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# The Doppler Effect and Spectral Energy Distribution of Blazars

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**Abstract** The relativistic beaming model is adopted to discuss quantitatively the observational differences between radio-selected BL Lac objects (RBLs) and X-ray-selected BL Lac objects (XBLs), and between BL Lac objects and flat spectrum radio quasars (FSRQs). The main results are the following: (1) In the Doppler corrected color-color ($\alpha_{\rm ro}^{\rm in} - \alpha_{\rm ox}^{\rm in}$) diagram, XBLs and FSRQs occupy separated regions, while RBLs bridge the gap between them. These properties suggest that similar intrinsic physical processes operate in all the objects under a range of intrinsic physical conditions. (2) Our results are consistent with the results of Sambruna, Maraschi and Urry (1996) from other methods. We show the $\alpha_{\rm xox}$ introduced by Sambruna to be a good index for describing the energy distribution because it represents the intrinsic energy distribution and includes the Doppler correction. (3) The Doppler effect of relativistic beaming is the main mechanism, and the physical differences (such as magnetic fields, electron energies) are also important complementary factors for understanding the relation between XBLs and RBLs;

**Key words:** Blazars: general — quasars: general — radiation mechanism: nonthermal

## 1 INTRODUCTION

Blazars, consisting of BL Lac objects and FSRQs (flat-spectrum radio quasars), are compact flat spectrum radio sources with highly variable and polarized nonthermal continuum emission extending up to X-ray and $\gamma$-ray frequencies. Traditionally, BL Lac objects discovered in radio sky surveys are called radio-selected BL Lac objects (RBLs), and those discovered in X-ray sky surveys, X-ray-selected BL Lacertae objects (XBLs). Recently a new classification has been introduced. The wavelength of the peak of the synchrotron luminosity in blazars anticorrelates with the ratio of X-ray to radio flux. On this basis, Padovani & Giommi (1995) divided BL Lac objects into high-frequency peaked (HBL) and low frequency peaked (LBL) objects, according to whether $\alpha_{\rm rx}$ (from 5 GHz to 1 keV) is $< 0.75$ (Urry & Padovani 1995) or 0.80 (Sambruna et al. 1996). In this scheme, most (but not all) RBLs are LBLs and most (but not all) XBLs are HBLs.

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The continuum emission in blazars is thought to arise from a relativistic jet oriented close to the observer (e.g. Ghisellini 1986). The observations of superluminal motion (Vermeulen & Cohen 1994), the rapid variation and luminous emission in the high-energy $\gamma$-rays suggests that the $\gamma$-ray emissions are relativistically beamed (Dondi & Ghisellini 1995; Hartman et al. 1999; Cheng et al. 1999). Approaching the connections among HBLs, LBLs, and FSRQs will substantially advance our understanding of the fundamental nature of blazars.

Sambruna et al. (1996) suggested that the spectral energy distributions of three subclasses of blazars are different but essentially continuous: HBLs (XBLs) and FSRQs occupy separate regions in broadband color-color diagrams, while LBLs (RBLs) bridge the gap between the two populations. Evidence for continuity in the observed spectral properties of BL Lac objects and FSRQs was also found from both the relevant data (Fossati et al. 1998) and a theoretical model fitting (Ghisellini 1998), who even gave a further continuity of HBLs, LBLs, HPQs (high polarized quasars) and LPQs (low polarized quasars).

Besides, the $\gamma$-ray observations also support the hypothesis that the differences between HBLs and LBLs are physical. In fact, out of the over 60 blazars detected by EGRET in the 100 MeV range, only two objects (Mrk 421, PKS 2155–304) are HBLs. But BL Lac objects detected at TeV are all HBLs. They are Mrk 421, Mrk 501, 2344+514, PKS 2155–304 and 1ES 2005–489. These new observations show that the radiation mechanism of blazars is very complicated and must be studied deeply.

