DISCOVERY OF $\gamma$-RAY EMISSION FROM THE RADIO-INTERMEDIATE QUASAR III ZW 2: VIOLENT JET ACTIVITY WITH INTRADAY $\gamma$-RAY VARIABILITY

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ABSTRACT

III Zw 2 is the prototype of radio-intermediate quasars. Although there is the evidence of possessing strong jet, significant $\gamma$-ray emission has not been reported before. In this work, we carry out a detailed analysis of the latest Fermi-LAT Pass 8 data. No significant $\gamma$-ray signal has been detected in the time-averaged 7-year Fermi-LAT data of III Zw 2; however, we have identified two distinct $\gamma$-ray flares with isotropic luminosities of $\sim 10^{42}$ erg s$^{-1}$. Multiwavelength data analysis (also including the optical photometric observations from Yunnan Observatories) are presented and the main finding is simultaneous optical and $\gamma$-ray flares of III Zw 2 appearing in 2009 November. Violent $\gamma$-ray variability with a doubling timescale of 2.5 hr was detected in another $\gamma$-ray flare in May 2010, for which the 3-hr $\gamma$-ray peak flux is $\sim$250 times of the average flux in 7 years. Rather similar behaviors are observed in blazars and the blazar model can reasonably reproduce the spectral energy distribution of III Zw 2 in a wide energy range, strongly suggesting that its central engine resembles that of blazars. In view of its core, which shares radio similarities with young radio sources, together with weak extended radio lobe emission, we suggest that III Zw 2 harbors a recurrent activity core and thus serves as a valuable target for investigating the fueling and triggering of the activity in radio-loud active galactic nuclei.

Key words: galaxies: active ~ galaxies: jets ~ quasars: individual (III Zw 2)

Supporting material: machine-readable table

1. INTRODUCTION

Active galactic nuclei (AGNs), the most luminous and persistent sources of electromagnetic radiation in the universe, are powered by the accretion of material onto supermassive black holes (SMBHs; Antonucci 1993; Urry & Padovani 1995). In optically selected samples (e.g., the Palomar-Green (PG) Quasar sample; Schmidt & Green 1983), quasars with similar optical properties exhibit very different properties in radio bands (Kellermann et al. 1989). The ratio of the radio flux at 5 GHz to the optical flux at the B-band (i.e., the radio loudness parameter $R \equiv f_{5\text{GHz}}/f_B$) has been adopted as an indicator of the radio properties of quasars (Kellermann et al. 1989). However, recent studies based on deep radio surveys, e.g., the Faint Images of the Radio Sky at Twenty cm survey and the NRAO VLA Sky Survey (Becker et al. 1995; Condon et al. 1998), and optical massive surveys, e.g., the Sloan Digital Sky Survey (SDSS) and the Two Degree Field Survey (York et al. 2000; Croom et al. 2001), suggest that the distribution of radio loudness of AGNs is not bimodal but rather is continuous (e.g., Ivezić et al. 2002; Laor 2003). Understanding the distribution of radio loudness of AGNs is crucial for addressing basic questions such as how jets are formed, accelerated, and collimated, and why the efficiency of jet production can be so different among objects that are very similar in all other aspects, as well as questions concerning jets in black hole and neutron star X-ray binaries (see review by Fender 2006, p. 381).

