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Gamma-ray Emission from the γ-ray-loud BL Lac Objects

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Abstract Using the HST observation data of BL Lac objects by Urry et al. and γ-ray observation data, we find that there is a correlation between F_γ and $F_{\rm O}^{\rm nuclei}$ for γ-ray-loud BL Lac objects (correlation coefficients: $\gamma = 0.63, p = 4.0 \times 10^{-2}$), but no correlation between F_γ and $F_{\rm O}^{\rm host}$, where $F_{\rm O}^{\rm nuclei}$ and $F_{\rm O}^{\rm host}$ are the fluxes of nuclei and host galaxy in V-band. For 19 γ-ray-loud BL Lac objects with observed spectral index in multi-wavebands, the spectral index correlations between any two bands are as follow: (1) there is a strong correlation between α_γ and α_K for 15 BL Lac objects($\gamma = 0.84, p = 3.11 \times 10^{-4}$); (2) the correlation between α_γ and α_O for 12 BL Lac objects is $\gamma = 0.82, p = 1.5 \times 10^{-3}$; (3) there is no correlation between α_γ and α_X for 16 BL Lac objects. The results, together with characteristic double-humped shape of their SEDs, show that the synchrotron self-Compton mechanism might be a main mechanism for the γ-ray emission of the BL Lac objects. The electrons emitting IR and optical radiation via synchrotron are also responsible for upscattering these photons to γ-rays, and a variability in IR-optical regime should be accompanied by a change in the γ-rays.

Key words: gamma rays — BL Lacertae objects: general

1 INTRODUCTION

Many blazar-type active galaxies have recently been detected in MeV–GeV γ-ray energy range by detectors on board the Compton Gamma-Ray Observatory (Von Montigny et al. 1995; Hartman et al. 1999). More recently, TeV emission is observed in some objects, such as Mrk 421 ($z = 0.031$, Punch et al. 1992), Mrk 501 ($z = 0.034$, Quinn et al. 1996), 1ES 2344+514 ($z = 0.044$, Catanese et al. 1998), PKS 2155–304 ($z = 0.117$, Chadwick et al. 1999), and 1ES 1959+650 ($z = 0.048$, Nishiyama 1999). The γ-ray emission of blazars is highly variable

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on different timescales, from months and weeks to a fraction of an hour (Gaidos et al. 1996). The detection of very fast variability at these high energies motivated new theoretical and observational studies. A variety of models have recently been proposed to explain the origin of the γ-ray emission, including synchrotron self-Compton (Maraschi et al. 1992), inverse Compton on photons produced by the ambient material (Xie et al. 1998) or by the broad-line clouds (Blandford et al. 1975), and synchrotron emission by ultra-relativistic electrons and positrons (Mannheim 1993), and the hadronic beam model (Beall & Bednarek 1999). As the large number of proposed models indicates, there is no consensus yet on the dominant emission process. It is well known that the emission models might imply different relations between the wave bands that can be used to distinguish the models observationally.

For a sample of 23 objects, Comastri found that there is a significant anti-correlation between α_X and α_γ when both FSRQs and BL Lac objects are considered. The anti-correlation is, however, weak if only FSRQs are considered and is not present for BL Lac objects alone (Comastri et al. 1997). The significant anti-correlation can be explained if the same relativistic electrons are responsible for both the radio to optical and the hard X-ray to γ-ray emission, via the synchrotron and the inverse Compton processes, respectively. The seed photons for the IC processes are X-ray photons for FSRQs (Comastri et al. 1997). But multi-frequency observations of blazars reveal that the overall spectra of blazars have two pronounced components: a low energy peak (LE) and a high energy peak (HE) (see e.g. Von Montigny 1995). The LE component peak is at the infrared-optical wavebands for the radio selected BL Lac objects (RBLs), and is at the UV-X-ray wavebands for the X-ray-selected BL Lac objects (Sambruna et al. 1996). The HE component, on the other hand, is in the MeV-GeV range for RBLs and, in the case of a few XBLs, it extends to the TeV range. It is well known that most of GeV γ-ray-loud BL Lac objects are RBLs.

In this paper we use new observations of the Hubble Space Telescope (HST) by Urry et al. (2000) to extend our sample (Xie et al. 1998) and to study possible correlations from theory to understand the roles of these physical processes in γ-ray-loud BL Lac objects.

2 THE SAMPLE AND CORRELATION ANALYSIS OF SPECTRAL INDICES BETWEEN VARIOUS WAVEBANDS

We present 19 γ-ray-loud BL Lac objects with well-observed γ-ray, X-ray optical and near-IR spectral indices in Table 1. The columns are: (1) IAU name; (2) photon number spectral index for K-band (α_K); (3) references for K-band data; (4) photon number spectral index for γ-ray band (α_γ); (5) references for the γ-ray band data; (6) photon number spectral index (α_X); (7) references for the X-ray band data; (8) photon number spectral index for V-band (α_O); (9) references for the optical (V-band) data; (10) nucleus flux of V band observed by HST (Urry et al. 2000); (11) γ-ray flux observed by EGRET (Hartman et al. 1999); (12) V flux of the host galaxy observed by HST (Urry et al. 2000).

