamma}$, α_{OX}, $\alpha_{\mathrm{O}\gamma}$ and $\alpha_{\mathrm{X}\gamma}$), namely $(\alpha_{\mathrm{RO}}, \alpha_{\mathrm{RX}})$, $(\alpha_{\mathrm{RO}}, \alpha_{\mathrm{R}\gamma})$, $(\alpha_{\mathrm{RO}}, \alpha_{\mathrm{OX}})$, $(\alpha_{\mathrm{RO}}, \alpha_{\mathrm{O}\gamma})$, $(\alpha_{\mathrm{RO}}, \alpha_{\mathrm{X}\gamma})$, $(\alpha_{\mathrm{RX}}, \alpha_{\mathrm{R}\gamma})$, $(\alpha_{\mathrm{RX}}, \alpha_{\mathrm{OX}})$, $(\alpha_{\mathrm{RX}}, \alpha_{\mathrm{O}\gamma})$, $(\alpha_{\mathrm{RX}}, \alpha_{\mathrm{X}\gamma})$, $(\alpha_{\mathrm{R}\gamma}, \alpha_{\mathrm{OX}})$, $(\alpha_{\mathrm{R}\gamma}, \alpha_{\mathrm{O}\gamma})$, $(\alpha_{\mathrm{R}\gamma}, \alpha_{\mathrm{X}\gamma})$, $(\alpha_{\mathrm{OX}}$,

$\alpha_{\mathrm{O}\gamma})$, $(\alpha_{\mathrm{OX}}, \alpha_{\mathrm{X}\gamma})$, and $(\alpha_{\mathrm{O}\gamma}, \alpha_{\mathrm{X}\gamma})$. Because not all blazars simultaneously have six effective spectral indices, some combinations are absent for part of the blazar sample. The numbers of blazars and their subclasses, BL Lacs and FSRQs, under each combination are shown in Table 1. In Table 1, $N_{\rm blazar}$, $N_{\rm BL\ Lac}$, and $N_{\rm FSRQ}$ denote, respectively, the numbers of blazars, BL Lacs, and FSRQs under each combination. The GK fuzzy clustering algorithm was used to perform clustering analysis on all spectral-index combinations for BL Lacs and FSRQs, yielding the GK fuzzy clustering results for BL Lacs and FSRQs under 15 combinations, as shown in Figure 1.

Table 1 Number of blazars and their subclasses (BL Lacs and FSRQs) under 15 effective spectral index combinations

Parameter combination	$N_{\rm blazar}$	$N_{\rm BL\ Lac}$	$N_{\rm FSRQ}$
$(\alpha_{\rm RO}, \alpha_{\rm RX})$	1251	761	490
$(\alpha_{\rm RO}, \alpha_{\rm R\gamma})$	2168	1344	824
$(\alpha_{\rm RO}, \alpha_{\rm OX})$	1251	761	490
$(\alpha_{\rm RO}, \alpha_{\rm O\gamma})$	2168	1344	824
$(\alpha_{\rm RO}, \alpha_{\rm X\gamma})$	1251	761	490
$(\alpha_{\rm RX}, \alpha_{\rm R\gamma})$	1264	770	494
$(\alpha_{\rm RX}, \alpha_{\rm OX})$	1251	761	490
$(\alpha_{\rm RX}, \alpha_{\rm O\gamma})$	1251	761	490
$(\alpha_{\rm RX}, \alpha_{\rm X\gamma})$	1264	770	494
$(\alpha_{\rm R\gamma}, \alpha_{\rm OX})$	1264	770	494
$(\alpha_{\rm R\gamma}, \alpha_{\rm O\gamma})$	2168	1344	824
$(\alpha_{\rm R\gamma}, \alpha_{\rm X\gamma})$	1264	770	494
$(\alpha_{\rm OX}, \alpha_{\rm O\gamma})$	1280	790	490
$(\alpha_{\rm OX}, \alpha_{\rm X\gamma})$	1280	790	490
$(\alpha_{\rm O\gamma}, \alpha_{\rm X\gamma})$	1280	790	490

From Figure 1, it can be seen that, after processing by the GK fuzzy clustering algorithm using combinations of effective spectral-index feature parameters, most BL Lacs and FSRQs are distributed around their respective cluster centers, and the separation is relatively clear. This indicates that the GK fuzzy clustering algorithm, combined with effective spectral-index feature parameters, can effectively complete unsupervised clustering analysis of BL Lacs and FSRQs.

