Comparison between Fermi Detected and non-Fermi Detected Superluminal Sources

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ABSTRACT

Active galactic nuclei (AGNs) have been attracting research attention due to their special observable properties. Specifically, a majority of AGNs are detected by Fermi-LAT missions, but not by Fermi-LAT, which raises the question of whether any differences exist between the two. To answer this issue, we compile a sample of 291 superluminal AGNs (189 FDSs and 102 non-FDSs) from available multi-wavelength radio, optical, and X-ray (or even $\gamma$-ray) data and Doppler factors and proper motion ($\mu$) (or apparent velocity ($\beta_{app}$)); calculated the apparent velocity from their proper motion, Lorentz factor ($\Gamma$), viewing angle ($\phi$) and co-moving viewing angle ($\phi_{co}$) for the sources with available Doppler factor ($\delta$); and performed some statistical analyses for both types. Our study indicated that 1. In terms of average values, FDSs have higher proper motions ($\mu$), apparent velocities ($\beta_{app}$), Doppler factor ($\delta$), Lorentz factor ($\Gamma$), and smaller viewing angle ($\phi$). Nevertheless, there is no clear difference in co-moving viewing angles ($\phi_{co}$). The results reveal that that FDSs show stronger beaming effect than non-FDSs. 2. In terms of correlations: (1) Both sources show positive, mutually correlated fluxes, which become closer in de-beamed fluxes; (2) With respect to apparent velocities and $\gamma$-ray luminosity, there is a tendency for the brighter sources to have higher velocities; (3) With regard to viewing angle and observed $\gamma$-ray luminosity, $\log \phi = -(0.23 \pm 0.04) \log L_\gamma + (11.14 \pm 1.93)$, while for the co-moving viewing angle and the intrinsic $\gamma$-ray luminosity, $\log \phi_{co} = (0.09 \pm 0.01) \log L_{\gamma}^{in} - (1.73 \pm 0.48)$. These correlations show that the luminous $\gamma$-ray sources have smaller viewing angles and a larger co-moving viewing angle, which indicate a stronger beaming effect in $\gamma$-ray emissions.

Keywords: active galactic nuclei, jets, $\gamma$-rays, Correlations
PCAS: 98.54.Cm; 98.58.Fd; 95.85.Pw; 98.62.Ve

1. INTRODUCTION

The nature of AGNs is still an open question in astrophysics. AGNs contain a broad wavelength band emission, from radio to very high energy (VHE) band. Blazars, as a very extreme subclass of AGNs, show rapid and high variability, high and variable polarization, variable and strong $\gamma$-ray emission and even superluminal motion (Fan et al. 2013a; Fan et al. 2013b). These extreme observational properties of blazars are due to the fact that they host a relativistic jet
pointing to the observer (Blandford & Königl. et al. 1979). Blazars have two subclasses, namely BL Lacertae objects (BL Lacs) and flat spectrum radio quasars (FSRQs). BL Lacs show weak or no emission lines while FSRQs show strong emission line features. The classifications of blazars based on the spectral energy distributions (SEDs) can be found in Padovani & Giommi. (1995), Nieppola et al. (2006), Abdo et al. (2010a), Fan et al. (2016), Lin & Fan. (2018) and Zhang & Fan. (2019).

The γ-ray emissions of blazars have caught astronomers’ attention to investigate the mechanism of the high energetic γ-ray emissions. There have been two generations of γ-ray experiment, EGRET (the Energetic Gamma-Ray Experiment Telescope, on-board the Compton Gamma – Ray Observatory) and Fermi-LAT (Fermi Large Area Gamma – Ray Space Telescope), which provide us good opportunities to detect strong γ-ray sources. Based on the observations of EGRET, correlation analyses between the γ-ray emissions and those at lower energy bands have been performed to study the beaming effect (Dondi & Ghisellini. 1995; Xie et al. 1997; Fan et al. 1999; Cheng et al. 2000, and reference therein). Fermi-LAT, a successor to ERGET, detected more than 1000 blazars (see Abdo et al. 2010b; Nolan et al. 2012; Acero et al. 2015; Ackermann. 2015). The strong γ-ray emissions in blazars suggest the existence of a relativistic beaming effect, which is discussed in many papers (see Arshakian et al. 2010; Fan et al. 2013a; Fan et al. 2013b; Fan et al. 2014; Fan et al. 2017; Fan & Ji. 2014; Giovannini et al. 2014; Giroletti et al. 2012; Kovalev et al. 2009; Massaro et al. 2013a; Massaro et al. 2013b; Pushkarev et al. 2010; Savolainen et al. 2010; Xiao et al. 2015; Pei et al. 2016; Yang et al. 2017; Yang et al. 2018a; Zhang & Fan. 2018). The γ-ray emissions are also used to estimate the beaming boosting factors (Doppler factors) for some γ-ray loud sources (Mattox et al. 1993; Dondi & Ghisellini. 1995; von Montigny et al. 1995; Cheng et al. 1999; Fan et al. 1999; Fan et al. 2013a; Fan et al. 2013b; Fan et al. 2014; Fan 2005). Yang et al. (2018b) studied the effective spectral index properties, then suggested that synchrotron self-Compton (SSC) model could explain the main process for highly energetic γ rays in BL Lacs. Moreover, the DAk Matter Particle Explorer (DAMPE), was successfully launched into a sun-synchronous orbit at the altitude of 500 km on 2015 December 17th from the Jiuquan launch base. DAMPE offers a new opportunity for advancing our knowledge of cosmic rays, dark matter, and gamma-ray astronomy as well (Chang et al. 2017). This marks a new generation of astrophysics, which has bound particles physics and astronomy together tightly.

For blazars, the Doppler factor ($\delta = \left[\Gamma (1 - \beta \cos \phi) \right]^{-1}$) is an important parameter, where $\Gamma = (1 - \beta^2)^{1/2}$ is a bulk Lorentz factor, $\beta$ is the jet speed in units of the speed of light, and $\phi$ is a viewing angle between the jet and the line-of-sight. The Doppler factor is a key quantity in jets since it determines how much flux densities are boosted and timescales compressed in the observer frame. The Doppler factor, although a crucial parameter in the blazar paradigm dictating all of the observed properties of blazars, is very difficult to estimate since there is no direct determining method for either $\beta$ or $\phi$. For this reason, many indirect methods have been proposed in order to estimate $\delta$, which usually involves different energetic (e.g., Ghisellini et al. 1993; Mattox et al. 1993; Fan et al. 2013a; Fan et al. 2014) and/or causality arguments (Lähteenmäki & Valtaoja. 1999; Hovatta et al. 2009; Jorstad et al. 2005; Jorstad et al. 2017; Liodakis et al. 2018) or fitting the spectral energy distribution (SED, Ghisellini et al. 2014; Zhang et al. 2012; Chen et al. 2018) of γ-ray emitting blazars. Lähteenmäki & Valtaoja. (1999) proposed to estimate the Doppler factor ($\delta_{\var 

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

here $\Delta T$ is the time scale in units of hour, $\alpha$ is the X-ray spectral index, $F_{1\text{KeV}}$ is the flux density at 1 KeV in units of $\mu$Jy, $E_{\gamma}$ is the energy in units of GeV, at which the $\gamma$-rays are detected, and $d_L$ is luminosity distance in units of Mpc.