Radio-quiet AGNs, such as, for example, the Seyferts, are usually hosted by late-type galaxies with “underluminous” or silent jets (e.g., Schawinski et al. 2011). On the other hand, it is known that radio-loud AGNs with strong radio jets almost never reside in the late-type, i.e., spiral galaxies (e.g., Best et al. 2005, but also see Morganti et al. 2011). Blazars, including flat-spectrum radio quasars (FSRQs) and BL Lacertae objects, are an extreme subclass of radio-loud AGNs. They are characterized by the luminous, rapidly variable, and polarized non-thermal continuum emissions, extending from radio to $\gamma$-ray (GeV and TeV) energies, which are widely accepted as being produced in the relativistic jets oriented close to the line of sight (Blandford & Rees 1978; Ulrich et al. 1997). Their spectral energy distributions (SEDs) have a universal two-bump structure in log$F_{\nu}$-log$\nu$ plot. The first bump is (likely) by synchrotron emission of relativistic electrons in magnetic fields, while the second bump, extending to $\gamma$-rays, is usually explained as inverse Compton (IC) scattering of soft photons from either inside and/or outside of the jet by the same population of relativistic electrons (Maraschi et al. 1992; Dermer & Schlickeiser 1993; Sikora et al. 1994; Blazekowski et al. 2000). Besides the typical radio-loud quasars and radio-quiet quasars, there are also the so-called “radio-intermediate quasars” (RIQs, Falcke et al. 1996a, 1996b; Wang et al. 2006). RIQs have compact radio cores at arcsecond scales, with relatively high brightness temperatures and flat and variable radio spectra in common, which are similar to radio-loud quasars. However, RIQs also possess low radio-to-optical ratios and weak extended steep-spectrum emission, which are atypical of radio-loud quasars. Therefore, RIQs bridge the classical radio-loud and radio-quiet AGNs and can be used to probe the connection between these two canonical groups.
Since the CGRO era, it has been recognized that blazars and radio galaxies are capable of generating strong γ-ray emissions (Hartman et al. 1999). In the current third Fermi Large Area Telescope (LAT, Atwood et al. 2009) source catalog (3FGL, Acero et al. 2015), the extragalactic γ-ray sky is dominated by radio-loud AGNs. The vast majority of these sources are blazars (Liao et al. 2014; Ackermann et al. 2015). And γ-ray emissions from a handful of radio-loud AGNs with misdirected jets (i.e., the so-called misaligned AGNs, including radio galaxies and steep-spectrum radio quasars) are also detected (Abdo et al. 2010a; Liao et al. 2015b). Except for several nearby galaxies whose γ-ray emissions are mainly from starburst activity (e.g., Abdo et al. 2010b; Hayashida et al. 2013), a new class of γ-ray AGNs, the radio-loud narrow-line Seyfert 1 galaxies, has been firmly established (Abdo et al. 2009a; Liao et al. 2015a). In this work we search for γ-ray emission from III Zw 2.

III Zw 2 is a triple galaxy group. The brightest source of the group, III Zw 2A (also named PG 0007+106 or Mrk 1501 at the redshift of z = 0.089; referred as III Zw 2 throughout this paper) is an AGN with a Seyfert I nuclei (Zwicky 1967; Arp 1968), and is also included in the PG quasar sample (Schmidt & Green 1983). Its host galaxy was identified as a spiral (e.g., Hutchings & Campbell 1983; Taylor et al. 1996). However, recent study of the bulge/disk decomposition on its Hubble Space Telescope H-band image indicates an elliptical morphology (Veilleux et al. 2009). An extended low surface brightness emission among the galaxy group and a tidal bridge from III Zw 2 with several knots of star-forming regions linking to a nearby companion III Zw 2B suggest an ongoing merging phase (Surace et al. 2001). Thus, considering the evidence of galaxy merging and following the morphological classification pattern of Schawinski et al. (2010), we refer to the host galaxy of III Zw 2 as an indeterminate-type class. III Zw 2 is famous for its large-amplitude radio variability, with over twentyfold increases on a timescale of years (e.g., Aller et al. 1985). Correlated flux variations from radio to X-rays have been observed (Salvi et al. 2002). It is also the first Seyfert with a detection of superluminal jet motion (the apparent jet speed lower limit is of 1.29 ± 0.05 c; Brunthaler et al. 2000). Other evidence of hosting a strong radio jet includes a core-dominated flat-spectrum radio morphology with a high brightness temperature core and a hard X-ray spectrum (Falcke et al. 1996a; Chen et al. 2012). However, the extended radio emission of III Zw 2 is rather weak compared with its core emission (Brunthaler et al. 2005; Cooper et al. 2007) and its radio-loudness is moderate (from several tens to ≲300, mainly due to the radio variability), which are typical behaviors for RIQs (Falcke et al. 1996a). Based on the violent radio variability and its multiwavelength SED, γ-ray emission for III Zw 2 is expected (Chen et al. 2010; Lister et al. 2015). Searching for the γ-ray emission of III Zw 2 both in GeV and TeV energies in the past, however, failed to yield significant detection (Aharonian et al. 2008; Abdo et al. 2009b; Teng et al. 2011; Ackermann et al. 2012).

In this paper, we carry out a detailed analysis of Fermi-LAT γ-ray data of III Zw 2, together with our optical multi-band photometric data from Yunnan Observatories and other multi-wavelength data from the public data archives and the literature. The paper is organized as follows. In Section 2 we describe the data analysis routines. The γ-ray emission characteristics of III Zw 2 are given in Section 3. Its multiwavelength variability properties are examined in Section 4. Finally, we present a discussion and summary of our study in the final section.