It should be pointed out that in view of the fact that all the sources in Table 1 are known to be variable, simultaneous observation data are required. Unfortunately, only 3C 279 has simultaneous observation data. When lacking simultaneous multi-waveband data for an EGRET source, one method is to seek the state of minimum flux in different multi-wavebands that have been reported for those objects in which flux variability has been measured (Dondi & Ghisellini 1995). It is believed that the state of minimal flux represents the quiescent state (or low state) of the sources. According to observations (Webb et al. 1988; Xie et al. 1992), the timescale of the quiescent phase is much longer than the timescale of the outburst phase. In the wide range of theoretical models, the outburst is produced by very complex physical process (e.g., variations of instability). But, owing to the low sensitivity and dynamic range of the EGRET data, the EGRET instrument may tend to detect sources in high γ-ray states. Thus, a second method is to choose the high state (Dondi & Ghisellini 1995). Because of these differences of observational data for optical and γ-ray, we do not make the correlation analysis of flux densities between different wavebands.

Table 1 Sample of γ–ray Loud BL Lac Objects

Source (1)	α_K (2)	Ref. (3)	α_γ (4)	Ref. (5)	α_X (6)	Ref. (7)	α_O (8)	Ref. (9)	F_O^{nuc} (10)	F_γ (11)	F_O^{host} (12)
0219+428	1.7	[2]	1.9±0.2	[8]	2.49	[1]	2.3	[18]			
0235+164	2.3	[3]	1.9±0.2	[8]	2.57	[1]	2.89	[2]	0.46	3.46	0.108
0521−365	2.5	[2]	2.63±0.42	[16]	1.89	[1]	3.1±0.1	[6]	1.62	1.74	3.026
0537−441	2.21	[2]	2.00±0.12	[17]	2.54	[11]	2.6	[2]	3.44	6.99	0.101
0716+714	2.0	[5]	2.19±0.06	[16]	3.02	[11]			4.58	3.77	0.021
0735+178	2.59	[6]	2.6±0.28	[16]	2.2	[12]	2.72±0.03	[6]	0.49	2.79	0.013
0829+046	2.1	[2]	2.47±0.44	[16]	3.26	[13]	2.79±0.03	[6]	0.83	2.71	0.378
0851+202	1.75	[2]	2.03±0.35	[16]	2.16	[11]	2.2	[15]	1.48	1.69	0.081
0954+658			1.9±0.2	[8]	1.24	[11]			0.48	1.19	0.03
1101+384	1.92	[2]	1.9±0.1	[9]	2.84±0.03	[14]	1.92	[2]			
1219+285	2.0	[2]	1.73±0.4	[16]	2.19±0.05	[18]	2.6	[2]			
1652+398	1.65	[2]	1.3±0.05	[10]	2.63	[11]	1.65	[2]			
2005−489			2.2	[9]	3.07	[11]	2.07±0.05	[15]	16.59	4.37	3.228
2032+107	2.48	[7]	2.83±0.17	[10]							
2155−304	1.5	[2]	1.71±0.2	[16]	2.78	[13]	1.7±0.05	[15]			
2200+420	2.5	[2]	2.6	[16]	1.95	[4]	3.3	[2]			
2251+158	2.20	[17]	2.21	[16]	2.1	[4]	2.55	[15]	7.68	2.83	1.476
2254+074									0.39	1.60	0.418
2344+514									0.38	0.62	5.164

References to Table 1:
[1] Comastri 1997 [2] Ghisellini 1986 [3] Brown 1989 [4] Falomo 1993 [5] Chapuis 1999
[6] Tanzi 1989 [7] Allen 1982 [8] Thompson 1995 [9] Chiang 1995 [10] Hartman 1999
[11] Urry 1996 [12] Urry 1997 [13] Ciliegi 1993 [14] Sambruna 1994
[15] Falomo 1994 [16] Lin 1999 [17] Ennis 1982 [18] Takalo 1992

The main results are as follows: (1) there is a significant correlation between α_γ and α_O for 12 BL Lac objects:

$$\alpha_\gamma = 0.59\alpha_O + 0.64\,. \tag{1}$$

The correlation analysis gives a large correlation coefficient $\gamma = 0.821$ with chance probability of $p = 1.5 \times 10^{-3}$ (see Fig. 1); (2) there is a very strong correlation between α_γ and α_K for 15 BL Lac objects (see Fig. 2), the linear regression equation is

$$\alpha_\gamma = 0.99\alpha_K + 0.05\,. \tag{2}$$

The correlation analysis gives $\gamma = 0.840$ with chance probability of $p = 3.1 \times 10^{-4}$; (3) there is no correlation between α_γ and α_X.