In this paper, based on the relativistic beaming model, we will discuss quantitatively the hypotheses mentioned above with the aim of finding which one is the main mechanism for understanding the relationship among XBLs, RBLs and FSRQs;—a very important point for the unification and evolution of blazars. To do so, we will discuss the intrinsic effective spectral indices relation, i.e., $\alpha_{\rm ro}^{\rm in} - \alpha_{\rm ox}^{\rm in}$ for the three subgroups (HBLs, LBLa, and FSRQs). In Section 2, we will present the available data and the results; In Section 3, we will give the discussion and conclusion.

## 2 MULTIFREQUENCY DATA FOR THE BLAZAR SAMPLES

In view of the large amplitude variation in the X-ray, optical, and radio flux densities, simultaneous observations are required. Unfortunately, no simultaneous observational data are available for most blazars, so it is very useful to seek the minimal flux in different frequency regions that have been reported for those sources in which flux has been measured. States with minimal flux represent the normal phases (low states of the sources) (Xie et al. 1991; Burbidge & Hewitt 1987).

The sample of blazars is listed in Table 1 for RBLs, FSRQs, and 4 TeV $\gamma$-ray sources. For RBLs and FSRQs, only those with known Doppler factors are considered here. Columns in Table 1 are respectively: (1) Name, (2) Class, (3) and (4) optical flux in mJy and references, (5) and (6) the optical spectral index and references, (7) and (8) the X-ray flux in $\mu$Jy and references, (9) and (10) the X-ray spectral index and references, (11) and (12) the radio flux in Jy and references, (13) the Doppler factor, (14) references for the Doppler factor, (15) the observed X-ray-to-optical index $\alpha_{\rm ox}$, (16) the observed radio-to-optical spectral index, $\alpha_{\rm ro}$, (17) the corrected X-ray-to-optical index, (18) the corrected radio-to-optical spectral index. The sample of the X-ray selected BL Lac objects is taken from the literature in Sambruna et al. (1996).

References for Table 1

Ang80: Angel & Stockman (1980);
B85: Bregman et al. (1985);
B83: Bassani et al. (1983);
B89: Brown et al. (1989);
BH89: Burbidge G & Hewitt (1989);
Ci93: Cilliegi et al. (1993);
Com97: Comastri et al. (1997);
Don95: Dondi & Ghisellini (1995);
En82: Ennis et al. (1982);
F94: Falomo et al. (1994);
FL99a: Fan & Lin (1999a);
FL99b: Fan & Lin (1999b);
Gh86: Ghisellini et al. (1986);
Gh93: Chisellini et al. (1993);
Gi90: Giommi et al. (1990);
Ku81: Kuhr et al. (1981);
Ku90: Kuhr & Schmit (1990);
Ku98: Kubo et al. (1998);
L85: Ledden & O'Dell (1985);
M83: Madejcki & Schwartz (1983);
Me90: Mead et al. (1990);
S94: Sambruna et al. (1994) ;
Sa97: Sambruna et al. (1997);
Sam96: Sambruna et al. (1996);
St91: Sticle et al. (1991);
U96: Urry et al. (1996);
U97: Urry et al. (1997);
UM: Data from the UMICH;
Vil97: Villata et al. (1997);
VV91: Veron-Cetty & Veron (1991);
VV93: Veron-Cetty & Veron (1993);
W90: Worrall & Wilkes (1990);
Wo94: Wolter et al. 1994;
Wp85: Wall & Peacock (1985);
X00: this paper;
X88: Xie et al. (1988);
X91: Xie et al. (1991);
X92: Xie et al. (1992);
X99: Xie et al. (1999);

To study the multifrequency energy spectral property, we can consider the effective spectral index, which is defined as