Based on the clustering models obtained from training (Figure 1), the Euclidean closeness was calculated according to the principle of proximity, thereby achieving the identification of FSRQs and BL Lacs. In each clustering-identification process, 300 sample data points were randomly selected as the test set, including 150 BL Lacs and 150 FSRQs. To reduce errors, the recognition rate (R) was calculated 10 times for each feature-parameter combination. The recognition rates (R) of the 10 classification results for the 15 feature-parameter combinations are shown in Table 2. As can be seen from Table 2, combinations using multi-band effective spectral indices as feature parameters can distinguish BL

Figure 1. GK fuzzy clustering of BL Lacs and FSRQs under 15 effective spectral-index combinations.

Figure 1: Figure 1. GK fuzzy clustering of BL Lacs and FSRQs under 15 effective spectral-index combinations.

Lacs from FSRQs relatively well. The 10-run average recognition rates (R_{Ave}) for all combinations are above 80%, and the overall average recognition rate is 87.10%. Among them, the combination ($\alpha_{\mathrm{RO}}, \alpha_{\mathrm{OX}}$) gives the best identification performance, with an average recognition rate of 91.23%.

5 GK Fuzzy Clustering and Type Identification of BCUs

The BCUs under the 15 effective spectral-index combinations were correspondingly placed into the GK fuzzy clustering models of blazars with known types (Figure 1(a)-(o)), and the distributions of BCUs in the 15 GK fuzzy clustering models were obtained, as shown in Figure 2(a)-(o). Based on the clustering centers of the known BL Lacs and FSRQs and the Euclidean closeness of each BCU, clustering analysis was performed on the BCU samples. The blazar sample in this paper contains 1177 BCUs, and the clustering-analysis results are shown in Table 3. In Table 3, columns (2)-(4) are, respectively, the number of BCUs under the parameter combination in column (1), and the numbers of BCUs classified as BL Lacs and FSRQs.

By calculating the effective spectral indices of the BCU samples and their Euclidean closeness to the standard cluster centers of BL Lacs and FSRQs, unsupervised classification of BCUs was achieved. The classification results of the BCU samples under the 15 effective spectral-index combinations, as well as the final preferred types, are shown in Table 4 (note: only part of the BCU classification results is given here; the complete data can be downloaded at: DOI: https://doi.org/10.57760/sciencedb.36222; CSTR: https://cstr.cn/31253.11.sciencedb.36222). In Table 4, label B indicates that the BCU is classified as a BL Lac, and F indicates that it is classified as an FSRQ. The numbers 1-15 in the header of Table 4 denote the 15 spectral-index combinations, respectively: ($\alpha_{\mathrm{RO}}, \alpha_{\mathrm{RX}}$), ($\alpha_{\mathrm{RO}}, \alpha_{\mathrm{R\gamma}}$), ($\alpha_{\mathrm{RO}}, \alpha_{\mathrm{OX}}$), ($\alpha_{\mathrm{RO}}, \alpha_{\mathrm{O\gamma}}$), ($\alpha_{\mathrm{RO}}, \alpha_{\mathrm{X\gamma}}$), ($\alpha_{\mathrm{RX}}, \alpha_{\mathrm{R\gamma}}$), ($\alpha_{\mathrm{RX}}, \alpha_{\mathrm{OX}}$), ($\alpha_{\mathrm{RX}}, \alpha_{\mathrm{O\gamma}}$), ($\alpha_{\mathrm{RX}}, \alpha_{\mathrm{X\gamma}}$), ($\alpha_{\mathrm{R\gamma}}, \alpha_{\mathrm{OX}}$), ($\alpha_{\mathrm{R\gamma}}, \alpha_{\mathrm{O\gamma}}$), ($\alpha_{\mathrm{R\gamma}}, \alpha_{\mathrm{X\gamma}}$), ($\alpha_{\mathrm{OX}}, \alpha_{\mathrm{O\gamma}}$), ($\alpha_{\mathrm{OX}}, \alpha_{\mathrm{X\gamma}}$), and ($\alpha_{\mathrm{O\gamma}}, \alpha_{\mathrm{X\gamma}}$). When the preferred type (C_{T}) of a BCU is given comprehensively, if the number of B labels exceeds the number of F labels, then the BCU is preferably classified as a BL Lac; otherwise, it is preferably classified as an FSRQ. Assuming that each pair of effective spectral indices has the same accuracy in identifying the BCU type, this paper defines the accuracy (p) of the preferred BCU type as follows: if the preferred type of a BCU source is BL Lac or FSRQ, then its accuracy is equal to the ratio of the number of B or F labels to the sum of the numbers of B and F labels. The accuracy p of the BCU preferred type obtained according to this definition is shown in the last column of Table 4.

