SEDs and Beaming Effect for Fermi Blazars

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In this work, based on our previous calculations of spectral energy distributions for a sample of Fermi blazars (Fan et al. 2015a), we calculated the radio loudness and performed correlation analyses. Our analysis results show that radio loudness is closely anti-correlated with synchrotron peak frequency and positively correlated with gamma-ray luminosity, suggesting that the gamma-ray emissions are strongly beamed.

Keywords: galaxies, active-galaxies, BL Lac-galaxies, jets

1. INTRODUCTION

As a special subclass of active galactic nuclei (AGNs), blazars are the major population in Fermi missions (Abdo et al. 2009, 2010a; Ackermann et al. 2011; Acero et al. 2015). They show some extreme observational properties: rapid and high amplitude variability, high and variable polarization, strong and variable gamma-ray emissions, superluminal motions, etc. (see Fan et al. 2011; Yang et al. 2012; Fan et al. 2013, 2014; Yang et al. 2014). Blazars have two subclasses, namely BL Lacertae objects (BL Lacs) and flat spectrum radio quasars (FSRQs). They both show common continuum but different emission lines. FSRQs have very strong emission lines while BL Lacs have weak emission lines or no emission line at all. BL Lacs can be classified as radio selected (RBLs) and X-ray selected (XBLs) BL Lacs from surveys, and they have different synchrotron peak frequencies with most XBLs showing synchrotron peak frequencies log νp > 15 Hz (highly peaked BL Lacs-HBLs) and RBLs showing log νp < 15 Hz (lowly peaked BL Lacs-LBLs) (Padovani & Giommi 1996). According to the peak frequency, BL Lacs can be divided into LBL, IBL, and HBL: LBL if log νp < 14 Hz, IBL if 14 Hz < log νp < 16.5 Hz, and HBL if log νp > 16.5 Hz (Nieppola et al. 2006); LBLs if log νp < 14 Hz, IBL if 14 Hz < log νp < 15 Hz, and HBL if log νp > 15 Hz (Abdo et al. 2010b); or LBL, log νp < 13.98 Hz, IBL 13.98 Hz < log νp < 15.30 Hz, and HBL if log νp > 15.30 Hz (Fan et al. 2015a). We can see that our previous classifications are similar to those of Abdo et al. (2010b).

The observations of strong gamma-ray emissions in blazars suggest the existence of a relativistic beaming effect, which has been discussed in some papers (see Savolainen et al. 2010; Giroletti et al. 2012; Fan et al. 2013, 2014; Lin & Fan 2016). Very recently, following the work by Mattox et al. (1993), the Doppler factors were evaluated for a sample of Fermi blazars by assuming time scales of 6 hr and 24 hr (Fan et al. 2013, 2014; Liodakis & Pavlidou 2015). In our previous papers, we also found that the Fermi detected blazars have larger core-dominance parameters (Pei et al. 2016) and the de-beamed gamma-ray flux densities show a close correlation with redshift (Xiao et al. 2015).

The present work follows our previous paper of Fan et al. (2015a), which reported the classifications of blazars and investigated the correlation between radio loudness and synchrotron peak frequency or gamma-ray luminosity. In section 2, we present the results and in Section 3 the discussions and conclusions. In our analysis, we adopt the Hubble constant H₀ = 73 km·s⁻¹·Mpc⁻¹, and the spectral index

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\( \alpha \) is defined as \( f \propto \nu^\alpha \) through this paper.

2. LUMINOSITY AND RADIO LOUDNESS

The \( \gamma \)-ray photon number per unit energy can be expressed as

\[
\frac{dN}{dE} = N_\gamma E^{-\Gamma}
\]

where \( \Gamma \) is the \( \gamma \)-ray photon spectral index. \( N_\gamma \) is a constant, and can be obtained by integrating Eq. (1):

\[
N_\gamma = N_\gamma \left( \frac{1 - \Gamma}{E_{U}^{\gamma} - E_{L}^{\gamma}} \right)
\]

for \( \Gamma = 2 \), then

\[
N_\gamma = N_\gamma \left( \frac{E_{U}^{\gamma} - E_{L}^{\gamma}}{E_{U}^{\gamma} - E_{L}^{\gamma}} \right)
\]

(2)

\( N \) is the \( \gamma \)-ray integral photon flux in units of photons-cm\(^{-2}\)-s\(^{-1}\) in the energy range of EL-EU, where EL and EU are the lower and upper energy limits, respectively, and EL = 1 GeV and EU = 100 GeV in this paper.