This results imply that the dominant mechanism of γ-ray emission in γ-ray-loud BL Lacs could be the synchrotron, or it could be the synchrotron self-Compton mechanism. The electrons emit IR and optical radiation via synchrotron and up-scatter these photons to γ-ray. Obviously, these results are consistent with the observed results of multi-frequency energy spectral distributions for BL Lac objects (Sambruna et al. 1996).

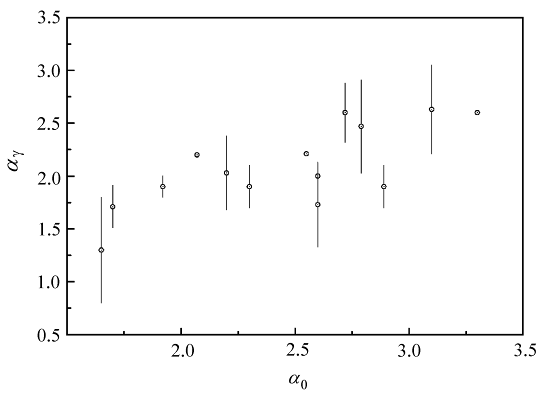

Fig. 1 Correlation between the spectral indices in the optical (V-band) and γ-rays.

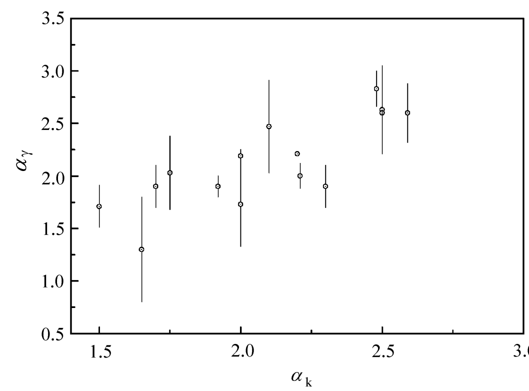

Fig. 2 Correlation between spectral indices in the K-band and γ-rays.

3 THE HST OBSERVATIONS AND CORRELATION ANALYSIS OF FLUX DENSITIES BETWEEN γ-RAY AND OPTICAL EMISSIONS

From the HST observational data (Urry et al. 2000), we obtain a sample of γ-ray-loud BL Lac objects with HST observed optical data of both the nuclei and host galaxies. Again, in view of the fact that all γ-ray-loud sources are known to be variable, simultaneous observations are required. We take, as simultaneous data, the median flux defined by

$$F_\nu^m = (F_\nu^H + F_\nu^L)/2\,, \tag{3}$$

where F_ν^H and F_ν^L are the maximum and minimum flux respectively, the K-correction having been considered,

$$F(\nu) = F_{\rm ob}(\nu)(1+z)^{\alpha-1}\,, \tag{4}$$

where z is the redshift and α is the spectral index at frequency ν, such that $f_\nu \propto \nu^{-\alpha}$. All the data are listed also in Table 1.

The main results are: (1) there is a correlation between F_γ^m and $F_{\rm O}$(nuclei) for 12 γ-ray-loud BL Lac objects, where $F_{\rm O}$(nuclei) is the K-corrected V-band flux of the nuclei obtained by Urry et al. (2000) with the HST survey. Linear regression is applied to the relevant data to analyze the correlation between F_γ and $F_{\rm O}$(nuclei). The linear regression equation is

$$\log F(\gamma) = 0.33 \log F_{\rm O}({\rm nuclei}) + 0.28\,. \tag{5}$$

The correlation coefficient is $\gamma = 0.63$ with chance probability of $p = 3.1 \times 10^{-2}$ (see Fig. 3). (2) there is no correlation between F_γ^m and $F_{\rm O}$(host) for 12 γ-ray-loud BL Lac objects, where $F_{\rm O}$(host) is the K-corrected V-band flux of the host galaxy.

From these results, we may say that the γ-ray emission of BL Lac objects comes from the nuclei of BL Lac objects and that the optical emission of BL Lac objects host galaxy are unaffected by beaming. Obviously, the results of the flux correlation analysis is consistent with the results of the correlation analysis of spectral index discussed in Section 2.

