Awakening of Two Gamma-Ray High-redshift, Flat-spectrum Radio Quasars in the Southern Hemisphere

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Abstract

High-redshift blazars are valuable tools to study the early universe. So far, only a handful of $\gamma$-ray blazars have been found at redshifts above 3. Gamma-ray signals are detected in the direction of PMN J2219–2719 ($z = 3.63$) and PMN J2321–0827 ($z = 3.16$) by analyzing the 10 yr Fermi-LAT Pass 8 data. PMN J2219–2719 is not distinguished from the background in the global analysis. During the 5 month epoch, the TS value is 47.8 and the flux is more than 10 times that of the 10 yr averaged flux. In addition, the angular distance between the $\gamma$-ray position and the radio position of PMN J2219–2719 is only 0′04. Moreover, the long timescale $\gamma$-ray and infrared light curves are very similar, which supports the association between the $\gamma$-ray source and PMN J2219–2719. The global analysis of PMN J2321–0827 suggest a new $\gamma$-ray source; during the flare phase, the TS value is 61.4 and the $\gamma$-ray flux increased significantly. The association probability suggests that PMN J2321–0827 may be the counterpart of the new $\gamma$-ray source. In the future, the number of high-redshift $\gamma$-ray sources will increase by combining Fermi-LAT and the upcoming Large Synoptic Survey Telescope.

Unified Astronomy Thesaurus concepts: Galaxy jets (601); Quasars (1319); Gamma-ray sources (633); Non-thermal radiation sources (1119); High-redshift galaxies (734)

1. Introduction

Blazars, known as a peculiar subclass of active galactic nuclei (AGNs) that includes flat-spectrum radio quasars (FSRQs) and BL Lacertae objects (BL Lacs), are among the most energetic phenomena in the universe (e.g., Ghisellini et al. 2014). Their jets are well aligned with our line of sight and hence the jet emissions are strongly boosted due to the relativistic beaming effects (Blandford & Rees 1978). The nonthermal jet emission is characterized by violent variability with variation timescales spanning from minutes to years (e.g., Ulrich et al. 1997). Meanwhile, it shows a universal two-bump structure in log $\nu$Fi-log $\nu$ plot. The first bump is attributed to synchrotron emission while the other one extends to the $\gamma$-ray domain. Blazars are the dominant population in the extragalactic $\gamma$-ray sky. There are about three thousand sources in the 3FGL catalog (Acero et al. 2015) and nearly five thousand in 4FGL catalog (4FGL, Abbodlallah et al. 2020). Of the number of sources in 4FGL, nearly three thousand are AGNs or blazars (4FGL, Abbodlallah et al. 2020). In the leptonic scenario, the $\gamma$-ray emission of blazars is usually explained as inverse Compton (IC) scattering of soft photons from either inside (the synchrotron self-Compton, or SSC) and/or outside of the jet (external Compton, or EC) by the same population of relativistic electrons that gives rise to the synchrotron emission (e.g., Konigl 1981; Marscher & Gear 1985; Sikora et al. 1994; Błazejowski et al. 2000). Alternatively, the coincidence between the arrival of the PeV neutrino and the $\gamma$-ray flares in TXS 0506+056 indicates that at least in some cases hadronic processes could play an important role (IceCube Collaboration et al. 2018).

Within the entire blazar population, high-redshift blazars are of special interest (e.g., Romani et al. 2004; Romani 2006). On the one hand, they are valuable targets for understanding the formation and growth of the first generation of supermassive black holes (SMBHs) as well as the cosmic evolution of AGN jets (Ghisellini et al. 2010; Volonteri 2010). On the other hand, their emissions carry crucial information of the early universe. Particularly, the $\gamma$-ray emission of high-redshift blazars is a powerful tool for probing the extragalactic background light (EBL, e.g., Fermi-LAT Collaboration et al. 2018). Stacking analysis suggests that high-redshift blazars are faint $\gamma$-ray emitters (Paliya et al. 2020). Considering their large distances, it is not surprising that the number of detected high-redshift (i.e., $z > 3$) $\gamma$-ray blazars is rather limited. As all of the blazars so far detected by Fermi-LAT beyond redshift 3 are FSRQs (Abbodlallah et al. 2020) and the peak of the high energy bump in their spectral energy distributions (SED) is beneath the lower energy threshold of Fermi-LAT, the significant cosmic redshift makes detection of $\gamma$-ray emission of high-redshift blazars more challenging. Right now there are only a handful of $\gamma$-ray blazars with redshifts over 3. In addition to the two bright blazars ($z \approx 3$) included in 3FGL (Ackermann et al. 2015), detections of five new such sources have been reported by the Fermi-LAT Collaboration (Ackermann et al. 2017), with the most distant one (NVSS J151002+570243) at $z = 4.3$. The 4FGL (Abbodlallah et al. 2020) has included four additional sources\textsuperscript{4}. Interestingly, a spatially soft transient $\gamma$-ray source toward B3 1428+422 ($z = 4.7$), which is the farthest source in the 105 month Swift-BAT all-sky hard X-ray survey (Oh et al. 2018), has been identified (Liao et al. 2018). Currently, this source holds the redshift record for the GeV $\gamma$-ray emitter candidate.