2. OBSERVATION AND DATA ANALYSIS

2.1. LAT Data Analysis

The Fermi-LAT (Atwood et al. 2009) is a pair-conversion γ-ray telescope that is sensitive to photon energies greater than 20 MeV. The LAT has a large peak effective area (∼8000 cm² for 1 GeV photons), viewing ∼2.4 sr of the full sky, with an angular resolution (68% containment radius) better than 1° at 1 GeV. In its routine survey mode, LAT performs a complete and uniform coverage of the sky every 3 hr. Note that the recently released Pass 8 data set has been significantly improved in comparison with the former ones, including a wide energy reach (changing from the range of 0.1–300 GeV to 60 MeV–500 GeV), an enhanced effective area, especially in the low energy range, and better localization. All these lead to an improvement of 30%–50% enhanced differential point-source sensitivity (Atwood et al. 2013).

The Pass 8 data used in this paper were collected during the first seven years operation of Fermi-LAT (i.e., from 2008 August 4th to 2015 August 4th). Photon events belonging to evclass 128 and evtype 3, with energy ranging from 100 MeV to 500 GeV, were taken into account. The updated standard ScienceTools software package version v10r0p5, with the instrument response functions of P8R2_SOURCE_V6, was adopted throughout the data analysis. For the LAT background files, we used gll_iem_v06.fit as the galactic diffuse model and iso_P8R2_SOURCE_V6_v06.txt for the isotropic diffuse emission template.6 The entire data set was filtered with gtselect and gtmktime tasks by following the standard analysis threads.7

The unbinned likelihood algorithm (Mattox et al. 1996) implemented in the gtlike task was used to extract the flux and spectrum. All 3FGL sources within 20° of the target were included. The flux and spectral parameters of sources within 10° region of interest (ROI), together with normalization factors of the two diffuse backgrounds were set to be free, while parameters of other sources were fixed at the 3FGL values. For the sub-day light curve analysis, following the method adopted in Liao & Bai (2015), we fixed the fluxes of the diffuse emission components at the values obtained by fitting the data collected over the flaring period. For the neighboring γ-ray emitters within the ROI at these special cases, their normalizations were still set free, while the spectral parameters were fixed as the 3FGL values. In the analysis we first added a presumed γ-ray source with power-law spectral template corresponding to III Zw 2 into the initial background model generated from make3FGLxml.py.8 Its γ-ray position was initially set as the same as its radio position. After the model fit we checked the test statistic (TS) value of the target and made a scale residual TS map. If any γ-ray excess with a TS value over 25 appeared in the TS map, we added a new source with a power-law spectrum into the background model to address it. The γ-ray locations of the target and the new background sources were obtained by the task gtfindsrc.

6 http://fermi.gsfc.nasa.gov/ssc/data/access/lat/BackgroundModels.html
7 http://fermi.gsfc.nasa.gov/ssc/data/analysis/scitools/
8 http://fermi.gsfc.nasa.gov/ssc/data/analysis/user
Then the updated background model was refitted to obtain the final result.

2.2. Swift Data Analysis

Since 2007, the space X-ray mission, Swift (Gehrels et al. 2004) has observed the source region nine times. We excluded the observation taken on 2010 February 2 (ObsID = 00036363004) because of short exposure (∼75 s). When available, we analyzed both XRT and UVOT data with the FTOOLS software version 6.17. For XRT data, we performed the initial event cleaning with the xrtpipeline using standard quality cuts, and then extracted the source spectra within circular regions with a radius of 20 pixels. The ancillary matrix files produced by the task xrtmkarf and the response matrix files (v012) were used for spectral analysis. We also grouped the spectra to have at least 20 counts per bin to ensure valid results using χ² statistical analysis. By linking the value of the hydrogen column density, we fitted the remaining eight observational data sets simultaneously with an absorbed power-law model; we summarize the results in Table 1. The parameter of absorption (NH = 3.96 × 10²² cm⁻²) is consistent with the values given by the data from other X-ray missions (e.g., Salvi et al. 2002). The UVOT has six filters: V, B, U, UVW1, UVM2, and UW2, with a coverage of 2.1–7.8 eV. We performed aperture photometry using uvotsource with a 5 arcsec circular aperture, and the background extraction was carried out in a larger source-free region.