Superluminal motion is also an interesting observational property of blazars. Thanks to the very large baseline interferometry (VLBI) established by Europe, Canada, United States, Russia and so on, with high angular resolution at milliarcsecond, many AGNs show interesting observational results, some compact radio sources consist of more than one component, and some of these components seem to be separating at apparent velocities being greater than the
speed of light. A parameter, $\beta_{\text{app}} (= v/c)$, is introduced to value the apparent velocity. If $\beta_{\text{app}} > 1$, then it is called to be superluminal, and this kind of sources are called superluminal sources.

The first apparent superluminal motion was observed from 3C 279, a component moving away from the quasar core at nearly ten times the speed of light was detected. Vermeulen & Cohen. (1994) listed 66 extragalactic sources, from which they found multi-epoch VLBI internal proper motions, then investigated several modifications to a simple relativistic beam concept and its statistical effects on apparent velocity. They also checked the distribution of $\beta_{\text{app}}$ for lobe-selected and core-selected quasars respectively and obtained the $\beta_{\text{app}}$ for different object categories to be in general agreement with an AGN unification model. In 1996, Fan et al. compiled a sample of 48 superluminal motion sources to investigate the beaming effect, found that the core dominance is an indicator of the orientation of the emission, and proposed that the superluminal motion and beaming effect are probably the same things. Kellermann et al. (2003) presented a sample of 96 superluminal sources to study the nature of the relativistic beaming effect in blazars and their surrounding environment of the massive black holes. They found that most of the blazars show an outward flow away from the centre core while a few sources show the opposite direction of features, and there is no simple correlation between timescale of flux changes and apparent velocities. In 2008, Zhang & Fan. collected an up-to-date sample of 123 superluminal sources including 84 quasars, 27 BL Lac objects and 12 galaxies, calculated the apparent velocities for each source, and found that the radio emissions are strongly boosted by the beaming effect and the superluminal motion is the same thing as the beaming effect in AGNs.

For the details of kinematics in superluminal motion, Britzen et al. (2008) presented a detailed kinematic analysis of the complete flux-density limited Caltech-Jodrell Bank Flat-spectrum (named CJF 1) sources. CJF survey computed 2D kinematic models based on the optimal model-fitting parameters of multi-epoch VLBA observations, then investigated possible correlations between the apparent proper motions and some other parameters in AGN jets. They found a strong correlation between the 5 GHz luminosity and apparent velocity. Based on the data of MOJAVE 2 (Monitoring of Jets in Active galactic nuclei with VLBA Experiments) sample, Lister et al. (2009) discussed the jet kinematics of a complete flux-density-limited sample of 135 radio-loud AGNs resulting from a 13-years program, investigated the structure and evolution of parsec-scale jet phenomena, and found there is an overwhelming tendency to display outward motions, only eight inward moving components. Lister et al. (2013) studied 200 AGNs parsec-scale jet orientation variations and superluminal motion, found a general trend of increasing apparent speed with distance down the jet for both radio galaxies and BL Lac objects.

Since Fermi-LAT was launched in 2008, the 4-year catalogue includes 1591 AGNs. Although AGNs are the main detection result by Fermi-LAT, while there are many AGNs are not detected by Fermi. Why are some AGNs detected by Fermi-LAT and others are not? To answer this question, we compile a large superluminal sample (189 FDSs and 102 non-FDSs) and use them to make a comparison between the FDS and the non-FDS sources and do some statistical analyses. This work is arranged as follows: In section 1, we introduce our superluminal sample, in section 2, we will give results, and discussions and conclusions are presented in sections 3 and 4.

Through this paper, a Λ-CDM model with $\Omega_{\Lambda} \simeq 0.7$, $\Omega_{M} \simeq 0.3$ and $\Omega_{K} \simeq 0.0$, and $H_0 = 73$ km s$^{-1}$Mpc$^{-1}$ is adopted.

2. SAMPLES AND RESULTS

2.1. Samples

From the available literature, we compile 291 sources with superluminal motions, including 189 (142 FSRQs, 39 BL Lacs, 5 galaxies and 2 uncertain type blazar candidates (BCU) and 1 unknown type of AGN without a known redshift) Fermi detected superluminal sources (FDS) and 102 (98 FSRQs, 1 BL Lac and 12 galaxies and 1 unknown type of AGN without a known redshift) non-Fermi detected superluminal (non-FDS) sources, where Fermi detected sources mean these sources are detected by Fermi-LAT telescope and listed in the Fermi AGN catalogues.

There are 816 components for the 189 FDS sources in total, 30 of them have just one component. In the present sample, we also include the γ-ray emission source, 0007+106 (III ZW 2), which was classified as an γ-ray source by Liao et al. (2016). All the FDS sources are listed in Table 1.

For the 102 non-FDS sources (88 FSRQs, 1 BL Lac, 12 galaxies and 1 unknown type of AGN) with 400 components totally, 17 of them have just one component, they are in Table 2.

1. http://www.mpifr-bonn.mpg.de/staff/sbritzen/cjf.html
2. http://www.physics.purdue.edu/MOJAVE/
Table 1. Superluminal Sources detected by Fermi-LAT