$$\alpha_{ij} = -\frac{\log(F_i/F_j)}{\log(\nu_i/\nu_j)}\,, \tag{1}$$

where $i$ and $j$ denote two arbitrary bands. The flux densities are reduced to the source's rest frame using the K-correction, $F = F^{\rm obs}(1+z)^{\alpha-1}$, where $\alpha$ is the spectral index in the appropriate band ($F_\nu = K\nu^{-\alpha}$); here, $\alpha_r = 0$ is adopted for the radio band, and $\alpha_x = 1$ and 0.5 for BL Lac objects and FSRQs, respectively, in the X-ray band (Fan 1997). From the relativistic beaming model, the observed and intrinsic flux densities are connected by the formula $F_{\rm ob} = \delta^{3+\alpha}F_{\rm in}$, which suggests that the effective spectral indices obtained from the observed data do not represent intrinsic property. One should investigate the continuity of blazars using the intrinsic effective spectral indices, which can be calculated from relation (1) by using $F^{\rm in}$ rather than $F^{\rm ob}$. But this was not done in Sambruna's work (1996). Doppler factors are estimated for some objects (see Xie et al. 1991, 2000 in the optical band; Ghisellini et al. 1993 for the radio band; Dondi & Ghisellini 1995 for the $\gamma$-ray band; also see Fan et al. 1999 and Cheng et al. 1999 for the $\gamma$-ray band). To get the intrinsic fluxes in all the three bands (X-ray, optical and radio), the corresponding Doppler factors should be known.

Based on the observational results, Ghisellini & Maraschi (1989) proposed that the jet plasma may accelerate outward so that the bulk Lorentz factor of the outgoing plasma increases with increasing distance from the center, and radiation is increasingly beamed along the jet. According to this proposal, we obtained an empirical formula of frequency-dependent Doppler factor, since X-ray is from the inner part while the radio emission is from the outer part of the jet.

$$\delta_\nu = \delta_o^{1+1/8\log(\nu_o/\nu)}\,, \tag{2}$$

where $\delta_{\rm o}$ is the optical Doppler factor (Fan et al. 1993). Therefore, the optical, radio and X-ray Doppler factors are correlated and two of them will be known if the other one is known. The optical Doppler factor of FSRQs are calculated using the formula in our previous paper (Xie et al. 1991). For objects with known optical Doppler factors, their radio and X-ray Doppler factors are obtained from the relation (2). And vice versa.

From the available radio, optical and X-ray data, the effective spectral indices obtained from the observed and the intrinsic data are obtained for the samples listed in Tables 1 and shown in Figs. 1 and 2. In Fig. 2 , we used the observed $\alpha_{\rm ro} - \alpha_{\rm ox}$ values of XBLs instead of the intrinsic ones, since the Doppler factor correction for XBLs is very small and can be neglected (see Xie et al. 1993; Fan & Xie 1996).

## 3 DISCUSSION AND CONCLUSION

In the two-index ($\alpha_{\rm ro} - \alpha_{\rm ox}$) diagram, the effective spectral indices obtained directly from the observed data indicate that XBLs are statistically well separated from both RBLs and FSRQs , while they do not distinguish FSRQs form RBLs. The results are shown in Fig. 1. It is well known that RBLs have no or only very weak emission lines as compared with FSRQs while they both have almost the same other properties, such as large amplitude variations, high and variable polarization, strong $\gamma$-ray emission, superluminal motion. So, the relation between RBLs and FSRQs is complicated. Since the observations of RBLs and FSRQs indicate that they are strongly beamed, it is necessary to discuss their intrinsic properties, i.e., the discussion should be based on the Doppler corrected (intrinsic) data. From the relation (2), we can get the radio and X-ray Doppler factors for sources with known optical Doppler factors, and get the optical and X-ray Doppler factors for those with known radio Doppler factors, the known factors being listed in Table 1. With those Doppler factors to correct the observed data, intrinsic effective indices were calculated and are shown in Fig. 2. As expected, the corrected RBLs are found to have moved to a region completely below the $\alpha_{rx} = 0.78$ line; the corrected FSRQs also moved in the same direction, but they all remained above the $\alpha_{\rm rx} = 0.78$ line.