2.3. Optical Observation and Data Analysis

The variability of III Zw 2 was photometrically monitored in optical bands at Yunnan Observatories, making use of the 2.4 m telescope⁹ and the 1.02 m telescope.¹⁰ Details regarding these telescopes were introduced in Liao et al. (2014). The standard differential photometric procedure was followed. The sky flat-field at dusk and dawn in good weather conditions and bias frames were taken on every observing night. Different exposure times were applied for various seeing and weather conditions. All frames were processed using bias and flat-field corrections from the task CCDRED package of the IRAF software, and the photometry was performed by the APHOT package. The magnitudes of the source were calculated with calibration stars in the image frame.¹¹

Note. The absorption column density for estimation of X-ray flux is constrained as 3.96 ± 0.22 × 10²² cm⁻², with χ²/dof of 211.0/216. Unabsorbed 0.5–10 keV X-ray fluxes are in units of 10⁻¹¹ erg cm⁻² s⁻¹. The extinction magnitudes in four UVOT bands are calculated as: AV = 0.275, A_UV1 = 0.582, A_UVM2 = 0.820, A_UW2 = 0.718. The absorption corrected optical/UV fluxes are in units of mJy.

| ObsID       | Date       | Γᵩ  | Fx     | V   | UW1 | UW2 | UW2 |
|-------------|------------|-----|--------|-----|-----|-----|-----|
| 00036363001 | 2007 Jun 21| 1.60±0.11 | 1.11±0.08 | …  | …  | …  | …  |
| 00036363002 | 2009 May 22| 1.66±0.10 | 1.11±0.08 | …  | …  | …  | …  |
| 00036363003 | 2009 Sep 03| 1.98±0.09 | 1.08±0.27 | …  | …  | …  | …  |
| 00036363005 | 2010 Feb 07| 1.69±0.10 | 1.08±0.07 | …  | …  | …  | …  |
| 00036363006 | 2010 Jul 08| 1.55±0.14 | 1.80±0.21 | 3.68±0.09 | 2.09±0.05 | 1.62±0.03 | 1.65±0.03 |
| 00036363007 | 2010 Jul 08| 1.64±0.12 | 1.77±0.14 | …  | …  | …  | …  |
| 00036363008 | 2012 Jan 03| 1.64±0.14 | 0.72±0.08 | 2.07±0.06 | 0.73±0.02 | 0.57±0.03 | 0.54±0.01 |
| 00049402001 | 2013 May 16| 1.43±0.31 | 1.42±0.34 | …  | 1.21±0.02 | 0.94±0.02 | 0.95±0.02 |

Table 1

| MJD⁹ | Mag⁹ | SigMag⁹ | Band¹¹ |
|------|------|---------|--------|
| 54373.71 | 14.58 | 0.09 | I |
| 54400.63 | 14.70 | 0.03 | I |

Table 2

Notes.

⁹ The observation date.

¹⁰ The nightly average magnitude. The correction for the interstellar extinction has been already completed.

¹¹ Uncertainty of magnitude.

¹² The photometric band.

(This table is available in its entirety in machine-readable form.)

Notes. The absorption column density for estimation of X-ray flux is constrained as 3.96 ± 0.22 × 10²² cm⁻², with χ²/dof of 211.0/216. Unabsorbed 0.5–10 keV X-ray fluxes are in units of 10⁻¹¹ erg cm⁻² s⁻¹. The extinction magnitudes in four UVOT bands are calculated as: AV = 0.275, A_UV1 = 0.582, A_UVM2 = 0.820, A_UW2 = 0.718. The absorption corrected optical/UV fluxes are in units of mJy.

Compensatory optical data were derived from the Catalina Real-time Transient Survey (CRTS; Drake et al. 2009; Djorgovski et al. 2011). The photometry was transformed from the unfiltered instrumental magnitude to Cousins V by V = V_CCS + 0.31(B − V)² + 0.04.¹² We averaged the values obtained during the same observing night. The CRTS daily light curve goes from MJD 53706 to MJD 56223, with 94 data points, nearly one observation per month, performing a good coverage on a timescale of years. The correction for the interstellar extinction and the color excess of the observed optical/UV magnitudes was adopted (Cardelli et al. 1989; Schlafly & Finkbeiner 2011). And optical photometric data were converted from a magnitude system to flux in Jansky (Bessell 2005). Consistency between different optical observation systems was checked. Note that the CRTS fluxes tend to be systematically higher than other fluxes. For example, a UVOT observation at MJD 55929.5 gave a V-band flux density of 2.1 mJy, while a CRTS observation at MJD 55930.1 provided a V-band flux density of 4.1 mJy. Since III Zw 2 was then at the optical low state, such a discrepancy could not be caused by intrinsic variability. Thus, the CRTS light curve was only used for the purpose of exhibiting a long timescale variability trend.