| FGL name      | Other name | Class | redshift | δR | Ref | m_o | Ext | S_R | S_X | $\Gamma_\gamma$ | F_γ | μ | comp | Ref | $\beta$ |
|---------------|------------|-------|----------|----|-----|-----|-----|-----|-----|---------------|-----|----|-------|-----|---------|
| 0007+106      | III Zw 2   | G     | 0.089    | 2.51| L18 | 15.8| 0.227| 98  | 6.14| 204±12        | 269±50| 4  | MOJAVE | 1.197±0.069 |
| 1FGL J1159.4-2149 |           | F     | 0.927    |     |     | 17.8| 0.104| 386 | 0   | 9.3±3.8       | 83±22 | 2  | MOJAVE | 0.46±0.19  |
| 1157-215      |            |       |          |    |     |     |      |     |     | 26.2±8.0      |       | 3  | MOJAVE | 4.1±1.1    |
| 1FGL J1245.8-0632 |       | F     | 1.286    |     |     | 19.6| 0.068| 551 | 0   | 358±53        |       | 1  | MOJAVE | 22.5±3.4   |
| 1243-072      |            |       |          |    |     |     |      |     |     | 17.6±8.9e    |       | 3  | MOJAVE | 1.11±0.56  |
|               |            |       |          |    |     |     |      |     |     | 40±16         |       | 4  | MOJAVE | 2.51±1.00  |
| 2FGL J2148.2+0659 |       | F     | 0.999    | 15.6| H09 | 15.9| 0.186| 2590| 1.46| 59.0±1.8      |      | 2a | MOJAVE | 3.092±0.096|
| 2145+067      |            |       |          |    |     |     |      |     |     | 50.1±9.1     |      | 3a | MOJAVE | 2.63±0.48  |
|               |            |       |          |    |     |     |      |     |     | 49.2±3.3     |      | 5  | MOJAVE | 2.58±0.17  |
|               |            |       |          |    |     |     |      |     |     | 59.3±3.8     |      | 7  | MOJAVE | 3.11±0.20  |
|               |            |       |          |    |     |     |      |     |     | 27.6±3.8     |      | 8  | MOJAVE | 1.45±0.20  |
| 3FGL J0006.4+3825 |       | F     | 0.229    | 17.6|     | 17.6| 0.205| 572 | 0.75| 2.617         |      |    | C1     | CJF | 0.12±0.52  |
| 0003+380      |            |       |          |    |     |     |      |     |     | 135±37        |      | C2 | CJF    | 1.85±0.51  |
|               |            |       |          |    |     |     |      |     |     | 145           |      | C3 | CJF    | 1.99±0.0  |
|               |            |       |          |    |     |     |      |     |     | 336           |      | C4 | CJF    | 4.6±0.0   |

Note—Only five objects were shown here and the whole Table will be given in the electronic version. Column (1) gives the Fermi name (other name), column (2) classification, F stands for FSRQs, B for BL Lacs, Sy for Seyfert galaxies, An for unknown type AGNs, column (3) redshift, column (4) Doppler factor, column (5) reference for Doppler factor, column (6) apparent magnitude ($m_o$) from BZCAT a (Massaro et al. 2009), column (7) Galactic extinction ($A_R$) from NED, column (8) flux density at 1.4 GHz from BZCAT, column (9) X-ray flux in the 0.1-2.4 KeV band from BZCAT, column (10) γ-ray photon spectral index, column (11) γ-ray photon flux range 1-100 GeV (Acero et al. 2015), column (12) proper motion $\mu$ in microarcsecond per year, column (13) components for proper motion, column (14) reference for proper motion, column (15) apparent velocity, $\beta_{app}$. 

a http://www.asdc.asi.it/bzcat/
### Table 2. Superluminal Sources not detected by Fermi-LAT

| FGL name   | Class | redshift | δ_R | Ref  | m_o | Ext  | S_R  | S_X  | μ     | comp | Ref  | β     |
|------------|-------|----------|-----|------|-----|------|------|------|-------|------|------|-------|
|            |       |          |     |      |     |      |      |      |       |      |      |       |
| 0003-066   | B     | 0.347    | 5.1 | H09  | 17.9| 0.087| 2051 | 0.82 | 191 ± 15 | 2    | MOJAVE | 4.09 ± 0.33 |
|            |       |          |     |      |     |      |      |      | 250 ± 39 | 3    | MOJAVE | 5.36 ± 0.83 |
|            |       |          |     |      |     |      |      |      | 50.4 ± 5.3 | 4a   | MOJAVE | 1.08 ± 0.11 |
|            |       |          |     |      |     |      |      |      | 100 ± 16 | 5    | MOJAVE | 2.15 ± 0.35 |
|            |       |          |     |      |     |      |      |      | 54 ± 11  | 6a   | MOJAVE | 1.16 ± 0.24 |
|            |       |          |     |      |     |      |      |      | 330.4 ± 9.8 | 8a  | MOJAVE | 7.08 ± 0.21 |
|            |       |          |     |      |     |      |      |      | 287 ± 25 | 9    | MOJAVE | 6.14 ± 0.53 |
|            |       |          |     |      |     |      |      |      | 116 ± 23 | 14   | MOJAVE | 2.48 ± 0.50 |
| 0010+405   | F     | 0.255    |  |     |     |      |      |      | 428 ± 40 | 1    | MOJAVE | 6.92 ± 0.64 |
|            |       |          |     |      |     |      |      |      | 2 ± 16  | 2    | MOJAVE | 0.04 ± 0.26 |
|            |       |          |     |      |     |      |      |      | 2.9 ± 4.3c | 3   | MOJAVE | 0.047 ± 0.070 |
|            |       |          |     |      |     |      |      |      | 1.1 ± 3.1c | 4   | MOJAVE | 0.018 ± 0.050 |
| 0014+813   | F     | 3.366    | 15.9 |     | 0.425| 693  | 0.77 | 4 ± 12 | C1    | B08  | 0.39 ± 1.18 |
|            |       |          |     |      |     |      |      |      | 86 ± 15 | C2   | B08  | 8.49 ± 1.48 |
|            |       |          |     |      |     |      |      |      | 111 ± 18 | C3  | B08  | 10.95 ± 1.78 |
| 0016+731   | F     | 1.781    | 7.9  | H09  | 18.2 | 0.735| 1136 | 0.11 | 106.2 ± 4.4 | 1a  | MOJAVE | 8.23 ± 0.34 |
| 0022+390   | F     | 1.946    |  |     |     |      |      |      | 113 ± 43 | C1   | B08  | 8.51 ± 3.24 |

Note—Only five objects were shown here and the whole Table will be given in the electronic version. Column (1) name, column (2) classification, F stand for FSRQs, B for BL Lacs, Sy for Seyfert galaxies, G for galaxies, column (3) redshift, column (4) Doppler factor, column (5) reference for Doppler factor, column (6) apparent magnitude \( R_{app} \) from BZCAT, column (7) Galactic extinction \( A_R \) from NED, column (8) flux at 1.4 GHz from BZCAT, column (9) X-ray flux in the 0.1-2.4 KeV band from BZCAT, column (10) proper motion \( \mu \) microarcsecond per year, column (11) components for proper motion, column (12) reference for proper motion, column (13) apparent velocity, \( \delta_{app} \).
2.2. Results

2.2.1. Proper Motion and Apparent Velocity Distribution

For a proper motion ($\mu$), an apparent velocity ($\beta_{\text{app}}$) can be computed by,

\[ \beta_{\text{app}} = \frac{\mu}{H_0} \int_{1+z}^{1+z} \frac{1}{\sqrt{\Omega_M x^3 + 1 - \Omega_M}} dx. \]  

(1)

Hence, we calculate apparent velocities from its given proper motions if its apparent velocities are not given by MOJAVE (Lister et al. 2013; Lister et al. 2016) or other reference literature for the sources in Tables 1 and 2. Then we compare their maximum proper motion ($\mu_{\text{max}}$) and maximum apparent velocity ($\beta_{\text{app}}^{\text{max}}$), averaged proper motion ($\mu_{\text{mean}}$) and averaged apparent velocity ($\beta_{\text{app}}^{\text{mean}}$) between FDS and non-FDS sources. The corresponding uncertainty of averaged value is expressed by an error-transmission format:

\[ \sigma = \sqrt{\sum_{i=1}^{n} \left( \frac{\partial f}{\partial x_i} \right)^2 \sigma_{x_i}^2}, \]

The distributions of the maximum and averaged proper motion and the apparent velocity for FDS and non-FDS sources are shown in Figures 1-2, where the red stepped line is for FDS, and the blue stepped line for non-FDS sources.