Legend: BLL; FSRQ; FSRQ cluster center; BLL cluster center; membership curve.

Fig. 1 GK fuzzy clustering of BL Lacs and FSRQs under 15 effective spectral-index combinations. (a) $(\alpha_{\rm RO}, \alpha_{\rm RX})$; (b) $(\alpha_{\rm RO}, \alpha_{\rm R\gamma})$; (c) $(\alpha_{\rm RO}, \alpha_{\rm OX})$; (d) $(\alpha_{\rm RO}, \alpha_{\rm O\gamma})$; (e) $(\alpha_{\rm RO}, \alpha_{\rm X\gamma})$; (f) $(\alpha_{\rm RX}, \alpha_{\rm R\gamma})$; (g) $(\alpha_{\rm RX}, \alpha_{\rm OX})$; (h) $(\alpha_{\rm RX}, \alpha_{\rm O\gamma})$; (i) $(\alpha_{\rm RX}, \alpha_{\rm X\gamma})$; (j) $(\alpha_{\rm R\gamma}, \alpha_{\rm OX})$; (k) $(\alpha_{\rm R\gamma}, \alpha_{\rm O\gamma})$; (l) $(\alpha_{\rm R\gamma}, \alpha_{\rm X\gamma})$; (m) $(\alpha_{\rm OX}, \alpha_{\rm O\gamma})$; (n) $(\alpha_{\rm OX}, \alpha_{\rm X\gamma})$; (o) $(\alpha_{\rm O\gamma}, \alpha_{\rm X\gamma})$.

Fig. 1 GK fuzzy clustering of BL Lacs and FSRQs under 15 effective spectral index combinations. (a) $(\alpha_{\rm RO}, \alpha_{\rm RX})$; (b) $(\alpha_{\rm RO}, \alpha_{\rm R\gamma})$; (c) $(\alpha_{\rm RO}, \alpha_{\rm OX})$; (d) $(\alpha_{\rm RO}, \alpha_{\rm O\gamma})$; (e) $(\alpha_{\rm RO}, \alpha_{\rm X\gamma})$; (f) $(\alpha_{\rm RX}, \alpha_{\rm R\gamma})$; (g) $(\alpha_{\rm RX}, \alpha_{\rm OX})$; (h) $(\alpha_{\rm RX}, \alpha_{\rm O\gamma})$; (i) $(\alpha_{\rm RX}, \alpha_{\rm X\gamma})$; (j) $(\alpha_{\rm R\gamma}, \alpha_{\rm OX})$; (k) $(\alpha_{\rm R\gamma}, \alpha_{\rm O\gamma})$; (l) $(\alpha_{\rm R\gamma}, \alpha_{\rm X\gamma})$; (m) $(\alpha_{\rm OX}, \alpha_{\rm O\gamma})$; (n) $(\alpha_{\rm OX}, \alpha_{\rm X\gamma})$; (o) $(\alpha_{\rm O\gamma}, \alpha_{\rm X\gamma})$.

Table 2 The recognition rates from 10 classification trials using 15 feature parameter combinations