\textsuperscript{4} However, two sources reported in Ackermann et al. (2017), NVSS J064632+445116 ($z = 3.4$) and NVSS J212912–153841 ($z = 3.3$), are absent in this latest catalog (Abbodlallah et al. 2020).
PMN J2219–2719 and PMN J2321–0827 (Griffith et al. 1994; Braude et al. 1981) have been known as flat-spectrum radio sources (Condon et al. 1978; Jackson et al. 2002; Healey et al. 2007). Based on the NRAO Very Large Array Sky Survey (NVSS, Condon et al. 1998) as well as the SuperCOSMOS data (Mahony et al. 2011), their radio-loudness (\(RL = f_{1.4\,GHz}/f_{\text{band}}\)) Kellermann et al. (1989) values are estimated to be as high as \(\sim 20,000\) and \(\sim 30,000\), respectively. X-ray observations by Chandra at different epochs reveal significant X-ray variability of PMN J2219–2719 (Lopez et al. 2006; Saez et al. 2011). In addition, a hard X-ray spectrum indicative of an overwhelming jet contribution has been also detected by Chandra (Saez et al. 2011). Meanwhile, a comparison between the SDSS \((r_{\text{mag}} = 20.96, \text{Adelman-McCarthy et al. 2008})\) and SuperCOSMOS \((r_{\text{mag}} = 20.08, \text{Mahony et al. 2011})\) data of PMN J2321–0827 suggests the existence of significant optical variability. Therefore, it is reasonable that they can be found in the Roma-BZCat (hereafter BZCAT, Massaro et al. 2009) and categorized as BZQ J2219–2719 and BZQ J2321–0827, respectively. The redshift estimations for PMN J2219–2719 \((z = 3.63, \text{Hook et al. 2002})\) and PMN J2321–0827 \((z = 3.169, \text{Titov et al. 2011})\) are given by spectroscopic observations, in which \(\text{L}_\alpha\) and \(C_\text{IV}\) emission lines are distinct. In this work, we report on analyses of Fermi-LAT \(\gamma\)-ray data of PMN J2219–2719 and PMN J2321–0827 that aim to increase the number of \(\gamma\)-ray blazars beyond redshift 3. In Section 2, details of our Fermi-LAT analysis are reported in Section 3; discussions are presented in Section 4; finally, we summarize our results. In the following, we adopt a \(\Lambda\)CDM cosmology with \(H_0 = 67 \text{ km s}^{-1} \text{Mpc}^{-1}\), \(\Omega_m = 0.32\), and \(\Omega_L = 0.68\) (Planck Collaboration et al. 2014).