Hence, the total \( \gamma \)-ray flux density in the range of EL-EU is

\[
F = \int_{E_{L}}^{E_{U}} E dN = 1.602 \times 10^{37} \cdot \frac{E_{U}^{\gamma} - E_{L}^{\gamma}}{E_{U}^{\gamma} - E_{L}^{\gamma}} \ln \frac{E_{U}^{\gamma} - E_{L}^{\gamma}}{E_{U}^{\gamma} - E_{L}^{\gamma}} \text{ if } \Gamma = 2,
\]

\[
F = \int_{E_{L}}^{E_{U}} E dN = 1.602 \times 10^{37} \cdot \frac{1 - \Gamma}{2 - \Gamma} \cdot \frac{E_{U}^{\gamma} - E_{L}^{\gamma}}{E_{U}^{\gamma} - E_{L}^{\gamma}} \text{ otherwise}
\]

(3)

The integral \( \gamma \)-ray luminosity is calculated by the formula

\[
L = 4 \pi d_{L} dF
\]

Radio loudness can be calculated as the ratio of the radio emissions to the optical emissions: \( R_{L} = R_{\nu} / R_{\alpha} \), where \( R_{\nu} \) and \( R_{\alpha} \) are radio and optical luminosities, respectively.

3. RESULTS

In our previous paper, we compiled multiwavelength data for a sample of 1,425 sources and successfully calculated spectral density distributions (SEDs) for 1,392 sources; among them 999 sources have shown redshift. Based on the calculated synchrotron peak frequency (\( \nu_{p} \)), we classified the subclasses of blazars as LBL if \( \log \nu_{p} < 13.98 \) Hz, IBL if \( 13.98 \) Hz < \( \log \nu_{p} < 15.3 \) Hz, and HBL if \( \log \nu_{p} > 15.3 \) Hz (Fan et al. 2015a). From Table 1 of Fan et al. (2015a), we can obtain a sub-sample of 983 sources with available redshift, radio-, optical-, and \( \gamma \)-ray luminosities.

Averaged values: For the 983 FSRQs, there are 447 FSRQs, 536 BL Lacs (148 HBLs, 339 IBLs, and 49 LBLs). The radio loudness \( < R_{L} > = 3.23 \pm 5.49 \) for FSRQs, \( < R_{L} > = 2.69 \pm 0.93 \) for LBLs, \( < R_{L} > = 2.11 \pm 0.80 \) for IBLs, and \( < R_{L} > = 1.66 \pm 0.56 \) for HBLs.

Correlations: From the relevant data of Fan et al. (2015a), we can obtain the following correlations. For RL and \( \nu_{p} \),

\[
\log R_{L} = -(0.46 \pm 0.02) \log \nu_{p} + 9.24 \pm 0.33 \text{ with a correlation coefficient } r = -0.54 \text{ and a chance probability } p = 10^{-4} \text{ for the whole sample, as shown in Fig. 1.}
\]

For the subclasses, FSRQs, LBLs, and HBLs, we have \( \log R_{L} = -(0.22 \pm 0.04) \log \nu_{p} + 6.29 \pm 0.54 \) with \( r = -0.54 \) and \( p < 10^{-4} \) for 447 FSRQs, \( \log R_{L} = (0.79 \pm 0.49) \log \nu_{p} - (7.84 \pm 6.52) \) with \( r = 0.23 \) and \( p = 11.3\% \) for 49 LBLs and \( \log R_{L} = (0.05 \pm 0.05) \log \nu_{p} + 0.83 \pm 0.87 \) with \( r = 0.08 \) and \( p = 33.4\% \) for 148 HBLs, as shown in Fig. 2.

For the radio loudness and the gamma-ray luminosity, we have

\[
\log L_{\gamma} = (0.72 \pm 0.06) \log R_{L} + (43.62 \pm 0.18) \text{ with } r = 0.51 \text{ and } p < 10^{-4} \text{ for 447 FSRQs,}
\]

\[
\log L_{\gamma} = (0.64 \pm 0.12) \log R_{L} + (43.31 \pm 0.23) \text{ with } r = 0.39 \text{ and } p < 10^{-4} \text{ for 148 HBLs, and}
\]

\[
\log L_{\gamma} = (0.42 \pm 0.36) \log R_{L} + (44.76 \pm 1.18) \text{ with } r = 0.17 \text{ and } p < 24.7\% \text{ for 49 LBLs, as shown in Fig. 3.}
\]

The corresponding correlation results are listed in Tables 1 and 2.