Parameter combination	1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th	$R_{\rm Ave}$/%
$(\alpha_{\rm RO}, \alpha_{\rm RX})$	88.63	89.75	89.38	90.88	93.00	88.75	90.63	92.63	87.50	92.00	90.32
$(\alpha_{\rm RO}, \alpha_{\rm R\gamma})$	85.63	83.25	84.50	85.25	86.63	85.25	84.63	85.88	83.25	86.13	85.04
$(\alpha_{\rm RO}, \alpha_{\rm OX})$	91.63	90.75	89.38	90.88	93.00	89.75	90.63	92.63	91.50	92.00	91.23
$(\alpha_{\rm RO}, \alpha_{\rm O\gamma})$	87.63	87.75	87.88	89.38	88.13	88.38	87.88	85.38	87.25	86.63	87.63
$(\alpha_{\rm RO}, \alpha_{\rm X\gamma})$	89.88	88.00	90.38	92.75	88.50	87.38	88.63	91.75	90.88	91.00	89.92
$(\alpha_{\rm RX}, \alpha_{\rm R\gamma})$	89.38	88.63	89.13	87.38	91.00	88.88	87.38	90.25	88.25	87.75	88.80
$(\alpha_{\rm RX}, \alpha_{\rm OX})$	86.50	87.63	85.25	86.00	87.75	86.50	86.25	87.88	86.88	85.50	86.61
$(\alpha_{\rm RX}, \alpha_{\rm O\gamma})$	88.63	89.25	88.50	92.38	91.75	90.63	87.75	88.63	89.63	91.00	89.82
$(\alpha_{\rm RX}, \alpha_{\rm X\gamma})$	86.63	87.75	88.88	89.38	88.13	87.38	85.88	86.38	87.25	86.00	88.27
$(\alpha_{\rm R\gamma}, \alpha_{\rm OX})$	80.38	83.25	80.63	83.75	81.63	81.00	83.75	78.38	82.50	81.75	81.60
$(\alpha_{\rm R\gamma}, \alpha_{\rm O\gamma})$	83.00	79.50	84.25	83.25	84.63	84.38	80.25	83.25	82.88	84.75	83.01
$(\alpha_{\rm R\gamma}, \alpha_{\rm X\gamma})$	87.75	89.25	86.88	90.38	88.75	87.25	88.50	91.00	88.13	87.38	88.53
$(\alpha_{\rm OX}, \alpha_{\rm O\gamma})$	85.63	85.25	83.25	87.00	85.88	84.88	86.00	85.50	86.75	85.25	85.54
$(\alpha_{\rm OX}, \alpha_{\rm X\gamma})$	83.25	83.63	86.63	84.13	84.75	82.38	84.75	83.13	85.00	84.13	84.19
$(\alpha_{\rm O\gamma}, \alpha_{\rm X\gamma})$	86.63	85.88	83.75	86.88	88.25	84.13	87.88	83.38	88.50	85.25	86.05

6 Discussion

6.1 Analysis of Results

As can be seen from Fig. 1(a)-(o), after the combinations using effective spectral indices as feature parameters are processed by the GK fuzzy clustering algorithm, most BL Lac objects and FSRQs are distributed around their respective cluster centers. Table 2 further shows that the average recognition rates for the blazar type obtained with each combination of effective spectral indices all exceed 80%; among them, the combination ($\alpha_{\mathrm{RO}},\ \alpha_{\mathrm{OX}}$) gives the highest recognition rate, reaching 91.23%. Statistical analysis of the classification results (Table 4) shows that 936 BCUs have completely consistent recognition results under the different parameter combinations, while 241 BCUs have inconsistent recognition results. According to the definition adopted in this paper, the average accuracy for objects recognized as FSRQs is 96.76%, the accuracy for objects recognized as BL Lacs is 81.37%, and the average accuracy of the overall recognition results is 93.18%. This result indicates that the clustering properties of FSRQs are more significant than those of BL Lacs. In summary, it is feasible to use effective spectral indices as feature parameters and apply the GK fuzzy clustering algorithm for unsupervised classification of BCUs.

The type of a blazar can be completely determined by its synchrotron-radiation properties. The spectral indices α_{RO} and α_{OX} can basically determine the synchrotron radiation spectrum [15-16]. Reference [26] studied the properties of the radio spectrum and found that radio radiation has a relatively strong influence on the synchrotron radiation spectrum, and that its influence on the synchrotron spectra of LBLs, FSRQs, and HBLs decreases in that order. References [42-43] discussed the degree of separation between HBLs and FSRQs in scatter plots of relations between effective spectral indices, and found that the smaller the difference in frequency range between two effective spectral indices, $\Delta \lg \nu$, the higher the degree of separation between the two in the plot. We analyzed the relationship between the recognition rates for blazar types obtained from the 15 pairs of spectral-index combinations and $\Delta \lg \nu$. The results show a negative correlation between them, with a correlation coefficient of -0.64 and a chance probability of 1.05%. The $\Delta \lg \nu$ of the combination ($\alpha_{\mathrm{RO}},\ \alpha_{\mathrm{OX}}$) is relatively small among the 15 pairs of combinations; therefore, the ($\alpha_{\mathrm{RO}},\ \alpha_{\mathrm{OX}}$) combination yields a relatively high recognition rate for the types of BCUs. From the above discussion, it can be concluded that the ($\alpha_{\mathrm{RO}},\ \alpha_{\mathrm{OX}}$) combination should perform very well in estimating blazar types.