2. Data Analysis

2.1. Fermi-LAT data analysis

Here, the \(\gamma\)-ray data (i.e., Fermi-LAT Pass 8 data, P8R3_SOURCE_V2, FRONT+BACK) analyses, using Fermi-tools software version 1.2.23, are based on the first ten-year (from 2008 August 4 to 2018 August 5) Fermi-LAT survey. The energy range of the data set is between 100 MeV and 500 GeV. In order to suppress the contamination from the Earth’s limb, the \(\gamma\)-ray events with zenith angle greater than 90° are eliminated. Meanwhile, the recommended quality-filter cuts (DATA_Q-\text{UAL}==1 && LAT_CONFIG==1) are also applied. We use the Unbinned likelihood analyses method in the gtlike task to derive the \(\gamma\)-ray flux and spectrum, in which photons within 10° regions of interest (ROIs) centered at locations of the targets are focused. The initial background models are generated by the script make4FGLxml.py\(^5\); including all 4FGL\(^6\) sources within 15° around the targets, as well as the diffuse \(\gamma\)-ray emission templates (i.e., gll_ism_v07.fits and iso_P8R3_SOURCE_V2_v1.txt). Since our targets have not been included in any current \(\gamma\)-ray catalogs, \(\gamma\)-ray sources located at the radio positions of the two high-redshift FSRQs are added into the analysis model file, assuming a single power-law spectrum model (i.e., \(dN/dE \propto E^{-\Gamma}\), where \(\Gamma\) is the spectral photon index). During the likelihood analysis, parameters of the targets and the 4FGL background sources lying within the ROIs, as well as the normalizations of the two diffuse emission backgrounds are set free. The test statistic (TS, Mattix et al. 1996) is used to quantify the significance of a \(\gamma\)-ray source, which is expressed as \(TS = -2\ln(L_0/L)\), where \(L\) and \(L_0\) are the best-fit likelihood values for the model with and without the putative target source, respectively. When the TS value is less than 10, we use the pyLikelihood UpperLimits tool to calculate the 95\% confidential level (CL) upper limit instead of estimating the flux. Furthermore, \(\gamma\)-ray light curves are also extracted, in which we fix the spectral parameters of background sources with the values from the global fit, unless they are brighter than or comparable to the target. Meanwhile, the weak (TS < 10) background sources are removed from the model during the temporal analysis.

2.2. WISE Data Analysis

The Wide field Infrared Survey Explorer\(^7\) (WISE, Wright et al. 2010) telescope has been conducting a repetitive all-sky survey since 2010, except for a gap between 2011 and 2013. For a typical sky location, the WISE telescope visits it every half a year and takes \(>10\) exposures during \(\sim 1\) days. Although initially four filters were used, most of the time only two filters, named W1 and W2, were used. The central wavelengths of the two filters are 3.4 \(\mu\)m and 4.6 \(\mu\)m, corresponding to rest-frame wavelengths of 0.7 \(\mu\)m and 1.0 \(\mu\)m, respectively. Some sources are relatively faint and only marginally detected in any single-exposure image. Therefore, we start from time-resolved coadds that were generated by Meisner et al. (2018) by stacking the single-exposure images taken during each WISE visit. We perform point spread function (PSF) fitting photometry on each coadd following Lang et al. (2014), and during the fitting the position is fixed to that from the infrared survey. In this way we obtain light curves sampled once every half a year from 2010 to 2019 at rest-frame 0.7 \(\mu\)m and 1.0 \(\mu\)m.

Of these two sources, only PMN J2219–2719 is included in the AllWISE Source Catalog. Therefore, we only explore whether there was a corresponding infrared variation in PMN J2219–2719 during the time when the \(\gamma\)-ray flare was detected, using the data from WISE. PMN J2219–2719 was detected during every WISE visit. Its infrared flux was steady for most of the time from 2010 to 2019 and showed a rise during the two WISE visits in 2015 November and 2016 May. We refer to the time period showing the flux rise as a high state and the rest of the time as a low state. In the low state, the flux of PMN J2219–2719 at 0.7 \(\mu\)m was around 65 \(\mu\)Jy with a standard deviation of 12 \(\mu\)Jy, and the flux at 1.0 \(\mu\)m was around 87 \(\mu\)Jy with a standard deviation of 24 \(\mu\)Jy. In the high state, the flux at 0.7 \(\mu\)m was 133 \(\pm 9\) \(\mu\)Jy and 112 \(\pm 8\) \(\mu\)Jy (at MJD 57575 and MJD 57698, respectively), which is 2.0 and 1.7 times the mean flux in the low state. The significance of the flux enhancements are at the level of 4.4\(\sigma\) and 3.1\(\sigma\), respectively, and when calculating the significance, both the measurement error in the high state and the internal dispersion in the low state are considered. The flux observed at 1.0 \(\mu\)m was 169 \(\pm 19\) and 147 \(\pm 18\) \(\mu\)Jy (at MJD 57575 and MJD 57698, respectively), which is 1.9 and 1.7 times the mean flux in the low state, and the significance of the flux increase is 2.7\(\sigma\) and 2.0\(\sigma\). These measures indicate that there was an infrared flare in the PMN

