Blazar Variability and Evolution in the GeV Regime

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One of the most important problem of the blazar astrophysics is to understand the physical origin of the blazar sequence. In this study, we focus on the GeV gamma-ray variability of blazars and evolution perspective we search the relation between the redshift and the variability amplitude of blazars for each blazar subclass. We analyzed the Fermi-LAT data of the TeV blazars and the bright AGNs (flux \( \geq 4 \times 10^{-9} \text{ cm}^{-2} \text{s}^{-1} \)) selected from the 2LAC (the 2nd LAT AGN catalog) data base. As a result, we found a hint of the correlation between the redshift and the variability amplitude in the FSRQs. Furthermore the BL Lacs which have relatively lower peak frequency of the synchrotron radiation and relatively lower redshift, have a tendency to have a smaller variability amplitude.

I. INTRODUCTION

The blazar is the class of the active galactic nuclei (AGN) which has the most number of extragalactic source in the very-high-energy gamma-ray regime \((E > 100 \text{ GeV})\)\(^{\text{12}}\). They are characterized by double-peaked nonthermal emission with spectral energy distribution (SED) in radio to gamma-ray regime. Blazars include BL Lacertae objects (BL Lac) and flat spectrum radio quasars (FSRQs). In addition BL Lacs include high-frequency peaked BL Lac objects (HBLs), intermediate-frequency peaked BL Lac objects (IBLs) and low-frequency peaked BL Lac objects (LBLs). In the leptonic model, the low and high bump of SED is explained by the synchrotron and the Synchrotron Self Compton (SSC) and/or External Compton (EC) radiations. The estimation of EC in the second hump is a matter of great importance in estimating external photons.

One of the characteristic of the blazar spectra is blazar sequence. In 1998, Fossati et al. combined three complete blazar samples\(^{\text{4}}\); The 2 Jy samples of FSRQs\(^{\text{8}}\), the radio selected 1 Jy samples of BL Lac\(^{\text{6}}\) and the X-ray selected sample(Einstein Slew Survey) of BL Lac\(^{\text{2}}\). The thirty-third sources of selected sample were detected in high-energy gamma-ray regime \((E > 100 \text{ MeV})\) by the EGRET instrument on-board the compton gamma ray observatory (CGRO). These sources were divided 5 bins based on the 5 GHz radio luminosity and averaged the SED of the each type of the blazars. The made SED suggested some relationship; first, the synchrotron peak frequency and the bolometric luminosity have the anti-correlation. second, the synchrotron peak frequency and the compton peak frequency have the positive-correlation. finally, the compton dominance (the ratio of the inverse Compton to synchrotron luminosity) and the bolometric luminosity have positive-correlation. These correlations are known as “the blazar sequence” in considering the blazar physics. We aim to reveal the relation between the evolution process of AGNs and the blazar sequence based on the systematical study for many blazars.

In this study, we calculated \( \sim 100 \) AGNs (blazars) to find the difference of the variability amplitude in blazar types and evolution of the variability amplitude (activity). We applied the fractional variability amplitude \( (F_{\text{var}}) \) to calculate the variability amplitude considering the error. The \( F_{\text{var}} \) is defined as Eq.\(^{\text{11}}\)

\[
F_{\text{var}} = \sqrt{\frac{S^2 - \sigma_{\text{err}}^2}{F^2}} \tag{1}
\]

Note that \( S^2 \) is the total variance of the light curve, \( \sigma_{\text{err}}^2 \) is the mean square of flux error and \( F \) is the square of mean flux. \( F_{\text{var}} \) (uncertainty) is defined as Eq.\(^{\text{3}}\) by Poutanen et al. (2008).

\[
\Delta F_{\text{var}} = \sqrt{F_{\text{var}}^2 + \text{err}(\sigma_{\text{NXS}}^2)} - F_{\text{var}} \tag{2}
\]

Where \( \text{err}(\sigma_{\text{NXS}}^2) \) is defined as Eq.\(^{\text{3}}\) by Vaughan et al. (2003)

\[
\text{err}(\sigma_{\text{NXS}}^2) = \sqrt{\left( \frac{\sigma_{\text{err}}^2}{N F^2} \right)^2 + \left( \frac{\sigma_{\text{err}}^2}{N F^2} \right)^2} \tag{3}
\]

\( F_{\text{var}} \) is often used in computation variability amplitude for each spectral band\(^{\text{3}}\).

In this study, we studied the flux variation of AGNs with the \( F_{\text{var}} \) on the high-energy gamma-ray regime to get the variation charactor of each class (type).

II. DATA SELECTION

We selected AGNs from the second LAT AGN catalog (2LAC)\(^{\text{3}}\) and TeVCat\(^{\text{12}}\). Selection criteria were as follows,

I : It was decided which subclass was belonged to (HBL or IBL or LBL or FSRQ).

II : It had known redshift.

III : \( \text{flux} \geq 4 \times 10^{-9} \text{ cm}^{-2} \text{s}^{-1} \) in 2LAC.
Table I shows the analyzed AGN list which 102 sources are included in. Source name, redshift, and class(type) are cited from 2LAC and TeVCat.

The redshift of PKS 1424+240 was referred to Furniss(2013)[2]. According to the TeVCat[12], the blazar class of S3 0218+357 (z=0.944) was not determined but we used it as high redshift VHE gamma-ray emitter.