6.2 Comparison with Results in the Literature

Reference [38] used SVM to classify BCUs; Reference [39] used RF, SVM, and ANN, respectively, to classify BCUs in 4FGL; and Reference [41] used five different supervised machine-learning algorithms—RF, LR, XGBoost, CatBoost, and ANN—to classify BCUs in 4FGL-DR3. We compared the classification results of this paper with those of References [38-39, 41].

Legend: FSRQ cluster center; BLL cluster center; membership curve; BCU.

Figure 2 In the blazar GK fuzzy clustering model, the distribution of BCUs under various spectral-index combinations. (a) $(\alpha_{\mathrm{RO}}, \alpha_{\mathrm{RX}})$; (b) $(\alpha_{\mathrm{RO}}, \alpha_{\mathrm{R\gamma}})$; (c) $(\alpha_{\mathrm{RO}}, \alpha_{\mathrm{OX}})$; (d) $(\alpha_{\mathrm{RO}}, \alpha_{\mathrm{O\gamma}})$; (e) $(\alpha_{\mathrm{RO}}, \alpha_{\mathrm{X\gamma}})$; (f) $(\alpha_{\mathrm{RX}}, \alpha_{\mathrm{R\gamma}})$; (g) $(\alpha_{\mathrm{RX}}, \alpha_{\mathrm{OX}})$; (h)

$(\alpha_{RX}, \alpha_{O\gamma})$; (i) $(\alpha_{RX}, \alpha_{X\gamma})$; (j) $(\alpha_{R\gamma}, \alpha_{OX})$; (k) $(\alpha_{R\gamma}, \alpha_{O\gamma})$; (l) $(\alpha_{R\gamma}, \alpha_{X\gamma})$; (m) $(\alpha_{OX}, \alpha_{O\gamma})$; (n) $(\alpha_{OX}, \alpha_{X\gamma})$; (o) $(\alpha_{O\gamma}, \alpha_{X\gamma})$.

Fig. 2 In the blazar GK fuzzy clustering model, the distribution of BCUs under various spectral index combinations. (a) $(\alpha_{RO}, \alpha_{RX})$; (b) $(\alpha_{RO}, \alpha_{R\gamma})$; (c) $(\alpha_{RO}, \alpha_{OX})$; (d) $(\alpha_{RO}, \alpha_{O\gamma})$; (e) $(\alpha_{RO}, \alpha_{X\gamma})$; (f) $(\alpha_{RX}, \alpha_{R\gamma})$; (g) $(\alpha_{RX}, \alpha_{OX})$; (h) $(\alpha_{RX}, \alpha_{O\gamma})$; (i) $(\alpha_{RX}, \alpha_{X\gamma})$; (j) $(\alpha_{R\gamma}, \alpha_{OX})$; (k) $(\alpha_{R\gamma}, \alpha_{O\gamma})$; (l) $(\alpha_{R\gamma}, \alpha_{X\gamma})$; (m) $(\alpha_{OX}, \alpha_{O\gamma})$; (n) $(\alpha_{OX}, \alpha_{X\gamma})$; (o) $(\alpha_{O\gamma}, \alpha_{X\gamma})$.

Table 3. The numbers of BCUs classified as BL Lacs and FSRQs under 15 combined-parameter sets

Parameter combination	N_{BCU}	$N_{BL\,Lac}$	N_{FSRQ}
(1)	(2)	(3)	(4)
$(\alpha_{RO}, \alpha_{RX})$	105	73	32
$(\alpha_{RO}, \alpha_{R\gamma})$	1154	193	961
$(\alpha_{RO}, \alpha_{OX})$	105	69	36
$(\alpha_{RO}, \alpha_{O\gamma})$	1154	215	939
$(\alpha_{RO}, \alpha_{X\gamma})$	105	67	38
$(\alpha_{RX}, \alpha_{R\gamma})$	114	70	44
$(\alpha_{RX}, \alpha_{OX})$	105	81	24
$(\alpha_{RX}, \alpha_{O\gamma})$	105	69	36
$(\alpha_{RX}, \alpha_{X\gamma})$	114	75	39
$(\alpha_{R\gamma}, \alpha_{OX})$	105	67	38
$(\alpha_{R\gamma}, \alpha_{O\gamma})$	1154	227	927
$(\alpha_{R\gamma}, \alpha_{X\gamma})$	114	70	44
$(\alpha_{OX}, \alpha_{O\gamma})$	119	60	59
$(\alpha_{OX}, \alpha_{X\gamma})$	119	88	31
$(\alpha_{O\gamma}, \alpha_{X\gamma})$	119	70	49