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5 https://fermi.gsfc.nasa.gov/ssc/data/analysis/user/make4FGLxml.py
6 https://fermi.gsfc.nasa.gov/ssc/data/access/lat/8yr_catalog/gll_psc_v21.fit
7 https://nasa.gov/mission_pages/WISE/main/index.html
J2219–2719 between 2015 and 2016, during which the infrared flux increased significantly (see the lower panel of Figure 1(a)).

3. Results
3.1. Gamma-Ray Properties

As we analyze the first 10 yr Fermi-LAT data and the 4FGL sources are based on the first 8 yr survey, we check whether there are new γ-ray sources (TS > 25) are present. The residual TS map of these two sources are generated from fits of the entire data set and there are indeed several new background sources. A majority of them are not close to the targets (>3°) and faint (TS < 100), except there is a bright γ-ray flare in 2016 July that is likely associated with a flat-spectrum radio source PKS 2247–131 (Healey et al. 2007; it is about 9° away from PMN J2321–0827) that has been reported in Buson (2016).

After updating the background model files, the likelihood analyses are carried out again. No significant γ-ray excess (TS ~ 5) has been found toward PMN J2219–2719 (see Figure 2(a)). However, there is a γ-ray source (TS ~ 27) in the direction of PMN J2321–0827\(^8\) (see Figure 3(a)). The optimized position are R.A. 350°.15 and decl. −8°.38, with a 95% CL radius of 0°.22. The radio position of PKS 2247–131 (Healey et al. 2007; it is about 9° away from PMN J2321–0827) that has been reported in Buson (2016).

8 When preparing for this manuscript, we noted that the Fermi-LAT collaboration presented a new version of the fourth Fermi-LAT catalog of gamma-ray sources (4FGL-DR2, Ballet et al. 2020), in which PMN J2321–0827 was included.

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**Figure 1.** Gamma-ray and infrared light curves of PMN J2219–2719 as well as the γ-ray light curve of a neighboring bright background source, (a) half-year bin and (b) 60 days bin. Horizontal solid lines along with two dashed lines in each panel represent the average flux and its 1σ error, within the whole time range.

**Figure 2.** TS maps for different epochs of PMN J2219–2719. The target source is not included in the model file. The three panels represent 5° × 5° TS maps with 0°.1 per pixel centered at PMN J2219–2719. (a) The 10 yr TS map between 0.1 and 500 GeV. (b) The 5 month flaring epoch TS map between 0.3 and 500 GeV. (c) TS map for the flaring epoch between 0.3 and 500 GeV. The radio position (J2000) is marked by the X-shaped symbol. The green circle in panel (b) is the 95% error circle of the γ-ray position. Locations of the nearby background sources considered in the analysis are marked.
J2321–0827 is offset by 0°.19 from the γ-ray location. Then, we derive a half-year bin γ-ray light curves for the two sources (see the middle panel of Figure 1(a) and the upper panel of Figure 4(a)). In the following, we present more details of the analysis.

3.1.1. PMN J2219–2719

The half-year bin light curve of PMN J2219–2719 displays only three consecutive bins (MJD 57422–57969, i.e., from 2016 February 4 to 2017 August 4) with relatively large TS values (TS > 4), including one bin with TS > 25 that suggests the existence of a γ-ray transient (see the middle panel of Figure 1(a)). In order to quantify the significance of the variability, we apply the method of Nolan et al. (2012) to calculate the variability index, and the corresponding variability significance level is 2.8σ. Due to the limited angular resolution of Fermi-LAT, such phenomena could come from a nearby flaring bright background source (e.g., Li et al. 2018). A very strong background source 4FGL J2158.8–3013 is 5°33 away from the target. Considering the limited angular resolution of Fermi-LAT at 100 MeV, we examine whether the new signal is contaminated by 4FGL J2158.8–3013. As shown in Figure 1(a), the appearance of the new source is not coincident with any brightening of 4FGL J2158.8–3013. Furthermore, we extract the two month bin γ-ray light curve of PMN J2219–2719 (see the middle panel of Figure 1(b)). In order to identify the exact flaring epoch, the monthly γ-ray light curve is also extracted. During a period between 2016 July 5 and 2016 December 4 (MJD 57574–57726), a significant γ-ray signal (TS ∼ 45) appeared in the direction of PMN J2219–2719 (see Figure 2(b)), confirming our finding based on the monthly γ-ray light curve.