From Fig. 2, we find that XBLs and FSRQs occupy separated regions in the $\alpha^{\rm in}_{\rm ro} - \alpha^{\rm in}_{\rm ox}$ diagram, while RBLs bridge the gap between the XBLs and FSRQs. Comparing the $\alpha^{\rm in}_{\rm ro} - \alpha^{\rm in}_{\rm ox}$ diagram with the $\alpha_{\rm ro} - \alpha_{\rm xox}$ diagram, we note the following differences: (1) Our effective spectral indices are intrinsic, but their $\alpha_{\rm ro}$ is not intrinsic although their $\alpha_{\rm xox}$ can be taken as intrinsic; (2)In the $\alpha_{\rm ro} - \alpha_{\rm xox}$ diagram, XBLs and FSRQs occupy different regions, but RBLs do not purely bridge the gap between XBLs and FSRQs while in the $\alpha^{\rm in}_{\rm ro} - \alpha^{\rm in}_{\rm ox}$ diagram, LBLs bridge the gap between HBLs and FSRQs. The difference arise from the fact that the $\alpha_{\rm ro} - \alpha_{\rm xox}$ diagram presents an observational value against an intrinsic value. Here , we show that $\alpha_{\rm xox} = \alpha_{\rm xo} - \alpha_{\rm x}$ to be intrinsic. It is known that the observed flux $F^{\rm ob}(\nu)$ must be Doppler-corrected and K-corrected to the intrinsic flux $F^{\rm in}(\nu)$,

$$F^{\rm in}(\nu) = (1+z)^{\alpha(\nu)-1} \delta(\nu)^{-3-\alpha(\nu)} F(\nu)^{\rm ob} , \tag{3}$$

where $z$ is the redshift, $\delta(\nu)$ is the Doppler factor and $\alpha(\nu)$ is the spectral index. Using Equations (1),(2) and (3) and after some simplification, we have

$$\alpha^{\rm in}_{\rm xox} = \alpha^{\rm in}_{\rm ox} - \alpha_{\rm x} = \alpha^{\rm ob}_{\rm ox} - \alpha_{\rm x} \left\{ 1 + \frac{1-\alpha_{\rm o}/\alpha_{\rm x}}{2.64} \log(1+z) - \frac{1+2\alpha_{\rm o}/\alpha_{\rm x} - 3/\alpha_{\rm x}}{5.28} \log \delta_{\rm o} \right\} , \tag{4}$$

where $\alpha_{\rm x}$ and $\alpha_{\rm o}$ are the X-ray and optical spectral indices, $\delta_{\rm o}$ is the optical Doppler factor and is $\leq 4$ (see Table 1). Using $\alpha_{\rm o} = \langle \alpha_{\rm o} \rangle = 1.05$, $\alpha_{\rm x} = \langle \alpha_{\rm x} \rangle = 1.0$ for RBLS $\alpha_{\rm o} = 1.38$ and $\alpha_{\rm x} = 0.5$ for FSRQs (Sambruna et al. 1996), we find the last two terms inside brackets on the right-hand side of above relation to be very small, i.e., $\frac{1-\alpha_{\rm o}/\alpha_{\rm x}}{2.64} \log(1+z) \ll 1$ and $\frac{1+2\alpha_{\rm o}/\alpha_{\rm x}-3/\alpha_{\rm x}}{5.28} \log \delta_{\rm o} \ll 1$. So Equation (4) becomes

$$\alpha^{\rm in}_{\rm xox} = \alpha^{\rm in}_{\rm ox} - \alpha_{\rm x} = \alpha^{\rm ob}_{\rm xox} . \tag{5}$$

From Equation (5), we can see that the $\alpha_{\rm xox} = \alpha_{\rm ox} - \alpha_{\rm x}$ introduced by Sambruna represents intrinsic energy distribution and includes the Doppler correction. In fact, the values of $\alpha_{\rm ro}$ are