Reference [38] used the pairwise relationships among the γ-ray photon spectral index (α_{ph}), γ-ray photon flux ($\lg F$), and γ-ray variability index ($\lg I_V$), and adopted an SVM classifier to classify 1517 BCUs in 4FGL. Among the classification results for the three parameter sets, namely $(\alpha_{ph}, \lg F)$, $(\alpha_{ph}, \lg I_V)$, and $(\lg F, \lg I_V)$, the classifications of 556 BCUs were not completely consistent. This work and reference [38] have 1045 BCU samples in common. In the final tendency classification results, 321 BCUs among the common samples of this work and reference [38] have inconsistent classifications. Among the inconsistent samples, 311 BCUs were classified as BL Lacs in reference [38] but as FSRQs in this work; the remaining 10 BCUs were classified as FSRQs in reference [38] but as BL Lacs in this work.

Reference [39] used multiple methods to classify BCUs, but the classification results obtained by the different methods were not completely identical. Among the 1312 BCUs classified by multiple methods, the classification results of 256 BCUs were not completely consistent. This work and reference [39] have 758 BCU samples in common. In the final tendency classification results, 238 BCUs among the common samples of this work and reference [39] have inconsistent classifications. Among the inconsistent samples, 216 BCUs were classified as BL Lacs in reference [39] but as FSRQs in this work; 22 BCUs were classified as FSRQs in reference [39] but as BL Lacs in this work.

In the final tendency classification results, 258 BCUs among the common samples of this work and reference [41] have inconsistent classifications. Among the inconsistent samples, 238 BCUs were classified as BL Lacs in reference [41] but as FSRQs in this work; 20 BCUs were classified as FSRQs in reference [41] but as BL Lacs in this work.

From the above comparison, the classification results of this work are largely consistent with those of references [38–39, 41]. Among the BCUs with different classification results, most were classified as FSRQs in this work, whereas they were classified as BL Lacs in references [38–39, 41].

Table 4. Classification of BCUs under different effective spectral-index combinations and their final tendency types

FGL Name	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	C_T	p
3FGL J0512.2+2918	B	F	B	F	B	B	B	B	B	B	F	B	F	B	B	B	0.73
4FGL J0003.1-5248	B	F	B	F	B	B	B	B	B	B	B	B	B	B	B	B	0.87
4FGL J0047.9+5448	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	1.00
4FGL J0049.5-4150	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	1.00
…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…

6.3 Analysis of Classification Differences

Judging from references [38–39, 41] and the results of this work, classifying BCUs with different parameters or different methods may also yield different results. There are many reasons for differences in classification results, such as the parameters'

Liu Bei et al.: Type Identification of Uncertain-Type Blazar Candidates Based on Effective Spectral Indices the accuracy is insufficient; the methods used have certain limitations; variability and changing-look sources make the types of some BCUs intrinsically uncertain, etc. Variability is one of the most typical observational properties of blazars, and it is manifested across the entire waveband. Spectral indices given by observations at different epochs may differ; therefore, variability may lead to different classification results. In addition, when blazars are in a flaring state, their synchrotron-radiation peak frequencies become higher and their spectra also become flatter

44

, which may cause classifications determined from spectral indices to differ. Therefore, in this paper the spectral indices were calculated based on the median values of the observed fluxes. On the surface, inconsistencies among different studies in the classification of the same BCU should be caused by differences in classification methods and in the feature parameters adopted. In fact, however, there is another important reason: whether the BL Lacs that we now classify as having low synchrotron peak frequencies, namely LBLs, are all truly BL Lacs.