¹² http://nessi.cacr.caltech.edu/DataRelease/FAQ2.html#improve
2.4. Radio Data

III Zw 2 is included in the Owens Valley Radio Observatory (OVRO) 40 m telescope monitoring program.13 This program encompasses over 1500 objects above a declination of 20°, most of which are blazars, with observations for each source occurring twice per week, at a frequency of 15 GHz (Richards et al. 2011). III Zw 2 is also included in the Monitoring of Jets in AGNs With VLBA Experiments (MOJAVE14) program (Lister et al. 2009), from which multi-epoch VLBA observations at 15 GHz of several hundreds of the brightest, most compact radio sources in the northern sky have been carried out. Recently, radio data of III Zw 2 from the MOJAVE program have been published, including core and jet light curves, as well as jet motion features (Lister et al. 2016).

3. RESULTS

3.1. Detecting Significant γ-ray Emission from III Zw 2

We initially performed a fit to the entire 7-year Fermi-LAT data and did not find a significant γ-ray source in the direction of III Zw 2. For the unbinned likelihood analysis, the TS value of the presumed γ-ray source is only ≳15 (<4σ), as shown in Figure 1, consistent with its absence in any γ-ray source catalogs. For the tentative γ-ray emission, a photon flux of \((6.6 \pm 2.1) \times 10^{-9} \text{ ph cm}^{-2} \text{ s}^{-1}\) and a photon index of 3.0 ± 0.3 are obtained (we refer to a spectral index \(\alpha\) as the energy index such that \(F_{\gamma} \propto \nu^{-\alpha}\), corresponding to a photon index \(\Gamma_{\text{ph}} = \alpha + 1\)). And the corresponding isotropic γ-ray luminosity in the range from 100 MeV to 500 GeV is \((4.6 \pm 1.3) \times 10^{31} \text{ erg s}^{-1}\) (throughout this paper we adopt a ΛCDM cosmology model with \(H_0 = 67 \text{ km s}^{-1} \text{ Mpc}^{-1}\), \(\Omega_m = 0.32\), \(\Omega_{\Lambda} = 0.68\); Planck Collaboration et al. 2014).

We then search for possible short-term γ-ray outbursts. First, the year-bin γ-ray light curve was extracted (see Figure 2). Except for the second and sixth bins, the TS values of the emission in other time bins are below 1. The TS value of the emission in the sixth time bin is also relatively low, which is ≳6 (i.e., <5σ). However, the TS value of the γ-ray emission in the second time bin is as high as 38 (>5σ). We also extracted a monthly γ-ray light curve for all of the 7-year LAT data. Except for the second-year LAT data, the highest TS value of the monthly bin was about 5, so III Zw 2 was not detected during most of the LAT observational time. The rather weak signal that appears in the sixth-year LAT data is likely due to the background fluctuation. On the other hand, two γ-ray flares were identified in the monthly γ-ray light curve in the second-year Fermi-LAT data. Furthermore, the 2-day time bin γ-ray light curves were extracted during these two periods. The start and end of the two flaring epochs were selected from MJ 55120 to MJ 55190, and MJ 55322 to MJ 55368, respectively (see Figures 3 and 4). Individual gtlike analyses for these two epochs give TS values of 35.3 and 50.9, respectively. Such significant signals are confirmed by the TS maps; see Figure 1. Since III Zw 2 is a high Galactic latitude source \((|l| > 50°)\), contamination from the uncertainty of Galactic diffuse emission is negligible. And during such short time periods, the newly emerging γ-ray source is one of the most dominant sources within the ROI. The only source with comparable γ-ray photon flux is >7° away. We thus conclude that the detection of γ-ray emission is robust. Furthermore, localization of the central excess is performed. The γ-ray positions of R.A. 2°621 and decl. 11°1232 are obtained for the flare in 2009, and R.A. 2°440 and decl. 10°9349 are for the other flare in 2010, with corresponding 95% confidential level (C.L.) error radii of 810° and 781°, respectively. Considering that the angular separations between the radio position and γ-ray locations are 535° and 683°, respectively, in both cases III Zw 2 falls into the 95% C.L. γ-ray location error radius, as shown in Figure 5. We also seek other potential counterparts through the SIMBAD database,15 especially for radio-loud AGNs. III Zw 2 is found to be the only radio-loud AGN within the 95% C.L. γ-ray location error radius. With these well-established facts we conclude that these significant γ-ray signals are from III Zw 2.