We carry out a localization analysis to identify the position of the new γ-ray source in the flare phase. The best-fit coordinates are R.A. 33°45.85 and decl. −27°33 with a 2σ error radius of 0°.12. Besides, the angular distance between the new γ-ray position and the radio position of PMN J2219–2719 is only 0°.04 (see Figure 2(b)). The Bayesian association method (for details, see Abdo et al. 2010b) was used to calculate the association probability. Our result shows a 96.9% association probability, and that is larger than the threshold of 80%, which supports the association between the γ-ray source
and PMN J2219–2719. Adopting the new γ-ray position, a single power-law function can well describe the γ-ray spectrum of the target. In the flare phase, the average photon flux reaches \((2.89 \pm 0.61) \times 10^{-8} \text{ ph cm}^{-2} \text{s}^{-1}\), with a TS value of 47.8 \((\Gamma = 2.56 \pm 0.13)\). If the high-redshift FSRQ PMN J2219–2719 is the counterpart of the new γ-ray transient, the isotropic γ-ray luminosity is \((3.82 \pm 1.3) \times 10^{48} \text{ erg s}^{-1}\). As the nearest background source is 2°4 away from the target and the 68% CL contamination angles of LAT for 300 MeV photons is \(\sim 2\circ3\), we perform a further analysis of the data with an energy range from 300 MeV to 500 GeV: the TS value is then \(\sim 35.5\). It is confirmed by the residual TS map (see Figure 2(c)). A subsequent localization analysis suggests that PMN J2219–2719 still falls within the error radius of the γ-ray location.

### 3.1.2. PMN J2321–0827

For the half-year bin γ-ray light curve, the TS values of the radiation in most bins are \(<4\). However, in three consecutive bins (MJD 57604.7–58152.6, from 2016 August 4 to 2018 February 3), the situations are different and in two bins we have TS \(>20\) (see the upper panel of Figure 4(a)), which suggests the presence of a new transient source. The significance of γ-ray variability is 3.6σ. One known γ-ray source in 4FGL (4FGL J2322.6–0735) is 0°9 away from the target. We also examine its temporal behavior. As shown in Figure 4(a), the temporal behavior of the new γ-ray source is not coincident with its neighbor, which suggests that the flares detected in 4FGL are not contributed by J2322.6–0735. Then we perform the fit in two time periods (MJD 54682–57604 and MJD 57604–58152, i.e., from 2008 August 4 to 2016 August 4 and 2016 August 4 to 2018 February 3). No significant signal was found in the first period, which explains the absence of PMN J2321–0827 in 4FGL (as the chosen time period is consistent with that of the 4FGL catalog). However, a significant γ-ray signal (TS \(\sim 55\)) appears at the location of PMN J2321–0827 in the second period, and the result is consistent with the half-year bin γ-ray light curve. In addition, we extract the monthly light curve for the second period (see the upper panel of Figure 4(b)) to resolve the exact flare phase. A period of 14 months is marked by red dashed vertical lines in the upper panel of Figure 4(b), ranging from 2016 October 4 to 2017 December 4 (MJD 57665–58091). During this period, the TS value of the γ-ray source toward PMN J2321–0827 is about 60 (see Figure 3(b)). The optimized γ-ray position of the new γ-ray source during the flare phase is R.A. 350°29 and decl. –8°48, with a 2σ error radius of 0°14. The γ-ray position is only offset 0°05 from the radio position (see Figure 3(b)), with the association probability calculated as 94%. Our results suggest that PMN J2321–0827 is the counterpart of the new γ-ray source. Using the new γ-ray position, the average flux is estimated as \((1.69 \pm 0.39) \times 10^{-8} \text{ ph cm}^{-2} \text{s}^{-1}\), with a TS value of 61.4. The spectral index is \(\Gamma = 2.46 \pm 0.14\) and the isotropic γ-ray luminosity is \((1.49 \pm 0.38) \times 10^{48} \text{ erg s}^{-1}\).