It is found that the maximum proper motion is distributed from 0.018 to 2.510 with a mean value of $\langle \mu_{\text{FDS}}^{\text{max}} \rangle = 0.361 \pm 0.037 \text{ mas yr}^{-1}$ for the FDS sources, and from 0.021 to 2.941 with $\langle \mu_{\text{non-FDS}}^{\text{max}} \rangle = 0.224 \pm 0.027 \text{ mas yr}^{-1}$ for the non-FDS sources.
the non-FDS sources. When a Kolmogorov-Smirnov (K-S) test is adopted to the two distributions, the probability for the two distributions to come from the same distribution is $p = 6.2 \times 10^{-5}$, see Figure 1.

The mean proper motion is distributed from 0.011 to 1.853 with $\langle \mu_{\text{mean}}^{\text{FDS}} \rangle = 0.233 \pm 0.021$ mas yr$^{-1}$ for the FDS sources and from 0.015 to 2.193 with $\langle \mu_{\text{mean}}^{\text{non-FDS}} \rangle = 0.158 \pm 0.015$ mas yr$^{-1}$ for the non-FDS sources, and $p = 1.6 \times 10^{-4}$, see Figure 1.

From the calculations, it is found that the maximum apparent velocity $\beta_{\text{max}}^{\text{app}}$ is distributed from 1.04 to 39.70 with $\langle \beta_{\text{max}}^{\text{FDS}} \rangle = 12.36 \pm 1.64$ for the FDS sources and from 1.08 to 58.04 with $\langle \beta_{\text{max}}^{\text{non-FDS}} \rangle = 8.75 \pm 1.32$ for non-FDS sources, and $p = 3.3 \times 10^{-7}$, see Figure 2.

For the mean apparent velocity, $\beta_{\text{mean}}^{\text{app}}$ is distributed from 0.53 to 34.80 with $\langle \beta_{\text{mean}}^{\text{FDS}} \rangle = 8.17 \pm 0.94$ for the FDS sources and from 0.61 to 29.33 with $\langle \beta_{\text{mean}}^{\text{non-FDS}} \rangle = 5.99 \pm 0.78$ for non-FDSs, and $p = 1.4 \times 10^{-4}$, see Figure 2.

2.2.2. Correlations between Proper Motion and Redshift

From the data listed in Tables 1 and 2, when a linear regression fitting is adopted to the proper motion and redshift, we have

$$\log \mu_{\text{FDS}}^{\text{max}} = -(0.35 \pm 0.10) \log z - (0.95 \pm 0.03)$$

with a correlation coefficient $r = -0.26$ and a chance probability of $p = 4.0 \times 10^{-4}$ for the FDSs, and

$$\log \mu_{\text{non-FDS}}^{\text{max}} = -(0.14 \pm 0.11) \log z - (0.96 \pm 0.04)$$

with $r = -0.13$ and $p = 20\%$ for the non-FDSs, see Figure 3.

2.2.3. Correlations between Apparent Velocity and Redshift

Figure 2. The distribution of maximum (left panel) / mean (right panel) apparent velocity ($\beta_{\text{max}}^{\text{app}} / \beta_{\text{mean}}^{\text{app}}$). The upper panel figures are their histograms of FDS and non-FDS sources, the lower panel figures are their cumulative probability distributions (CPD).
Figure 3. The plot of the maximum proper motion (log $\mu_{\text{max}}$) against redshift (log $z$). The black plus stands for FDS sources and blue circle stands for non-FDS sources, black solid line and blue solid line stand for the best fitting results for FDS sources and non-FDS.

For the apparent velocity ($\beta_{\text{app}}$), we have following results for the maximum and average values of apparent velocity ($\beta_{\text{app}}$),

$$
\log \beta_{\text{FDS}}^{\text{max}} = (0.36 \pm 0.09) \log z + (0.76 \pm 0.03), \quad r = 0.28 \quad \text{and} \quad p = 1.4 \times 10^{-4},
$$

$$
\log \beta_{\text{FDS}}^{\text{mean}} = (0.30 \pm 0.09) \log z + (0.55 \pm 0.03), \quad r = 0.24 \quad \text{and} \quad p = 1.0 \times 10^{-3},
$$

for the 186 FDSs (3 excluded sources without redshift from NED ), and

$$
\log \beta_{\text{non-FDS}}^{\text{max}} = (0.59 \pm 0.10) \log z + (0.73 \pm 0.03), \quad r = 0.50 \quad \text{and} \quad p = 1.6 \times 10^{-7},
$$

$$
\log \beta_{\text{non-FDS}}^{\text{mean}} = (0.54 \pm 0.11) \log z + (0.55 \pm 0.03), \quad r = 0.46 \quad \text{and} \quad p = 2.8 \times 10^{-6},
$$

for the 101 non-FDS as shown in Figure 4.

2.2.4. Correlation between Apparent Velocity and $\gamma$-Ray Luminosity

For the $\gamma$-ray sources, the integral flux ($f$) in units of GeV $\cdot$ cm$^{-2} \cdot$ s$^{-1}$, can be expressed in the form (Fan et al. 2013b)

$$
N_{(E_L \sim E_U)} \left( \frac{1}{E_U} - \frac{1}{E_L} \right) \ln \left( \frac{E_U}{E_L} \right), \quad \text{if} \quad \alpha_{\text{ph}} = 2,
$$

otherwise

$$
N_{(E_L \sim E_U)} \frac{1 - \alpha_{\text{ph}}}{2 - \alpha_{\text{ph}}} \frac{E_{-\alpha_{\text{ph}}}^2 - E_{-\alpha_{\text{ph}}}^2}{E_{-\alpha_{\text{ph}}}^2 - E_{-\alpha_{\text{ph}}}^2} \quad \left(2\right)
$$

here $N_{(E_L \sim E_U)}$ is the integral photons in the energy range of $E_L$ and $E_U$. In this work, $E_L$ and $E_U$ are corresponding to 1 GeV and 100 GeV respectively. Then, we calculate the $\gamma$-ray luminosity ($L_\gamma$) in units of erg $\cdot$ s$^{-1}$ by