Taking the two combinations of feature parameters used in this paper, $(\alpha_{\rm RO}, \alpha_{\rm OX})$ and $(\alpha_{\rm RO}, \alpha_{\rm RX})$, as examples, the GK fuzzy clustering of LBLs and FSRQs was analyzed (Fig. 3). In Fig. 3, the red open squares are the cluster centers of LBLs, and the blue filled circles are the cluster centers of FSRQs. It can be clearly seen from Fig. 3 that LBLs and FSRQs are basically distributed in the same region in the clustering diagrams, and the cluster centers of LBLs and FSRQs almost overlap. Therefore, when BCUs are classified according to the method of this paper, BCUs with low synchrotron peak frequencies (LBLs) will, with high probability, be classified as FSRQs. This is also the reason why, among most BCUs for which the classification results of this paper differ from those in the literature, our classification results are FSRQs whereas the literature results are BL Lacs. By statistically analyzing the effective spectral indices calculated in this paper, the mean values of the six effective spectral indices for FSRQs and LBLs are obtained as follows: $\bar{\alpha}_{\rm RO}({\rm FSRQ, LBL}) = (0.59, 0.60)$, $\bar{\alpha}_{\rm RX}({\rm FSRQ, LBL}) = (0.74, 0.73)$, $\bar{\alpha}_{{\rm R}\gamma}({\rm FSRQ, LBL}) = (0.81, 0.81)$, $\bar{\alpha}_{\rm OX}({\rm FSRQ, LBL}) = (1.05, 0.97)$, $\bar{\alpha}_{{\rm O}\gamma}({\rm FSRQ, LBL}) = (0.95, 0.95)$, and $\bar{\alpha}_{{\rm X}\gamma}({\rm FSRQ, LBL}) = (0.91, 0.92)$. Therefore, the mean values of the multiband effective spectral indices of LBLs and FSRQs are basically the same. Multiband effective spectral indices are physical quantities related to multiband radiation mechanisms, and they are typical parameters reflecting the basic properties of blazars. Thus, the above results indicate that LBLs and FSRQs should have similar multiband radiation properties, and they can be grouped into one class. Here, only from the perspective of spectral properties, LBLs and FSRQs may be grouped into one class; however, whether LBLs truly belong to FSRQs still needs to be confirmed from some of their physical properties.

Figure text: (a) horizontal axis: Normalized $\alpha_{\rm RO}$; vertical axis: Normalized $\alpha_{\rm OX}$. (b) horizontal axis: Normalized $\alpha_{\rm RO}$; vertical axis: Normalized $\alpha_{\rm RX}$. Legend: FSRQ; FSRQ cluster center; LBL; LBL cluster center.

Fig. 3 GK fuzzy clustering of LBLs and FSRQs under the combinations of ($\alpha_{\mathrm{RO}}, \alpha_{\mathrm{OX}}$) and ($\alpha_{\mathrm{RO}}, \alpha_{\mathrm{RX}}$)

Fig. 3 GK fuzzy clustering of LBLs and FSRQs under the combinations of ($\alpha_{\mathrm{RO}}, \alpha_{\mathrm{OX}}$) and ($\alpha_{\mathrm{RO}}, \alpha_{\mathrm{RX}}$)

Giommi et al.

45

studied the classification of Fermi/LAT blazars under the unified model. They found that LBLs and FSRQs have similar spectral energy distributions; in the relation between the gamma-ray photon spectral index and gamma-ray luminosity, and in the relation between radio flux density and gamma-ray flux density, a large number of BL Lacs and FSRQs have similar distribution properties. Reference

45

argued that nearly three quarters of Fermi/LAT BL Lacs, as well as essentially all blazars without determined redshifts, are in fact FSRQs, because their emission lines are swamped by the nonthermal continuum. We analyzed the relation between gamma-ray luminosity and the gamma-ray photon spectral index, as well as the relation between radio and gamma-ray flux densities. From the scatter-point distributions in the correlation diagrams, it is clearly visible that LBLs and FSRQs have a relatively large overlapping region in the diagrams, whereas HBLs have almost no overlap with FSRQs. Therefore, most of the BL Lacs that Ref.

45

argued should be classified as FSRQs should be LBLs. To determine the class of a blazar···

type; according to the definition, it is still necessary to examine whether emission lines are present and the strength of those emission lines. Of course, we can also determine the physical differences between BL Lac objects and FSRQs from their spectral energy distributions, the ratio of broad-line-region luminosity to Eddington luminosity, and the equivalent widths of their emission lines[^46], thereby determining their types.

In summary, according to the results of Ref. [45] and the finding in this paper that LBLs and FSRQs have similar spectral indices and similar clustering properties, if LBLs and FSRQs have similar radiation properties in multiple wavebands, they should be classified into the same category. That is to say, LBLs may be FSRQs. If LBLs and FSRQs are indeed the same class of objects, then the classification results for BCUs in this paper should be closer to the true situation than the results in the literature.