Besides the detailed individual γ-ray analyses for the two flaring epochs, we also perform a joint analysis to increase the significance of the γ-ray detection, and the TS value increase, to 83. The γ-ray localization has been improved (the location error is 658°), which is still larger than the source separation of 470°, rendering III Zw 2 as the only radio-loud AGN candidate within the 95% C.L. γ-ray location error radius (see Figure 5). The updated γ-ray location is R.A. 2°523 and decl. 11°0536, and all γ-ray results throughout this paper are based on this position. A joint analysis is also performed by adopting the Pass 7 REP data; similar results are obtained but with a much lower TS value ≳38.

A single power-law function provides an acceptable description of the γ-ray spectrum of III Zw 2 during the flaring state, i.e.,

\[
\frac{dN}{dE} = (5.25 \pm 0.78) \times 10^{-12} \left(\frac{E}{374.1 \text{ MeV}}\right)^{-(2.53 \pm 0.14)} \tag{1}
\]

and the photon flux is \((9.7 \pm 1.7) \times 10^{-8} \text{ ph cm}^{-2} \text{ s}^{-1}\). Note that it is one order of magnitude higher than the 7-year averaged flux. The isotropic γ-ray luminosity is \((9.6 \pm 1.6) \times 10^{44} \text{ erg s}^{-1}\). No significant improvement of the fit is found when more sophisticated spectral models are used. We also perform an individual spectral analysis for each flare and the spectral indexes do not change significantly.

It is worth noting that signs of intraday γ-ray variability are shown in the 2-day light curves. For the flare in 2009, a fast flux decline is detected, from \((3.6 \pm 1.3) \times 10^{-7} \text{ ph cm}^{-2} \text{ s}^{-1}\) at MJ 55140.1 to \((0.8 \pm 0.7) \times 10^{-7} \text{ ph cm}^{-2} \text{ s}^{-1}\) at MJ 55142.1. Adopting the classical method, \(\tau_d = \Delta t \times \ln 2 / \ln(F_1/F_2)\), the flux-doubling timescale is estimated as ≳0.9 day. However, the relatively low TS values prevent further investigation. On the other hand, intraday γ-ray light curves are extracted for the flare in 2010. From the 12 hr light curve, it is remarkable to see that III Zw 2 is undergoing a giant flare for 12 hr; see Figure 3. This flare suddenly appeared with a peak flux of \((1.2 \pm 0.3) \times 10^{-6} \text{ ph cm}^{-2} \text{ s}^{-1}\) and the TS value is high up to ~73. Since a 3 hr bin is the smallest bin allowed by the standard Fermi-LAT data analysis procedure with the standard software, the γ-ray light curve in such a short time bin is extracted to derive the minimum γ-ray variability timescale of III Zw 2; also see Figure 3. The γ-ray flux maintains a high value, \(\geq 10^{-6} \text{ ph cm}^{-2} \text{ s}^{-1}\) within 12 hr, and the 3-hr peak flux is \((1.7 \pm 0.6) \times 10^{-6} \text{ ph cm}^{-2} \text{ s}^{-1}\). It is roughly 250 times the 7-year average γ-ray flux. Such a large-amplitude variability is

13 http://www.astro.caltech.edu/ovroblazars/
14 http://www.physics.purdue.edu/astro/MOJAVE/index.html
15 http://simbad.u-strasbg.fr/simbad/
extreme even for blazars. In the ascent phase, $\gamma$-ray flux raises from $(0.3 \pm 0.2) \times 10^{-6}$ to $(1.5 \pm 0.6) \times 10^{-6}$ ph cm$^{-2}$ s$^{-1}$ within 6 hr. A corresponding flux-doubling timescale is estimated as $\approx 2.6$ hr. A simple exponential function can describe the 3-hr light curve,

$$F(t) = 2F_0 [e^{(t-t_0)/\tau} + e^{(t-t_0)/\tau}]^{-1},$$

(2)

where $F_0$ and $t_0$ are set as the flux and time of the peak, respectively. The variability timescale is estimated as about 3.4 hr and the corresponding doubling timescale is about 2.4 hr. Since the light curve is extracted during the survey mode operation of LAT, due to the limited exposure time, doubling timescales of III Zw 2 should be treated as upper limits only. Despite the extremely large variability amplitude, such a short doubling timescale ($\approx 2$–3 hr) is detected at only a handful blazars (e.g., Foschini et al. 2011; Liao & Bai 2015).