$$
L_\gamma = 4\pi d_L^2 (1+z)^{\alpha_{\text{ph}}-2} f
$$

Here, $L_\gamma$ is the $\gamma$-ray luminosity, $d_L = \frac{c(1+z)}{H_0} \int_1^{1+z} \frac{1}{\sqrt{1 + \Omega_M x}} dx$ is a luminosity distance, $(1+z)^{\alpha_{\text{ph}}-2}$ stands for a K-correction, $\alpha_{\text{ph}}$ for $\gamma$-ray photon spectral index.
Figure 4. The plot of apparent velocity (log $\beta_{\text{app}}$) against redshift (log $z$) for FDS and non-FDS sources. The dot stands for FSRQs, triangle for BL Lacs and square for Galaxies including Seyfert galaxies and normal galaxies, (a): maximum apparent velocity against redshift of FDS, (b): mean apparent velocity against redshift of FDS, and (c): maximum apparent velocity against redshift of non-FDS, (d): mean apparent velocity against redshift of non-FDS. Black solid lines in this figure represent its corresponding best linear fitting results.

Figure 5 shows the maximum and average apparent velocity against the $\gamma$-ray luminosity. The dash curved upper envelope is described by Cohen et al. (2007), the upper envelope of this distribution traces out a single source of a given bulk Lorentz factor and intrinsic luminosity in the $(L, \beta_{\text{app}})$ plane as the viewing angle $\phi$ changes. Such an aspect curve is plotted in Figure 5 for a jet with a bulk Lorentz factor of 42 and an intrinsic luminosity of log $L_{\text{in}} = 42$, assuming Doppler boosting by a factor of $\delta^3$, by these formulas: $\delta = \frac{1}{\Gamma(1-\beta \cos \phi)}$, $\beta_{\text{app}} = \frac{\beta \sin \phi}{\Gamma(1-\beta \cos \phi)}$, $L = L_{\text{in}} \delta^3$.

2.2.5. Flux Density-Flux Density Correlations

The multi-wavelength (radio, optical and X-ray) data are from the BZCAT, the optical magnitude is made galactic extinction correction and then transferred into optical flux density. The optical, radio and X-ray flux densities are also K-corrected by $(1 + z)^{\alpha_{\text{K}}-1}$, where $\alpha$ ($F_{\nu} \propto \nu^{-\alpha}$) is the spectral index in the given band. For the spectral indexes, we adopt $\alpha_r = 0$ for radio band (Donato et al. 2001, Abdo et al. 2010a), while for optical band, $\alpha_o = 0.5$ for BLs and $\alpha_o = 1$ for the rest of the sources as did by Donato et al. (2001), $\alpha_X = 0.78$ for FSRQs, $\alpha_X = 1.30$ for BLs and $\alpha_X = 1.05$ for BCUs from Fan et al. (2016). For any two bands, we have

$$\log S_r = (0.28 \pm 0.04) \log F_o + (6.15 \pm 0.49), \quad r = 0.51 \text{ and } p = 5.9 \times 10^{-14},$$

$$\log F_x = (0.46 \pm 0.04) \log F_o + (5.46 \pm 0.51), \quad r = 0.64 \text{ and } p = 6.8 \times 10^{-22}, \text{ and}$$

$$\log F_X = (0.53 \pm 0.08) \log S_r - (1.65 \pm 0.22), \quad r = 0.46 \text{ and } p = 1.0 \times 10^{-10}$$

for FDSs, and

$$\log S_r = (0.28 \pm 0.07) \log F_o + (6.21 \pm 0.82), \quad r = 0.38 \text{ and } p = 4.0 \times 10^{-4},$$

$$\log F_x = (0.46 \pm 0.04) \log F_o + (5.46 \pm 0.51), \quad r = 0.64 \text{ and } p = 6.8 \times 10^{-22}, \text{ and}$$

$$\log F_X = (0.53 \pm 0.08) \log S_r - (1.65 \pm 0.22), \quad r = 0.46 \text{ and } p = 1.0 \times 10^{-10}$$

for non-FDS sources.
Figure 5. The plot of apparent velocity ($\beta_{\text{app}}$) against the logarithmic $\gamma$-ray luminosity ($\log L_{\gamma}$) for FDS sources. The dot stands for FSRQs, triangle for BL Lacs and square for galaxies. The dashed curve represents an envelope with fixed $\Gamma = 42$ and $\log L_{\text{in}} = 42$.

$$
\log F_x = (0.40 \pm 0.06)\log F_{\gamma} + (4.63 \pm 0.78), \ r = 0.47 \text{ and } p = 1.8 \times 10^{-5}, \text{ and}
$$

$$
\log F_x = (0.51 \pm 0.11)\log S_{\gamma} - (1.70 \pm 0.30), \ r = 0.50 \text{ and } p = 3.7 \times 10^{-6}
$$

for non-FDSs. These corresponding results are shown in Figure 6.

For the subclasses of BL Lacs and FSRQs, their correlations are shown in Table 3 for FDSs and non-FDSs.

3. DISCUSSIONS

As a subclass of AGNs, blazar has many extreme observation properties, which may be attributed to a relativistic beaming effect. We compile proper motions, $\mu$ for 1216 components for 291 sources, including 189 FDS and 102 non-FDS sources. Then we collect and calculate the corresponding apparent velocity ($\beta_{\text{app}}$), get their multi-wavelength
Comparison between FDS and non-FDS Superluminal Sources

Figure 6. Plots for optical magnitude ($\log F_o$), radio flux density ($\log S_r$), X-ray flux ($\log F_x$). Left-hand panel for FDS sources, right-hand panel for non-FDS sources. Upper panel for radio against optical, middle panel for X-ray against optical and lower panel for X-ray against radio. Dot stands for FSRQs, triangle for BL Lacs and square for galaxies. The solid lines stand for best linear fitting results.
data, and Doppler factors from available references (BZACT, MOJAVE, Fermi-3rd catalogue, and so on), make comparisons between FDSs and non-FDSs, and then investigate some statistical correlations.

3.1. Averaged Values for Superluminal Motions

The averaged maximum values of proper motion for FDSs and non-FDSs are \( \langle \mu_{\text{FDS}}^{\text{max}} \rangle = 0.361 \pm 0.037 \) and \( \langle \mu_{\text{non-FDS}}^{\text{max}} \rangle = 0.224 \pm 0.027 \); while the averaged mean values of proper motion are \( \langle \mu_{\text{FDS}}^{\text{mean}} \rangle = 0.233 \pm 0.021 \) and \( \langle \mu_{\text{non-FDS}}^{\text{mean}} \rangle = 0.158 \pm 0.015 \) respectively. The averaged maximum values of apparent velocity for FDS and non-FDS sources are \( \langle \beta_{\text{FDS}}^{\text{max}} \rangle = 12.36 \pm 1.64 \) and \( \langle \beta_{\text{non-FDS}}^{\text{max}} \rangle = 8.75 \pm 1.32 \); the averaged mean values are \( \langle \beta_{\text{FDS}}^{\text{mean}} \rangle = 8.17 \pm 0.94 \) and \( \langle \beta_{\text{non-FDS}}^{\text{mean}} \rangle = 5.99 \pm 0.78 \).