7 Summary

Using blazars observed by Fermi/LAT as the sample, this paper calculated the six effective spectral indices between each pair of the radio (R), optical (O), X-ray (X), and γ-ray (γ) bands: α_{RO}, α_{Rx}, $\alpha_{\mathrm{R}\gamma}$, α_{Ox}, $\alpha_{\mathrm{O}\gamma}$, and $\alpha_{\mathrm{X}\gamma}$. A sample of 3387 blazars with two or more effective spectral indices was obtained, including 828 FSRQs, 1382 BL Lac objects, and 1177 BCUs. Taking the effective spectral indices as feature parameters, the GK fuzzy clustering algorithm was used to predict the types of the 1177 BCUs. The following results and conclusions were obtained.

(1) For the 3387 blazars in the 8-year Fermi/LAT source catalog, six effective spectral indices between each pair of the four wavebands at 1.4 GHz, 2.43×10^{14} Hz, 1 keV, and 1 GeV were given.

(2) Taking the effective spectral indices as feature parameters, it is feasible to use the GK fuzzy clustering algorithm to perform unsupervised classification of blazars of uncertain type (BCUs). The classification results show that, among the 1177 BCUs, there are 904 FSRQs and 273 BL Lac objects.

(3) Statistics show that the mean values of the six effective spectral indices of LBLs and FSRQs are basically the same. The GK fuzzy-clustering centers of LBLs and FSRQs, with the effective spectral indices as feature parameters, almost overlap. Therefore, LBLs and FSRQs have similar radiation properties in multiple wavebands and should be classified into the same category. That is, LBLs may be FSRQs.

(4) Among the BCUs for which the classification results in this paper differ from those in the literature, most are classified by us as FSRQs but are classified in the literature as BL Lac objects. According to the research results of Giommi et al.[^45] and the results of this paper, if LBLs are indeed FSRQs, then the classification results for BCUs in this paper should be closer to the true situation.

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The Recognition of Blazar Candidate of Uncertain Type Based on Effective Spectral Index

LIU Bei1,2 YANG Jiang-he1,2,3 FAN Jun-hui3 YANG Wen-xin3 WANG Sheng-hui1,2
TUO Man-xian1,2 BAI Hong-zi1,2 CHEN Guang-qiang1,2 NIE Jian-jun1,2

(1 College of Mathematics and Physics Science, Hunan University of Arts and Science, Changde 415000)
(2 Hunan Provincial Key Laboratory of Optoelectronic Information Integration and Optical Manufacturing Technology, Changde 415000)
(3 Center for Astrophysics, Guangzhou University, Guangzhou 510006)

Abstract The Fermi/LAT (Large Area Telescope) source catalog contains approximately 4000 blazars, of which over 40% are classified as Blazar Candidates of Uncertain type (BCUs). Determining the precise classification of these BCUs is crucial for advancing our understanding of blazar properties. In this study, we analyzed a sample of Fermi blazars by calculating their effective spectral indices between radio (R), optical (O), X-ray (X), and γ-ray (γ) bands, including $\alpha_{\rm RO}$, $\alpha_{\rm RX}$, $\alpha_{\rm R\gamma}$, $\alpha_{\rm OX}$, $\alpha_{\rm O\gamma}$, and $\alpha_{\rm X\gamma}$. From this analysis, we obtained a sample of 3387 blazars with at least two valid spectral indices, consisting of 828 flat-spectrum radio quasars (FSRQs), 1382 BL Lacertae objects (BL Lacs), and 1177 BCUs. Using the effective spectral indices as feature parameters, we performed unsupervised classification on the 1177 BCUs via the Gustafson-Kessel (GK) fuzzy clustering algorithm. The results show that: among the 1177 BCUs, 904 were classified as FSRQs and 273 as BL Lacs. For sources with inconsistent classifications between our study and previous literature, most were identified as FSRQs in our work but as BL Lacs in previous studies. From the perspective of multi-wavelength spectral indices, low-synchrotron-peaked BL Lacs (LBLs) exhibit similar radiation properties to FSRQs across multiple bands.

Key words galaxies: active, galaxies: nuclei, quasars: general, BL Lacertae objects: general, methods: statistical

Note: Figure translations are in progress. See original paper for figures.