Further endeavors to eliminate the influence from 4FGL J2322.6–0735 are made. In addition to analyses of the entire flaring epoch (marked as A in the upper panel of Figure 4(b)), we also analyze the data in two separated “periods” (marked as B and C in the lower panel of Figure 4(b)), when the TS values are 28.5 and 41.3, respectively. The radio position of PMN J2321–0827 is within the γ-ray error circles. We then merge the data in the two periods; the joint analysis gives a TS value of 67.4 and the corresponding γ-ray position is only offset by 0°03 from the radio position. Note that in this case 4FGL J2322.6–0735 is removed from the background model file due to its small TS value (<5), and the nearest background source is \(\sim 2\circ3\) away. Since the 68% CL contamination angles of LAT for 300 MeV and 1 GeV photons decrease to \(\sim 2\circ3\) and \(\sim 0°8\), individual analyses of Fermi-LAT data between 300 MeV and 500 GeV as well as between 1 GeV and 500 GeV are performed, and the TS values are 46.5 and 33, respectively. The results are confirmed by the corresponding residual TS Maps (see Figure 3(c)). In conclusion, the γ-ray source is robust and likely associated with PMN J2321–0827.

### 4. Discussion

So far, only five FSRQs with redshifts greater than 3.1 have been detected by Fermi-LAT in the latest catalog of AGN (4LAC; Ajello et al. 2020), three of them with redshifts larger than 3.5. Our results enrich the samples of γ-ray sources with redshift >3.1. Particularly, PMN J2219–2719 (\(z = 3.63\)) is the fourth farthest γ-ray FSRQ. The high-redshift γ-ray sources carry information about the extragalactic background light (EBL). However, the most energetic γ-ray photons from the transients of PMN J2219–2719 and PMN J2321–0827 are just 10.8 GeV and 5.1 GeV, respectively, which are insufficient to challenge the current EBL models \((E_{\text{horizon}} \sim 40 \text{ GeV for } z \sim 3\), Finke et al. 2010). Detections of high-redshift γ-ray FSRQs are helpful to reconstruct the evolution of the γ-ray luminosity function (GLF) of blazars at high redshift. So far, the most distant γ-ray sample used to calculate the blazar GLFs (e.g., Ajello et al. 2012; Zeng et al. 2013) has \(z = 3.1\). Therefore, the detection of new high-redshift γ-ray FSRQs, especially the new sources with redshift > 3.1 is very important to update the GLF of blazars.

In Figure 5, we compare the two newly detected distant objects with the high-redshift FSRQs \((z > 2)\) reported in the 4FGL catalog. The 10 yr averaged emission of these two sources locate them in the region of low γ-ray luminosities \((L_{\gamma} < 5 \times 10^{37} \text{ erg s}^{-1}\)). While in the flare phases, their γ-ray luminosities are similar to those of high-redshift FSRQs. This is not surprising, as we can only detect distant sources with high luminosities. It is likely that there are much more dim γ-ray FSRQs, which can only be detected when they are flaring, or alternatively by a future space GeV detector that is much more sensitive than Fermi-LAT.

Generally, simultaneous multiwavelength observations are crucial to pin down the counterpart. So far, simultaneous γ-ray and optical flares have been frequently detected for FSRQs (e.g., Abdo et al. 2010a). In addition, simultaneous γ-ray and infrared flares also have been detected for the high-redshift blazar CGRaBSJ0733+0456 (Liao et al. 2019). Recently, the simultaneous brightening of γ-ray and optical emissions of a high-redshift blazar GB 1508+5714 is reported in Liao et al. (2020). Therefore, the simultaneous multiwavelength observations for PMN J2219–2719 and PMN J2321–0827 are very important. Fortunately, for PMN J2219–2719, a sign of a WISE W1 and W2 flare appeared between 2015 and 2016, overlapping with the γ-ray flare (see Figure 1(a)), which suggests that PMN 2219–2719 is the low energy counterpart of the γ-ray source. However, due to the limited data, it is not possible to directly establish the association of the γ-ray and the infrared emission in the 60 days bin light curves (see Figure 1(b)). Meanwhile, we have tried to find other potential...
counterparts, especially blazars or blazar candidates included in the BZCAT list (Massaro et al. 2009) and other radio surveys (e.g., Condon et al. 1998; Myers et al. 2003; Healey et al. 2007, 2008). For PMN J2219–2719, we do not find other potential counterparts within the 2σ error radius. These facts support PMN J2219–2719 as the counterpart of the γ-ray source. A transient γ-ray source toward B3 1428+422 (z = 4.72) is detected by Fermi-LAT (Liao et al. 2018), but...
minimal and maximum energies of the electrons are set as 10 and 100 times of the particle number density; $\gamma$ is the break energy of the electron distribution; $K$ is the normalization of the particle number density. Meanwhile, the radius of the emission blob is often constrained by the normalization of the particle number density. The local temperature at a certain radius $R_d$ is,}
\begin{equation}
T^4 = \frac{3R_dL_d}{16\pi\rho_MBR^2}\left[1 - \left(\frac{3R_d}{R_d}\right)^{1/2}\right].
\end{equation}