Based on MOJAVE 1.5 Jy flux density-limited samples, Lister et al. (2016) get a less than 0.02 % probability that the LAT and non-LAT sub-samples come from the same parent distribution according to K-S tests. When a K-S test is adapted to these distributions of FDSs and non-FDSs, we find that probability for the distributions of FDSs and non-FDSs to be from the same distribution is less than 1.6 \times 10^{-4} as shown in Figure 1-2, suggesting FDSs and non-FDSs should be from two different distributions. Our result confirms the result by Lister et al. (2016). We can say that FDSs have a larger proper motion and apparent velocity than do non-FDSs.

These results are consistent with other results. Jorstad et al. (2001) indicated that the sources with γ-ray emission show greater apparent velocities (\( \beta_{\text{app}} \)) than these sources without γ-ray emissions. Lister et al. (2009), Lister et al. (2016) and Piner et al. (2012) also confirmed this result, which means that the γ-ray sources are highly beamed. Our result based on the largest superluminal sample also confirms their results.

3.2. Correlations

Vermeulen & Cohen. (1994) collected 66 sources with proper motions, they showed that the proper motion decreases with increasing redshift (see also, Cohen et al. 2005). In our previous work (Zhang & Fan. 2008), we collected a sample of 123 superluminal sources, investigated the correlation between proper motion and redshift, and got \( \log \mu \sim -0.28 \log z \).

In this paper, we obtained \( \log \mu^{\text{max}} = -(0.28 \pm 0.07) \log z - (0.95 \pm 0.02) \) with \( r = 0.22 \) and a chance probability of \( p = 1.2 \times 10^{-4} \) for the whole sample. The result indicates clearly that the proper motion decreases with the increasing redshift, which is consistent with the results from others’ (Vermeulen & Cohen, 1994, Cohen et al. 2005 and Zhang & Fan, 2008). When we consider FDS and non-FDS separately, there is an anti-correlation with a slope of −0.35 for the FDSs, and an anti-correlation tendency with a slope of −0.14 for the non-FDSs.

When we investigate linear correlations between apparent velocities (\( \log \beta_{\text{app}} \)) and redshift (\( \log z \)), slopes are 0.36 and 0.59 are obtained from the \( \log \beta_{\text{app}} \sim \log z \) fitting for FDS and non-FDS sources respectively, which means the apparent velocity increases with redshift. Obviously, for non-FDS, the positive correlation is much better which with a chance probability is \( p = 1.6 \times 10^{-7} \). Lister et al. (2009) plotted maximum apparent velocity against redshift for their sample.

| Type   | band | Sample | \( a + \Delta a \) | \( b + \Delta b \) | \( N \) | \( r \) | \( p \) |
|--------|------|--------|-------------------|-------------------|-------|-------|-------|
| FDS    | BL Lac | whole | 0.28 ± 0.04 | 6.15 ± 0.49 | 186 | 0.51 | 5.9 \times 10^{-14} |
|        | FSRQ  | whole | 0.34 ± 0.05 | 7.00 ± 0.64 | 144 | 0.49 | 3.3 \times 10^{-10} |
|        | BL Lac | whole | 0.46 ± 0.04 | 5.46 ± 0.51 | 180 | 0.64 | 6.8 \times 10^{-22} |
|        | FSRQ  | whole | 0.41 ± 0.05 | 4.87 ± 0.60 | 139 | 0.59 | 1.4 \times 10^{-14} |
|        | BL Lac | whole | 0.55 ± 0.08 | −1.65 ± 0.22 | 179 | 0.46 | 1.0 \times 10^{-10} |
|        | FSRQ  | whole | 0.52 ± 0.07 | −1.72 ± 0.20 | 138 | 0.52 | 3.9 \times 10^{-11} |
| non-FDS | BL Lac | whole | 0.28 ± 0.07 | 6.21 ± 0.82 | 82 | 0.38 | 4.0 \times 10^{-4} |
|        | FSRQ  | whole | 0.28 ± 0.07 | 6.22 ± 0.86 | 77 | 0.43 | 1.0 \times 10^{-4} |
|        | BL Lac | whole | 0.40 ± 0.06 | 4.63 ± 0.78 | 76 | 0.47 | 1.8 \times 10^{-5} |
|        | FSRQ  | whole | 0.36 ± 0.07 | 4.22 ± 0.85 | 71 | 0.54 | 1.2 \times 10^{-6} |
|        | BL Lac | whole | 0.51 ± 0.11 | −1.70 ± 0.30 | 76 | 0.50 | 3.7 \times 10^{-6} |
|        | FSRQ  | whole | 0.51 ± 0.11 | −1.68 ± 0.30 | 71 | 0.49 | 1.5 \times 10^{-5} |
and showed that the maximum superluminal velocity increases with redshift. In the MOJAVE survey, the minimum detectable luminosity rises sharply with redshift, creating a classical Malmquist bias and the high redshift sources have higher apparent luminosities, which they achieved primarily via Doppler boosting (Lister et al. 2009). Our result is consistent with theirs.

Kellermann et al. (2007) quoted their result of apparent velocity and luminosity and indicated that there are no low luminosity sources with fast motions. The high luminosity sources show a wider range of apparent velocity. In Figure 5, we also find such a tendency that the brighter \( \gamma \)-ray sources show a higher apparent velocity. It is due to a beaming effect because a source with a higher velocity suggests a corresponding higher Doppler factor, and a higher Doppler boosting results in a higher luminosity.

From Fig. 5, we can see a tendency for higher apparent velocity source to have higher \( \gamma \)-ray luminosity. However, we can also see that some luminous \( \gamma \)-ray source have also low apparent velocity. Actually, there is an envelope between apparent velocity and \( \gamma \)-ray luminosity in Figure 5, which is similar to that seen in the Caltech-Jodrell Bank Flat Spectrum (CJF) survey (Vermeulen. 1995), the 2 cm Survey (Kellermann et al. 2004), and the MOJAVE survey (Cohen et al. 2007; Lister et al. 2009; Piner et al. 2012). This upper envelope is not due to selection effects, although its precise physical origin is unclear. Lister et al. (2009) speculated that such an envelope may arise because of an intrinsic relation between jet speed and luminosity in the parent population.