4. DISCUSSION AND CONCLUSION

Blazars consist of FSRQs and BL Lacs, and BLs are composed

| Table 1. Correlation for log\( R_{L} \) and log\( \nu_{p} \) |
|-------------------------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|
| Sample | \( a \) | \( \Delta a \) | \( b \) | \( \Delta b \) | \( r \) | \( n \) | \( p \) |
|-------------------------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|
| Total | 9.24 | 0.33 | -0.46 | 0.02 | -0.54 | 983 | <0.0001 |
| FSRQ | 6.29 | 0.54 | -0.22 | 0.04 | -0.26 | 447 | <0.0001 |
| HBL | 0.83 | 0.87 | 0.05 | 0.05 | 0.08 | 148 | 0.3396 |
| LBL | -7.84 | 6.52 | 0.79 | 0.49 | 0.23 | 49 | 0.1129 |

Fig. 1. Plot of radio loudness (log\( R_{L} \)) against peak frequency (log\( \nu_{p} \)) for the whole sample (983 sources).
of radio selected BL Lacs and X-ray selected BL Lacs from surveys or high synchrotron peak BL Lacs (HBLs), intermediate synchrotron peak BL Lacs (IBLs), and low synchrotron peak BL Lacs (LBLs) from their peak frequency in their spectral energy distributions. Generally, FSRQs are low synchrotron peak sources; therefore, in the paper of Abdo et al. (2010b), the authors classified blazars as low synchrotron peak sources (LSPs), intermediate synchrotron peak sources (ISPs) and high synchrotron peak sources (HBLs). Blazars are the main population detected in the Fermi missions (See Acero et al. 2015 and references therein). To date, some blazars are TeV emitters and most are HSPs with smaller radio to optical spectral indexes and hard GeV spectral indexes (Lin & Fan 2016). Observations show that the gamma-ray emissions in Fermi blazars are strongly beamed. The gamma-ray beaming factor can be estimated by (Fan et al. 2013, 2014).

\[
\delta \geq [1.54 \times 10^{-1}(1 + z)^{2.6} \left(\frac{d_L}{Mpc}\right)^{0.4} \left(\frac{\Delta T}{hr}\right)^{-1} \left(\frac{F_{\nu \gamma}}{\mu Jy}\right)\left(\frac{E_{\gamma}}{GeV}\right)^{1.05}]^{0.23} \tag{4}
\]

Here, \( z \) is the redshift, \( d_L \) is the luminosity distance, \( \Delta T \) is the variability time scale, \( F_{\nu \gamma} \) is the X-ray flux density, and \( E_{\gamma} \) is the gamma-ray energy. The Doppler factor (boosting factor) can be estimated using available observations.

It is known that the radio emissions in blazars are strongly beamed and the beaming factors were estimated in our previous work (Fan et al. 2009), and the de-beamed gamma-ray flux density is closely correlated with the redshift (Xiao et al. 2015) and the Fermi blazars show higher core-dominance parameters than those of non-Fermi detected blazars (Wu et al. 2014; Pei et al. 2016). For the correlation between radio loudness and peak frequency (Table 1 and Figs. 1 and 2), we find that the anti-correlation is strong for FSRQs but almost non-existent for both LBLs (\( r = 0.23 \)) and HBLs (\( r = 0.08 \)). If the radio emissions are strongly beamed, then the radio loudness is an indicator of beaming effect since \( R_\gamma \propto \delta^{-1} \). The results of the correlation are then consistent with the result that FSRQs show a higher Doppler factor than BL Lacs. The anti-correlation between the radio loudness and peak frequency is similar to the anti-correlation between the Doppler factor and the peak frequency (Nieppola et al. 2006). In this sense, we expect that the de-beamed radio loudness will be positively beamed with the peak frequency. Fortunately, the correlation for HBLs showing a positive tendency appears to support our expectation.

From Fig. 3 and Table 2, we can see that the gamma-ray luminosity increases with radio loudness, and the slope in FSRQs is steeper than that in HBLs and LBLs, which suggests that the Fermi blazars are radio loud and the gamma-ray emissions in FSRQs are more beamed. From our analyses, we can conclude that the gamma-ray sources are radio loud and beamed.

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