The nonthermal jet emission is described by a simple homogeneous one-zone leptonic scenario, including synchrotron and IC (both SSC and EC) processes along with the synchrotron self-absorption process and the Klein–Nishina effect in the IC scattering. A relativistic compact blob with a radius of $R'$ embedded in the magnetic field is responsible for the jet emission, assuming that the emitting electrons follow a broken power-law distribution,
\begin{equation}
N(\gamma) = \begin{cases} K\gamma^{-p_1}, & \gamma_{\text{min}} \leq \gamma \leq \gamma_{\text{br}}, \\ K\gamma_{\text{br}}^{-p_1}\gamma^{-p_2}, & \gamma_{\text{br}} < \gamma \leq \gamma_{\text{max}}, \end{cases}
\end{equation}

where the $p_1,2$ are indices of the broken power-law radiative electron distribution; $\gamma_{\text{br}}$ is the break energy of the electron distribution; $K$ is the normalization of the particle number density; $B$ is the magnetic field strength; $\delta$ is the Doppler boosting factor; and $R_d$ is the radius of the emission blob in the jet comoving frame. The minimum and maximum energies of the electrons are set as 10 and 100 times of the $\gamma_{\text{br}}$, respectively. The energy density of the Ly$\alpha$ line emission is estimated to be $2 \times 10^{-2}$ erg cm$^{-3}$ in the rest frame.

### Table 1

| Model              | $p_1$ | $p_2$ | $\gamma_{\text{br}}$ | $K$(cm$^{-3}$) | $B$(Gauss) | $\delta$ | $R_d$(cm) |
|--------------------|-------|-------|-----------------------|----------------|------------|----------|-----------|
| Flaring state      | 2.0   | 6.0   | 496                   | $3.5 \times 10^4$ | 2.1        | 16.7     | $9.3 \times 10^{15}$ |
| Quiescent state    | 2.0   | 6.0   | 476                   | $1.2 \times 10^5$ | 4.1        | 7.2      | $2.0 \times 10^{16}$ |

Note. $p_1,2$ are the indexes of the broken power-law radiative electron distribution; $\gamma_{\text{br}}$ is the break energy of the electron distribution; $K$ is the normalization of the particle number density; $B$ is the magnetic field strength; $\delta$ is the Doppler boosting factor; and $R_d$ is the radius of the emission blob in the jet comoving frame. The nonthermal jet emission is described by a simple homogeneous one-zone leptonic scenario, including synchrotron and IC (both SSC and EC) processes along with the synchrotron self-absorption process and the Klein–Nishina effect in the IC scattering. A relativistic compact blob with a radius of $R'$ embedded in the magnetic field is responsible for the jet emission, assuming that the emitting electrons follow a broken power-law distribution.}

Due to limited statistics, such information is not available for PMN J2219–2719. Nevertheless, we set typical values for the variability timescale: $R' \lesssim c \tau_{\text{var}} \delta (1+z)^{-1}$, where $c$ is the speed of the light and $\delta$ is the Doppler factor of the jet blob. Due to limited statistics, such information is not available for PMN J2219–2719. Nevertheless, we set typical values for the variability timescale: $R' \lesssim c \tau_{\text{var}} \delta (1+z)^{-1}$, where $c$ is the speed of the light and $\delta$ is the Doppler factor of the jet blob. Due to limited statistics, such information is not available for PMN J2219–2719. Nevertheless, we set typical values for the variability timescale: $R' \lesssim c \tau_{\text{var}} \delta (1+z)^{-1}$, where $c$ is the speed of the light and $\delta$ is the Doppler factor of the jet blob.