### 3.3. Flux-Flux Correlations

The mutual correlations between fluxes were investigated in literature. Fan et al. (1994) compiled 52 X-ray selected BL Lacs to study the mutual correlations among radio, X-ray and optical data and found closely mutual correlations. Dondi & Ghisellini. (1995) studied correlations between \( L_\gamma \) versus \( \bar{L}_r \), \( \bar{L}_o \) and \( \bar{L}_X \), for a sample of quasars detected by EGRET, obtained positive correlations, and found that \( \bar{L}_\gamma \) correlates closer with \( \bar{L}_r \) than with \( \bar{L}_o \) or \( \bar{L}_X \). In the present work, we investigate mutual correlations for radio, optical and X-ray fluxes for both FDS and non-FDS sources. For our flux-flux correlation analysis, we can see positive correlations and that there is no significant difference in slopes and intercepts between FDSs and non-FDSs. In 2010, Abdo et al. used quasi-simultaneous data to calculate the SEDs for a sample of 48 LAT Bright AGN sample sources (LBAS). From their multwavelength data, we get following corresponding results,

\[
\log S_r = (0.13 \pm 0.06) \log F_o + (4.37 \pm 0.71), \quad r = 0.37 \quad \text{and} \quad p = 1.2%,
\]

\[
\log F_X = (0.58 \pm 0.09) \log F_o + (7.10 \pm 1.06), \quad r = 0.80 \quad \text{and} \quad p = 3.1 \times 10^{-7}, \quad \text{and}
\]

\[
\log F_X = (0.68 \pm 0.23) \log S_r - (1.87 \pm 0.69), \quad r = 0.36 \quad \text{and} \quad p = 1.7%.
\]

We can see that the results based on the quasi-simultaneous data are similar to our results.

The emissions from AGNs are mainly from the jet, however there are contaminations from the host galaxy (especially for BL Lac objects) as well as the big blue bump (especially for FSRQs) in the optical band, together with the contribution from the accretion system in the X-ray domain. Since the sample considered here is all superluminal, their jet emission should be strongly boosted, which make the contaminations in the optical and X-ray bands be relatively small.

Ghisellini et al. (1989) proposed that the bulk velocity of the plasma increases with distance from the core and synchrotron X-rays are weakly beamed, while optical and radio emissions are more strongly beamed. Fan et al. (1993) proposed an empirical frequency dependent Doppler factor: \( \delta_v = \delta_o^{1 + 1/8 \log(\nu_c/\nu)} \), where \( \delta_o \) is the optical Doppler factor, then \( \delta_X \sim \delta_o^{0.5}, \delta_r \sim \delta_o^{1.5}, \delta_X \) and \( \delta_r \) are the X-ray and radio Doppler factors (Fan et al. 1993). In a beaming model, the observed emission, \( f^{ob} \), is strongly boosted, namely, \( f^{ob} = \delta^p f^m \), where \( f^m \) is the intrinsic emission in the source frame, \( \delta \) is the Doppler factor, \( p = 3 + \alpha \) is for a moving compact source or \( p = 2 + \alpha \) for a continuous jet (Lind & Blandford. 1985). Here \( p = 2 + \alpha \) is used as we did before (Xiao et al. 2015). In the work, Doppler factors are available for 151 sources, which makes it possible for us to investigate the mutual correlations for the intrinsic (de-beamed) radio, optical and X-ray flux emissions. For the 151 sources, we have

\[
\log S_r = (0.16 \pm 0.04) \log F_o + (4.86 \pm 0.47), \quad r = 0.34 \quad \text{and} \quad p = 1.5 \times 10^{-7},
\]

\[
\log F_X = (0.47 \pm 0.04) \log F_o + (5.61 \pm 0.47), \quad r = 0.60 \quad \text{and} \quad p = 9.6 \times 10^{-23},
\]

\[
\log F_X = (0.42 \pm 0.07) \log S_r - (1.41 \pm 0.23), \quad r = 0.36 \quad \text{and} \quad p = 5.4 \times 10^{-8}.
\]
for the observed data; and

\[
\log F_{\gamma}^{\text{beamed}} = (0.79 \pm 0.03) \log F_{\gamma}^{\text{beamed}} + (12.02 \pm 0.42), \quad r = 0.88 \quad \text{and} \quad p = 2.2 \times 10^{-74},
\]

\[
\log F_{\alpha}^{\text{beamed}} = (0.48 \pm 0.02) \log F_{\alpha}^{\text{beamed}} + (5.80 \pm 0.28), \quad r = 0.86 \quad \text{and} \quad p = 7.4 \times 10^{-63},
\]

\[
\log F_{\delta}^{\text{beamed}} = (0.53 \pm 0.02) \log F_{\delta}^{\text{beamed}} - (1.56 \pm 0.03), \quad r = 0.85 \quad \text{and} \quad p = 4.8 \times 10^{-62},
\]

for the intrinsic data. It is clear that the correlations between any two bands become much closer when the beaming effect is removed. The result indicates that the beaming effect affects the observed broad band correlations. The comparison results are shown in Figure 7.

### 3.4. Basic parameters for Jets

#### 3.4.1. Doppler Factor, Lorentz Factor and Viewing Angle

Doppler factors are important but not easy to estimate, although several methods were proposed. In the present work, we collect Doppler factor for 229 sources (151 FDS and 78 non-FDS) and list them in Column 4 in Tables 1 and 2.

In a beaming model, the Lorentz factor (\(\Gamma\)) and viewing angle (\(\phi\)) can be obtained from \(\delta\) and \(\beta_{\text{app}}\):

\[
\Gamma = \frac{\beta_{\text{app}}^2 + \delta^2 + 1}{2\delta}, \quad \tan \phi = \frac{2\beta_{\text{app}}}{\beta_{\text{app}}^2 + \delta^2 - 1}.
\]

From the Doppler factors in Tables 1 and 2, we have,

\[
\langle \delta^{\text{FDS}} \rangle = 17.23 \pm 12.54 \quad \text{and} \quad \langle \delta^{\text{non-FDS}} \rangle = 9.48 \pm 8.86,
\]

a K-S test result shows that the probability for the two distributions to be from the same one is \(7.5 \times 10^{-7}\).

For the sources with available Doppler factors, we can calculate \(\Gamma\) and \(\phi\), and get their mean values:

\[
\langle \Gamma^{\text{FDS}} \rangle = 21.41 \pm 21.59 \quad \text{and} \quad \langle \Gamma^{\text{non-FDS}} \rangle = 13.57 \pm 12.75,
\]

and

\[
\langle \phi^{\text{FDS}} \rangle = 5.64^\circ \pm 9.69^\circ \quad \text{and} \quad \langle \phi^{\text{non-FDS}} \rangle = 8.94^\circ \pm 7.77^\circ,
\]

with chance probabilities being \(p = 5.2 \times 10^{-5}\) and \(p = 1.5 \times 10^{-7}\) respectively, which show significant difference in Lorentz factor and viewing angle between FDS and non-FDS sources.

