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Relativistic Beaming Effect in Fermi Blazars

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Abstract. The most identified sources observed by Fermi/LAT are blazars, based on which we can investigate the emission mechanisms and beaming effect in the γ-ray bands for blazars. Here, we used the compiled around 450 Fermi blazars with the available X-ray observations to estimate their Doppler factors and compared them with the integral γ-ray luminosity in the range of 1–100 GeV. It is interesting that the integral γ-ray luminosity is closely correlated with the estimated Doppler factor, $\log \nu_\gamma L_{\nu_\gamma} = (2.95 \pm 0.09)\log \delta + 43.59 \pm 0.08$ for the whole sample. When the dependence of the correlation between them and the X-ray luminosity is removed, the correlation is still strong, which suggests that the γ-ray emissions are strongly beamed.

Key words. Galaxies: active-galaxies: BL Lacertae objects—galaxies: quasars—galaxies: jets—Fermi (LAT)

1. Introduction

Blazars are a special subgroup of Active Galactic Nuclei (AGNs) with some extreme observation properties. They have two subclasses, namely BL Lacertae objects (BLs) and Flat Spectral Radio Quasars (FSRQs). BLs consist of radio selected BLs and X-ray selected BLs from surveys or low frequency-peaked BL Lacertae objects (LBLs) and high frequency-peaked BL Lacertae objects (HBLs) from the Spectrum Energy Distribution (SEDs) (Urry & Padovani 1995) while FSRQs can be divided into Highly Polarized Quasars (HPQs), Optically Violently Variable quasars (OVVs), Core Dominated Quasars (CDQs), Superluminal Motion sources (SMs), etc. Therefore, an extragalactic source can be identified as a blazar if it shows rapid and high amplitude variability or high and variable polarization, superluminal radio components, non-emission line feature or have strong emission lines (see Fan 2005; Fan *et al*. 2011 for review). From the γ-ray detections (Abdo *et al*. 2009, 2010;

Ackermann *et al*. 2011; Nolan *et al*. 2012), we can say that the γ-ray emissions are also one of the typical observation properties for blazars (Fan *et al.* 2013a).

The structure of the central regions and the emission mechanism of blazars are open problems. Variability is its typical observation properties. The variability is complex with short time scale variability superposed on the slow variations (Fan 2005).

Blazars were detected to emit γ-ray emissions by EGRET, they are believed to be strongly beamed. Some authors tried to discuss the relativistic beaming effect from the correlations between the γ-ray emissions and the radio emissions (see Dondi & Ghisellini 1995; Fan *et al*. 1998; Huang *et al*. 1999). The γ-ray Doppler factors are also determined for some γ-ray loud blazars with available X-ray data and variability time scales (Mattox *et al*. 1993; von Montigny *et al*. 1995; Fan *et al*. 1999, 2013b; Fan 2005).

After the launch of the new generation γ-ray detector, Fermi has detected more than 1000 blazars (see Abdo *et al.* 2010; Ackermann *et al*. 2011; Nolan *et al*. 2012), which provide us with very good opportunity to discuss the relativistic beaming effect in the Fermi blazars (see Kovalev *et al*. 2009; Arshakian *et al*. 2010; Savolainen *et al*. 2010; Pushkarev *et al*. 2010). However, all of the discussions are based on the lower energetic bands, the radio Doppler factor, the radio polarization, the brightness temperature, and the superluminal motions. It is known that the Doppler factors are important in the discussion of blazars. So, if one can determine the Doppler factor in the γ-ray region, then it is very helpful in the discussion of relativistic beaming effect for γ-ray emissions. That is the main motivation of the present work. In § 2, we describe the sample and the calculation results; in § 3, we give some discussions and a brief conclusion. We adopt $H_0 = 73\ \mathrm{km\,s^{-1}Mpc^{-1}}$, and the spectral index α is defined as $f_\nu \propto \nu^{-\alpha}$ throughout this paper.

2. Sample and results

2.1 *Pair-production optical depth*

The γ-ray emissions from blazars suggest strong beaming effects in those sources, otherwise, the γ-rays should have been absorbed due to the pair production on collision with the lower energetic photons. Mattox *et al*. (1993) (see also Von Montigny *et al*. 1995) considered the pair-production optical depth. They assumed that (1) both the X-ray and the γ-rays are produced in the same region, and that a similar X-ray intensity was extant at the time of the γ-ray observation, (2) the emission region is spherical, (3) the emissions are isotropic, and the emission region size, R can be constrained by the time variation, namely $R = c\Delta T/(1+z)$, where ΔT is the timescale of variability, c is the speed of light, and z is the redshift. Finally, they got the optical depth as

$$\tau = 2\times 10^3[(1+z)/\delta]^{(4+2\alpha)}(1+z-\sqrt{1+z})^2 h_{75}^{-2}\Delta T_5^{-1} \times \frac{F_{\mathrm{KeV}}}{\mu\mathrm{Jy}}\left(\frac{E_\gamma}{\mathrm{GeV}}\right)^\alpha, \quad (1)$$

where α is the X-ray spectral index ($F_{\nu_\mathrm{X}} \propto \nu_\mathrm{X}^{-\alpha}$), δ is the Doppler factor, $h_{75} = H_0/75$, $\Delta T_5 = \Delta T/(10^5\ \mathrm{s})$, F_{keV} is the flux density at 1 KeV, E_γ is the energy at