### III. DATA ANALYSIS

We analysed the Fermi reprocessed pass 7 data between 2008 August 04 and 2014 June 09, using the unbinned likelihood analysis with the Fermi Science Tools package version v9r33p0 available from the Fermi Science Support Center (FSSC)[13]. The likelihood analysis was selected that the events with photon energies in the range of 0.1-300 GeV and a Region Of Interest (ROI) of 10 degrees cen-
FIG. 1: Examples of the gamma-ray light curve about 6 years in 0.1–300 GeV. Blue plots: data points with a bin size of 30 days (bin size of last it is only about 4.4 days). Red allows : 95% C.L. upper limits. Green dotted lines: average flux of whole period. Left panel: Mrk 421(HBL). Right panel: PKS 0454-234(FSRQ).

tered at the position of Table I sources. We used “SOURCE” class (“evclass = 2”) including both front and back events, because the “SOURCE” class is recommended for off-plane point source analysis by the likelihood analysis [15]. We excluded events with zenith angles larger than 100 degrees and time intervals when the rocking angle was larger than 52 degrees. The set of the instrument response functions of “P7REP

SOURCE

V15” was applied. Models which were used in this study include the isotropic diffuse background (iso

target blazars (Table I) were fitted with a Log-Parabola (LP):

because LP is typically used for modeling blazar spectra [10]. Where \( N_0 [\text{cm}^{-2} \text{s}^{-1} \text{MeV}^{-1}] \) is normalization parameter, \( E_0 [\text{MeV}] \) is scale parameter, \(- (\alpha + \beta \log(E/E_0)) \) is spectrum index. If the parameter \( \beta \) is zero, LP is equal to Power-Law spectrum. In this paper we fixed \( E_0 \) parameter of targets to \( E_0 = 100 \text{ MeV} \).

We judged the flux variation of target sources by some steps.

Step I: gamma-ray light curves, which width of the time bins was fixed on 30 days (shortest bin in this study), was made.

Step II: if calculated \( F_{\text{var}} \) was not required “Selection Criteria”, we adopted more large bin size (60 days, 90 days, 150 days, and 300 days).

“I Selection Criteria” were as follows, I. More than 40% of the calculated integral flux of each bin were detected. II. Significant (over 2σ) variation was detected by the \( \chi^2 \) test in the analyzed period. If the selection criteria I. and II. cleared, \( F_{\text{var}} \) of the target could be calculated.

IV. RESULTS AND DISCUSSION

Figure 1 shows the light curves of Mrk 421 and PKS 0454-234 as the light curve samples, which are the typical HBL and FSRQ sources, respectively. The green dashed lines represent the average flux of whole period. Each \( F_{\text{var}} \) and averaged flux were calculated as Mrk421: \( F_{\text{var}} = 39.3 \pm 1.3 \% \) averaged flux = \( (2.1 \pm 0.22) \times 10^{-7} \text{ cm}^{-2} \text{s}^{-1} \), PKS0454: \( F_{\text{var}} = 58.7 \pm 1.3 \% \) averaged flux = \( (3.07 \pm 0.32) \times 10^{-7} \text{ cm}^{-2} \text{s}^{-1} \). Note, the \( F_{\text{var}} \) calculation was performed only over the 9 TS bins.

Another \( F_{\text{var}} \)s were obtained in the same method and the \( F_{\text{var}} \) as a function of the redshift is shown in Fig.2. Square and circle marks indicate TeVCat and not TeVCat sources, respectively. Each subclass of blazars are plotted in different colors (Blue:FSRQ, Red: HBL, Magenta: IBL, Green: LBL, Yellow: FRI, Black: uncertain type.). In Figure 2 Fvar indicates the variability amplitude of the GeV gamma-ray light curve. GeV gamma ray from FSRQs could be detected at high redshift \( (z > 0.5) \) and have the large Fvar. In addition, HBL and IBL assemble in \( z < 0.5 \). From these features, blazar subclass seems to change along the increasing redshift.

Peculiar features were as follows; AO 0235+164 (z = 0.94, LBL) has particularly high
$F_{\text{var}}$ (117 $\pm$ 2.8) in LBLs. This source was discussed that it might be FSRQ type blazar [1, 10]; therefore, high $F_{\text{var}}$ value of this source might be caused by the FSRQ like characters. S3 0218+357 ($z = 0.944$, Uncertain type) which has the highest $F_{\text{var}}$ (190 $\pm$ 2.8) in this analyzed sources is a gravitationally lensed blazar [17], hence the very high $F_{\text{var}}$ value might be enhanced by the gravitationally lensed effect.

From Fig. 2, the $F_{\text{var}}$ as a function of the redshift seems connection with FSRQs $\rightarrow$ LBLs $\rightarrow$ HBLs (IBLs). This trend shows possibility of the activity evolution and blazar class evolution.

Figure 3 shows the $F_{\text{var}}$ histogram which is projected in the vertical axis of Fig. 2. The different colors show each subclass of blazars (Blue: FSRQ, Red: HBL, Magenta: IBL, Green: LBL, Yellow: FRI, Black: uncertain type).

However, there are some problems in this study. First, the middle-high redshift ($z > 0.2$) low $F_{\text{var}}$ sources were not sufficient for discussions without selection effects. Second, this study could not consider the short time scale variability ($< 30$ days). Thus, it is necessary to analyze the low $F_{\text{var}}$ sources and short time scale.

V. CONCLUSIONS

We selected 102 AGNs (blazars) to reveal the relation between the evolution process of AGNs and the blazar sequence. We applied the fractional variability amplitude ($F_{\text{var}}$) to calculate the variability amplitude considering the error.

The analyzed AGNs were selected from the second LAT AGN catalog (2LAC) [3] and TeVCat [12]. The analyzed data was Fermi reprocessed pass 7 data between 2008 August 04 and 2014 June 09, using the unbinned likelihood analysis with the Fermi Science Tools.

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