The rapid $\gamma$-ray variation allows us to make a constraint on the Doppler factor, avoiding heavy absorption from the soft photons within the radiation radius through the $\gamma\gamma$ process (e.g., Begelman et al. 2008). The synchrotron emission is considered as the target photons. The optical depth of $\gamma\gamma$ absorption between the $\gamma$ rays and the soft photons can simply be calculated as (Dondi & Ghisellini 1995)

$$\tau_{\gamma\gamma}(x') = \frac{\sigma_T n'(x') x'R'}{S},$$

(3)

where $\sigma_T$ is the scattering Thomson cross-section, $n'(x')$ is the number density of the target photon, $x'_t$ is the energy of the target photon in dimensionless units, and $R'$ is the absorption length. A doubling time of 2.5 hr is used to constrain the emission region. The absorption length is the radius of the emission blob, $R' = c \tau_{\text{obs}} \delta (1 + z)^{-1}$. And the luminosity of the absorbing X-ray synchrotron emission at several keVs is set as a relatively low value, $10^{33}$ erg s$^{-1}$ (Salvi et al. 2002). A lower-limit Doppler factor is then constrained as $\delta \gtrsim 9$. For the $\gamma$-ray flare in 2009, a similar constraint can also be estimated, i.e., $\delta \gtrsim 6$.

3.2. Multiwavelength Variability of III Zw 2

3.2.1. Simultaneous Optical and $\gamma$-ray Variability in 2009 November

In the classic leptonic radiation model of FSRQs, both the non-thermal optical and $\gamma$-ray emissions are generated from the same population of high energy electrons and hence simultaneous variability of these emissions is expected. Actually, for $\gamma$-ray
FSRQs, such predictions have been observed \(\text{e.g.},\) Bonning et al. 2012. And the simultaneous optical and \(\gamma\)-ray variation is a powerful tool to identify the association between the \(\gamma\)-ray source and the counterpart. We have monitored III Zw 2 in 2009 October and November at Yunnan Observatories. Fluxes in three bands (\text{i.e.}, Johnson \(R\), \(B\) and Cousins \(I\)) all exhibit brightening around 2009 November \(\text{see Figure 2}\). A zoomed-in of the flaring epoch is shown in Figure 4. The \(R\)-band light curve is adopted to study optical variability during this epoch. When \(R\)-band magnitudes are unavailable, simultaneous \(I\)-band magnitudes are extrapolated into \(R\)-band based on the observed \(R - I\) color. Within 15 days, the optical flux of III Zw 2 exhibited an increase of about 40\%. The peak time of the optical flare was at MJD 55145.6. If the optical monitoring time was over one hour, we also searched for optical intraday variability. However, no significant intraday variability is found. The peak flux is about 3 times as the flux at the optical low status, \text{e.g.}, MJD 55832.8. Such a large optical variability amplitude is likely from the jet of III Zw 2. The 2009 \(\gamma\)-ray flare peaked on MJD 55140, suggesting that the optical and \(\gamma\)-ray flares were simultaneous \(\text{i.e.},\) the optical flare lagged behind the \(\gamma\)-ray flare less than one week, consistent with studies of other FSRQs; Bonning et al. 2012. Because the detection of the 2009 \(\gamma\)-ray flare alone is significant \((>5\sigma)\), together with the simultaneous optical and \(\gamma\)-ray flares, we claim the discovery of \(\gamma\)-ray emission for III Zw 2. Furthermore, the optical spectral variability is studied by the simultaneous \(R\) and \(B\) photometric observations. No significant spectral variability is found during the flaring epoch. Also, no significant spectral difference is detected when comparing to the SDSS observation at an optical low state \(\text{see Figure 6}\), indicating that the accretion disk emission significantly contributes to the optical/UV domain even for the case of the 2009 \(\gamma\)-ray flare.

3.2.2. X-ray and Radio Variability

Because the \textit{Swift} observations were sparse and there were no X-ray observations during two \(\gamma\)-ray flares, it is impossible to directly study the connection between \(\gamma\)-ray and X-ray emissions. However, we note that X-ray flux at MJD 55385, just 45 days after the \(\gamma\)-ray flare at MJD 55340, is roughly two times that of other flares; \text{see Table 1}. Nevertheless, comparing to the historical X-ray data with tenfold X-ray variability and 1–2 keV X-ray flux as high as \(\approx 10^{−11}\text{ erg cm}^{−2}\text{ s}^{−1}\) \(\text{Salvi et al. 2002}\), the X-ray variability observed by \textit{Swift} is not