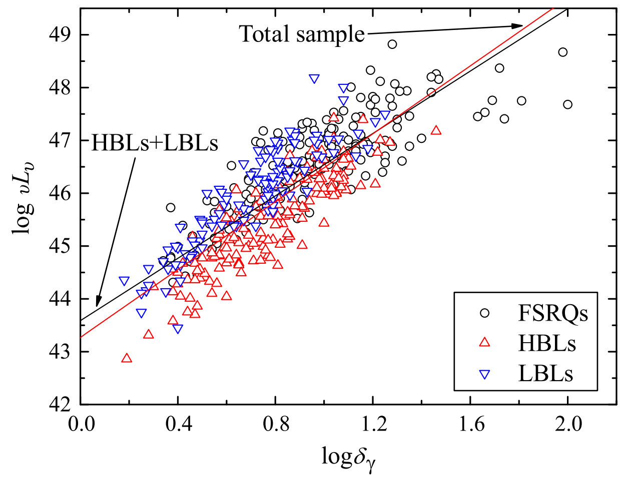

Figure 1. Plot of the γ-ray luminosity, log νL_ν (ergs/s) vs. the γ-Doppler factor, log δ_γ for the Fermi blazars. The open circles stand for FSRQs, triangles for HBLs, inverted triangles for LBLs. The red line stands for the best fitting result of the total sample, and the black line stands for the fitting result of HBLs+LBLs.

which the γ-rays are detected. When the $\Lambda-$CDM model (Pedro & Priyamvada 2007) is adopted for the luminosity distance,

$$d_L = \frac{c}{H_0}\int_1^{1+z}\frac{1}{\sqrt{\Omega_M x^3 + 1 - \Omega_M}}\mathrm{d}x \tag{2}$$

with $\Omega_\Lambda \simeq 0.7$, $\Omega_M \simeq 0.3$ and $\Omega_K \simeq 0.0$, then we have

$$\tau = 1.54\times 10^{-3}\left(\frac{1+z}{\delta}\right)^{4+2\alpha}\left(\frac{d_L}{\mathrm{Mpc}}\right)^2\left(\frac{\Delta T}{\mathrm{hr}}\right)^{-1}\left(\frac{F_{\mathrm{KeV}}}{\mu\mathrm{Jy}}\right)\left(\frac{E_\gamma}{\mathrm{GeV}}\right)^{\alpha}. \tag{3}$$

In this sense, the lower limit of the Doppler factor can be determined if we constrain the optical depth to be less than unity (see Fan *et al*. 2013a).

$$\delta \geq \left[1.54\times 10^{-3}(1+z)^{4+2\alpha}\left(\frac{d_L}{\mathrm{Mpc}}\right)^2\left(\frac{\Delta T}{\mathrm{hr}}\right)^{-1}\left(\frac{F_{\mathrm{KeV}}}{\mu\mathrm{Jy}}\right)\left(\frac{E_\gamma}{\mathrm{GeV}}\right)^{\alpha}\right]^{\frac{1}{4+2\alpha}}. \tag{4}$$

2.2 *Sample and results*

From the 2FGL catalogue (Nolan *et al.* 2012), we compiled a sample of 451 blazars with available X-ray data from the literatures (see Fan *et al*. (2013b) for details).

From the available data, we can see that in some of the sources, there is no X-ray spectral index, while for others, there are no redshifts. In this sense, we adopted the average value of $\langle\alpha_X\rangle = 2.201$ for those sources whose X-ray photon spectral indexes are unknown, and $\langle z\rangle = 0.761$ for those unknown redshifts. The average energy of the γ-ray photons $\langle E\rangle = \frac{\int E\mathrm{d}N}{\int \mathrm{d}N}$ is adopted for the photon which collide with the X-ray photons. In this sense, we can calculate the lower limits for the Doppler factors by equation (4). When we investigated the correlation between the γ-ray luminosity and the γ-ray Doppler factor, we got a close correlation (see Fig. 1)

$$\log\ \nu_\gamma L_{\nu_\gamma} = (2.95 \pm 0.09) \log\ \delta + 43.59 \pm 0.08.$$

3. Discussions and conclusion

From the above discussions, it was found that there is a strong correlation between the γ-ray luminosity and the γ-ray Doppler factors suggesting a strong beaming effect in the γ-ray emissions. However, from equation (4), we can see that the correlation is probably from the strong correlation between the γ-ray luminosity and the X-ray luminosity. Therefore, the effect must be removed. To do so, we adopted the method by Padovani (1992). Let r_{12} be the correlation coefficient between variables 1 and 2, r_{13} be the correlation coefficient between variables 1 and 3, and r_{23} be the correlation coefficient between variables 2 and 3. Then the correlation coefficient between variables 1 and 2 after removing the effect of variable 3 can be expressed as $r_{12,3} = \frac{r_{12} - r_{13} r_{23}}{\sqrt{(1-r_{13}^2)(1-r_{23}^2)}}$. When the effect of the X-ray luminosity is removed, the correlation between the Doppler factor and the γ-ray luminosity is still close, suggesting that the γ-ray emissions are really beamed.

When we take the core-dominance parameter R into account, the R for the blazars detected by Fermi/LAT is higher than that for the rest of the blazars, which supports that the γ-ray loud blazars are beamed (Li *et al.* 2013).

We also investigated the correlation between the γ-ray luminosity with both the radio core luminosity and total luminosity, and found that the gamma-ray luminosity is closely correlated with both radio core and total luminosities. Since the radio emissions are known to be beamed, we can say that the γ-rays are also beamed (Wu *et al.* 2013).

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