Savolainen et al. (2010) obtained that for the photons arriving to us at an angle \(\phi\), the jet flow is at an angle \(\phi_{\text{co}}\) in the co-moving frame:

\[
\phi_{\text{co}} = \arccos \left( \cos \phi - \beta \frac{1}{\Gamma - \beta \cos \phi} \right)
\]

then, from the obtained \(\Gamma\) and \(\phi\), we can get \(\phi_{\text{co}}\), and their mean values are

\[
\langle \phi_{\text{co}}^{\text{FDS}} \rangle = 82.76^\circ \pm 46.83^\circ \quad \text{and} \quad \langle \phi_{\text{co}}^{\text{non-FDS}} \rangle = 93.68^\circ \pm 43.21^\circ
\]

with a K-S test result of \(p = 15.8\%\) suggesting no clear difference in co-moving viewing angle between FDSs and non-FDSs.

From K-S test results, we can see that there are significant differences in Doppler factor, viewing angle and Lorentz factor between FDSs and non-FDSs. FDSs show higher Doppler factors, higher Lorentz factor, and smaller viewing angle than do non-FDSs. The fact that FDS sources have larger Doppler factor also confirmed by Lister et al. (2015) who used the MOJAVE sample as well. However, the co-moving viewing angles show no clear difference between FDSs and non-FDSs. It means that FDS and non-FDS jets have similar cone in the comoving frame.

Above analysis results suggest that the difference between Fermi detected superluminal sources and non-Fermi detected superluminal sources comes from their difference beaming effect with FDSs being strongly beamed than non-FDSs. The superluminal source 0007+106 (III ZW2) was not listed in the 3FGL, but it was classified as a \(\gamma\)-ray source by Liao et al. (2016). So, we propose that the superluminal source is a \(\gamma\)-ray candidate and the \(\gamma\)-ray source should be a superluminal source. Our sample gives that \(\langle \beta_{\text{max}}^{\text{non-FDS}} \rangle = 8.75 \pm 1.32\) for non-FDS sources, and \(\langle \beta_{\text{max}}^{\text{FDS}} \rangle = 12.36 \pm 1.64\) for the FDS sources. If we take non-Fermi sources with \(\beta_{\text{max}}^{\text{non-FDS}} > \langle \beta_{\text{max}}^{\text{FDS}} \rangle + 5\sigma\) as the candidate of \(\gamma\)-ray emitter, then there are 6 \(\gamma\)-ray emitting candidates, and they are 0153+744, 0208-512, 0536+145, 0552+398, 2223+210, 2351+456.
Figure 7. Mutual correlations between two bands flux densities. Left-hand panel for the observed data, right-hand panel for the removed beaming effect data. The upper panel, (a): radio flux density against optical flux density, (b): de-beamed radio flux density against de-beamed optical flux density; the middle panel, (c): X-ray flux density against optical flux density, (d): de-beamed X-ray flux density against de-beamed optical flux density; and the lower panel, (e): X-ray flux density against radio flux density, (f): de-beamed X-ray flux density against de-beamed radio flux density. The black plus for FDS sources and the blue circle for non-FDS sources and solid lines stand for best linear fitting results.
3.4.2. \(\gamma\)-Ray Luminosity and Viewing Angle

For \(\gamma\)-ray luminosity \((L_\gamma)\) and viewing angle \((\phi)\), there is a significant anti-correlation,

\[
\log \phi = - (0.23 \pm 0.04) \log L_\gamma + (11.14 \pm 1.93),
\]

with \(r = -0.38\) and \(p = 2.2 \times 10^{-6}\). The best fitting result is shown in Figure 8 with a solid line. The results imply that the more luminous \(\gamma\)-ray sources have smaller viewing angles.

However, in a beaming model, the observed flux density, \(f^{ob}\), is correlated with the intrinsic flux density, \(f^{in}\), by

\[
f^{ob} = \delta^p f^{in},
\]

where \(p = 3 + \alpha\) for a discrete case and \(p = 2 + \alpha\) for a continuous case. So, for the luminosity, we have

\[
L^{ob} = \delta^{3+\alpha} L^{in}
\]

for a discrete case, or

\[
L^{ob} = \delta^{2+\alpha} L^{in}
\]

for the continuous case. For sources with available \(\delta\), we can get their intrinsic luminosity and co-moving viewing angle, which show

\[
\log \phi_{co} = (0.09 \pm 0.01) \log L^{in}_{\gamma} - (1.73 \pm 0.48),
\]

with \(r = 0.69\) and \(p = 7.3 \times 10^{-22}\), the result is shown in Figure 9 with a solid line.

Obviously, there is a positive correlation between co-moving viewing angle and intrinsic luminosity, which suggests that the luminous intrinsic \(\gamma\)-ray luminosity corresponds to a wider co-moving viewing angle. If the emission per solid angle in the comoving is similar for Fermi-LAT sources, then the larger co-moving angle corresponds to larger solid angle frame, then the emission is stronger.

From Figures 5-9, we can see that FDS and non-FDS sources are different. FDSs show higher proper motion \((\mu)\), higher apparent velocity \((\beta_{app})\), higher Doppler factor \((\delta)\), higher Lorentz factor \((\Gamma)\) and smaller viewing angle \((\phi)\) than non-FDSs. We can say that FDSs have stronger beaming effect than do non-FDSs.

4. CONCLUSIONS

The 291 superluminal sources had 1216 components. We collected their multi-wavelength data and Doppler factors and calculated the apparent velocity for each component, the Lorentz factor and viewing angle (co-moving angle) for those with an available Doppler factor, calculate the \(\gamma\)-ray luminosity for the 3GFL sources. Subsequently, we investigated the relationships between FDS and non-FDS sources. Our main conclusions are summarized as follows:
1. FDS sources show higher proper motion, apparent velocity, Doppler factor, Lorentz factor and smaller viewing angles than non-FDS sources. For superluminal sources, FDSs are more beamed.

2. The intrinsic (de-beamed) fluxes show much closer mutual correlations among radio, optical and X-ray bands than the observed data.

3. A higher apparent velocity source has the tendency to exhibit higher γ-ray luminosity, and the superluminal sources may be the γ-ray emission candidates; moreover γ-ray sources with no known superluminal velocity can be superluminal candidates.

4. The γ-ray brighter source shows a smaller viewing angle, which suggest a strong Doppler effect. High energetic γ-ray emissions per solid angle are probably similar in the co-moving frame; thus the de-beamed γ-ray luminosity is positively correlated with the co-moving viewing angle.

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