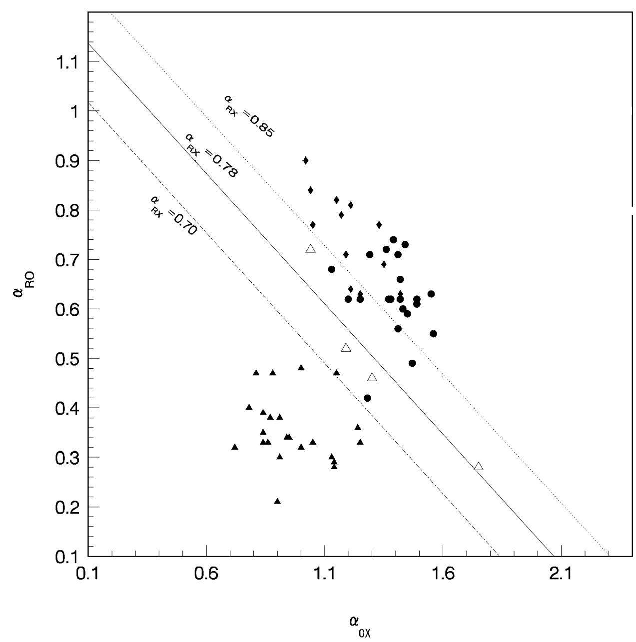


Fig. 1 The $\alpha_{\rm ox} - \alpha_{\rm ro}$ diagram. Filled triangles for XBLs(HBLs), open triangle for TeV $\gamma$-ray BL Lac objects, filled circles for RBLs(LBLs) and diamonds for FSRQs.

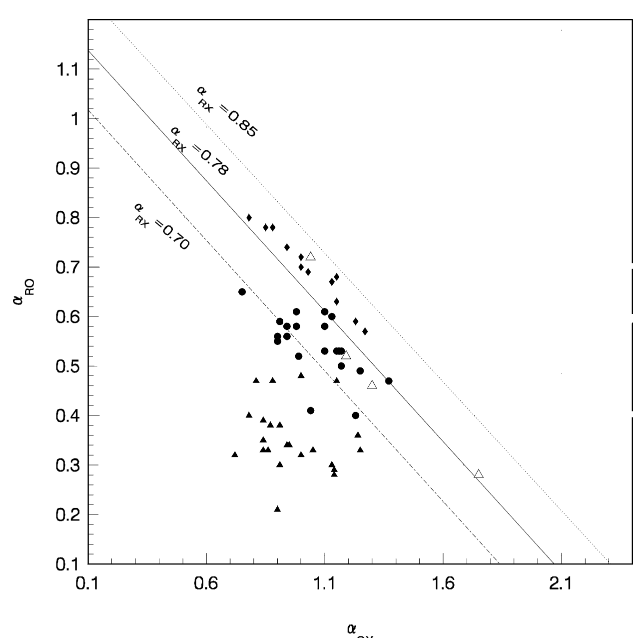


Fig. 2 The $\alpha_{\rm ox}^{in} - \alpha_{\rm ro}^{in}$ diagram. Same symbols as in Fig. 1

not Doppler corrected. We have tested the relation between the optical Doppler factor and radio Doppler factor by using Formula (2). The results are that for most (80%) of the sample of 35 objects, Formula (2) is self-consistent for the optical and radio Doppler factors which have been obtained by Xie in 1991 and Ghisellini in 1993. Only 7 sources (20%) are not self-consistent for the optical and the radio Doppler factors. These are 0420–014, 0537–441, 1156–295, 1253–055, 1210–089, 1749+096 and 2223–052. The reason is that Formula (2) is an experimental result, if we change Formula (2) to the following form

$$\delta_\nu = \delta_{\rm o}^{1+1/a\log(\nu_{\rm o}/\nu)}\,, \tag{6}$$

then the self-consistent problem will be solved. Here $a$ is a constant determined from the optical and radio Doppler factors. In this paper, the radio Doppler factors are deduced from the optical Doppler factors according to Formula (2).

On the basis of the results above, the main conclusions are the following: (1) XBLs, RBLs and FSRQs can be arranged in a continuous spectral sequence in the Doppler corrected color-color diagram, $\alpha_{\rm ro}^{\rm in} - \alpha_{\rm ox}^{\rm in}$, suggesting that similar intrinsic physical processes operated in all of them under a range of intrinsic physical conditions or beaming parameters; (2) the Doppler beaming effect of relativistic beaming is the main mechanism for understanding the properties of, and the relation between LBLs, HBLs and FSRQs; (3) Physical differences are important complementary factors. The relation between FSRQs and BL Lac objects, thus, shows that FSRQs and BL Lac objects are the same class of objects in different stages of evolution; (4) Blazars form a unique population with the same emission processes operating under a range of physical conditions; (5) Our results are consistent the results of Sambruna (1996), Fossati (1998) and Ghisellini (1998).

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