Broadband SEDs of PMN J2219–2719 are shown in Figure 6. Multiwavelength data, including radio flux densities obtained from NED and median five-band optical fluxes from the second data release from the Panoramic Survey Telescope and Rapid Response System, are collected. The X-ray fluxes from a Chandra observation on 2009 September 12 (Saez et al. 2011), ALLWISE W1 and W2 fluxes, a Spitzer MIPS 24 $\mu$m flux observed on 2007 November 27, and the first 8 yr Fermi-LAT 95 CL upper limit represent the low flux state SED, while WISE W1 and W2 fluxes on 2016 November 5 and a 5 month averaged Fermi-LAT $\gamma$-ray spectrum centered on 2016 September 19 correspond to the high flux state SED. The Pan-STARRS and the ALLWISE data are obtained by the emission from a standard Shakura & Sunyaev (1973) disk, extending from 3 $R_s$ to 2000 $R_s$, where $R_s$ is the Schwarzschild radius. The accretion disk produces a total luminosity $L_d = \eta M c^2$ in which $M$ is the accretion rate and the accretion efficiency $\eta$ is set as a typical value, 0.1. The accretion disk emission follows a multitemperature radial profile, and the
6930 is the farthest known blazar and it has not been identified as a $\gamma$-ray source so far; its SED is revisited (An & Romani 2018). Moreover, the parameters of the radio jet of QSO J0906+6930 are determined based on very long baseline interferometry data: Doppler factor = 6.1 ± 0.8 and Lorentz factor = 3.6 ± 0.5 (An et al. 2020). In order to explain the $\gamma$-ray “off” SED, the bound is set as $6 < \delta < 11.5$. In short, the input parameters of the jet radiation models here are consistent with SED modeling studies for other high-redshift blazars.

5. Conclusion

In this work, we have systematically analyzed the Fermi-LAT Pass 8 data of two high-redshift FSRQs (PMN J2219–2719 and PMN J2321–0827). In the following, we give a brief summary.

1. We report the first detection of $\gamma$-ray signals in the direction of PMN J2219–2719 and PMN J2321–0827. Our findings increase the sample of $\gamma$-ray sources with redshift $>3$.

2. During the flare period of PMN J2219–2719, the flux is $2.89 \times 10^{-8}$ ph cm$^{-2}$ s$^{-1}$ ($\Gamma = 2.56 \pm 0.13$), and the corresponding TS value is 47.8. Comparing with the 95% CL upper limit of the 10 yr averaged flux ($2.58 \times 10^{-9}$ ph cm$^{-2}$ s$^{-1}$), the $\gamma$-ray flux enhancement is a factor of 10. In the flare phase of PMN J2321–0827, the TS value is 61.4 and the flux is $1.69 \times 10^{-8}$ ph cm$^{-2}$ s$^{-1}$, about 4 times that of the 10 yr averaged flux ($3.8 \times 10^{-9}$ ph cm$^{-2}$ s$^{-1}$). It is likely that there are several more dim high-redshift $\gamma$-ray FSRQs, which can only be detected when they are flaring.

3. Considering the similarity between the $\gamma$-ray and infrared light curves and the spatial association between the $\gamma$-ray source and PMN J2219–2719, we suggest that PMN J2219–2719 is the low energy counterpart of the new transient GeV source.

4. The broadband SED of PMN J2219–2719 during the high activity state is similar to that observed from other high-redshift blazars.

In the future, the number of high-redshift $\gamma$-ray sources will increase due to the continual successful operation of Fermi-LAT. Moreover, with upcoming wide-depth-fast sky survey facilities, such as the Large Synoptic Survey Telescope (Ivezic, 2019) and other future time-domain observational facilities (e.g., the Wide-Field InfraRed Survey Telescope, Green et al. 2012; the Einstein Probe, Yuan et al. 2015), a comprehensive broadband dynamic view of high-redshift $\gamma$-ray sources will be achieved.

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Facilities: Fermi-LAT, WISE.

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