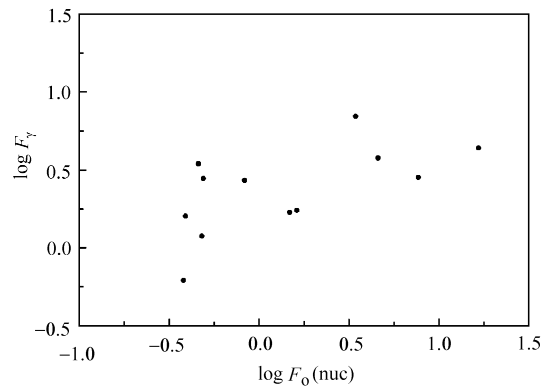

Fig. 3 Correlation between the GeV γ-ray flux and the optical flux of the nucleus of γ–ray–loud BL Lacs.

4 DISCUSSION AND CONCLUSIONS

We assume the relativistic electrons with Lorentz factor γ in the frame co-moving with jet have an isotropic power-law energy distribution (You et al. 1982),

$$N(\gamma) = N_0 \gamma^{-n}, \qquad (\gamma_1 < \gamma < \gamma_2), \tag{6}$$

the target photons have a uniform density $n_{\rm ph}(\nu_i)$ in the AGN frame, where $h\nu_i$ is the photon energy. The Compton spectral emissivity for the general case is (Sambruna et al. 1996)

$$J(\nu) = 8\pi r_0^2 hc \int_\gamma \int_{\nu_i} N(\gamma) f(X) n_{\rm ph}(\nu_i) {\rm d}\nu_i {\rm d}\gamma, \tag{7}$$

where $X = \nu/4\pi\nu_i$, r_0 is the classical electron radius.

If the isotropic soft photon field has a nonthermal spectrum with photon number density,

$$n_{\rm ph}(\nu_i) = n_0 \nu_i^{-\alpha_f}, \qquad (\nu_a < \nu_i < \nu_b)\,, \tag{8}$$

then

$$J(\nu) = 2^{2\alpha_f+1}\pi r_0^2 chn_0 \nu^{-\alpha_f+1}\left[\frac{1}{\alpha_f} - \frac{2}{2\alpha_f+2} + \frac{\alpha_f - 1}{(\alpha_f+1)^2}\right]\int \gamma^{2\alpha_f-2}N(\gamma)d\gamma\,. \tag{9}$$

The spectral relation of Compton scattered photons spectral index, α_c, and the spectral index of the soft photons is given by

$$\alpha_c = \alpha_f - 1\,. \tag{10}$$

The fact that there is a strong correlation between α_γ and $\alpha_{\rm O}$ (see Fig. 1 and Table 1) and a significant correlation between α_γ and α_K indicates that the origin of the optical and near IR photons for the IC process is synchrotron radiation mechanism. In a simple, one-zone model, the synchrotron branches of the spectrum are in close correspondence with the Compton spectrum. On the other hand, for RBLs, the LE component peaks in the IR-optical wave band. Thus the electrons emit IR and optical radiation via synchrotron and up-scatter them to γ-ray. Variability in the IR and optical regime should be accompanied by changes in the γ-rays. Similarly, in the more complex inhomogeneous model, we also expect that the synchrotron and IC flux to vary in step (Xie et al. 1993). This argument was applied to the case of the well-studied blazar 3C 279 to account for the large correlated variability in the IR-optical and GeV energies (Maraschi et al. 1992).

The new findings that there exists a weak correlation between F_γ and $F_{\rm O}$(nuclei), but not between F_γ and $F_{\rm O}$(host), place a constraint on the gamma-ray radiation mechanism, which can be applied to test the radiation models, because the origination of HST observed point source flux ($F_{\rm O}$(nuclei)) could be dominated by synchrotron emission from an unresolved jet (Urry et al. 2000). Beaming effect may smear out a possible correlation between the intrinsic fluxes (Mucke et al. 1997). Thus, that there is a correlation between F_γ and $F_{\rm O}$(nuclei) and that there is none between F_γ and $F_{\rm O}$(host) shows that the relativistic Doppler factor (δ_γ) for the γ-ray is equal to the relativistic Doppler factor ($\delta_{\rm O}$) for the V-band. That is, the γ-ray and nucleus optical emission regions are co-spatial, and it is possible to explain the γ-ray emission as being directly related to the nucleus optical radiation. These results seem to provide new and direct evidence that the γ-ray emissions are created by inverse Compton (IC) scattering of optical photons by a relativistic electron beaming.

It is well known that the position of the synchrotron peak has recently led to the introduction of a new nomenclature to designate subclasses of BL Lac objects, based on the spectral energy distribution. Objects with peak synchrotron emission at low frequencies (infrared-optical) have been called low frequency-peaked BL Lac objects, while objects with the peak at high energies (ultraviolet or even in soft X-ray) have been called high frequency-peaked BL Lac objects. It is interesting to note that most of the γ-ray-loud BL Lac objects are low frequency-peaked BL Lac objects (see Table 1). These facts also support our results in this paper.

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