![Figure 2. The multiwavelength light curves of III Zw 2. In the \(\gamma\)-ray panel, the \(\gamma\)-ray fluxes are in units of \(10^{−8}\text{ ph cm}^{−2}\text{ s}^{−1}\), the black circles correspond to the fluxes, and the red triangles are the 2\(\sigma\) upper limits. The red bars are the TS values in each data bin. In the X-ray panel, unabsorbed 0.5–10 keV X-ray fluxes are in units of \(10^{−11}\text{ erg cm}^{−2}\text{ s}^{−1}\). In the optical panel, green, blue, and yellow circles are the magnitudes of the \(I\)-, \(R\)-, and \(B\)-bands observed at Yunnan Observatories (YO), respectively. The red circles are CRTS \(V\)-band magnitudes plus 0.8 mag. In the radio panel, the green circles are OVRO single-dish fluxes, and the blue and red squares are the MOJAVE core and parsec jet VLBA fluxes. The purple stars and diamonds correspond to offsets between core and parsec jets for two different jets. The two solid red vertical lines mark the peaking times of the two \(\gamma\)-ray flares and the dashed red vertical line correspond to the time of the simultaneous \textit{Planck}, \textit{Swift}, and \textit{Fermi} campaigns.

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extreme. Because of the low signal-to-noise ratio of the Swift data, a single power-law function is adopted to describe the X-ray spectra and more complicated features reported in the literature cannot be checked (e.g., Piconcelli et al. 2005). The X-ray photon indices remain ~1.7, consistent with other studies (e.g., Salvi et al. 2002).

Strong radio variability is observed by OVRO, as shown in Figure 2. The maximum and minimum fluxes of the 15 GHz OVRO light curve are about 1.82 and 0.08 Jy, respectively, indicating an over twentyfold variability, consistent with other studies (e.g., Aller et al. 1985). Differing from rapid optical and γ-ray variability that usually lasts only several days, the typical timescale of a radio flare is as long as several hundred days. There are four main flares in the OVRO light curve and none of these radio flares simultaneously coincided with γ-ray flares. Cross-correlation analyses between γ-ray and radio light curves for Fermi bright blazars suggest that the radio emission typically lags behind the γ-ray emission for a few months (e.g., Fuhrmann et al. 2014; Max-Moerbeck et al. 2014). Interestingly, the peaking time of the strongest radio flare in the OVRO light curve is at MJD 55223, about 80 days behind the first γ-ray flare at MJD 55140. Moreover, in the descent phase of this radio flare, there is a plateau indicative a radio sub-flare at MJD 55432, which is also about 80 days behind the second γ-ray flare at MJD 55340. However, there are no γ-ray flares corresponding to other radio flares. Since the radio core and the parsec jet are resolved by the MOJAVE VLBA observations, radio light curves and angular offsets for these two components are provided (Lister et al. 2016); see Figure 2. The core light curve is consistent with the OVRO light curve because III Zw 2 exhibits a core-dominated radio morphology. It is interesting that the parsec jet flux at MJD 55389 (0.13 Jy) is significantly higher than that at MJD 54985 (0.007 Jy), together with a shorter offset from the core; see Figure 2. This evidence suggests that there are new ejecta coming out since MJD 55389. And parsec jets from MJD 53046 to MJD 54985 and from MJD 55389 to 56445 are marked as different jet components, with apparent speeds of \( \beta_{\text{app}} = 1.2 \pm 0.07 \) and \( \beta_{\text{app}} = 1.58 \pm 0.29 \), respectively (Lister et al. 2016). Note that the observation of the newly emerging ejecta is just about 50 days after the γ-ray flare at MJD 55340 when the violent intraday γ-ray variability was detected, indicating that the γ-ray flare may link to the ejection of the new jet knot; see the MOJAVE radio image\(^{16} \) (Figure 7). Such ejection speeds are

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\(^{16}\) http://www.physics.purdue.edu/astro/MOJAVE/sourcepages/0007+106.shtml
significantly lower than those of other γ-ray FSRQs (β_app > 10) with detections of γ-ray variability on a timescale of hours (e.g., Jorstad et al. 2005). Dense VLBA observations coincident with future γ-ray flaring epochs might yield a β_app that is much higher than that inferred from the long-term observational data.

4. DISCUSSIONS

Since the last piece of information on the electromagnetic emission (i.e., the γ rays) of III Zw 2 has been collected, its radio to γ-ray SED has been investigated for the first time. A homogeneous one-zone synchrotron plus IC model is used to calculate the jet emission. The broadband electromagnetic emission comes from a compact homogeneous blob with a relativistic speed, with a radius of R embedded in the magnetic field. A broken power-law spectrum for particle distribution has been assumed, i.e.,

\[
N(\gamma) = \begin{cases} 
K\gamma^{-p_1} & \gamma_{\text{min}} \leq \gamma \leq \gamma_{\text{br}} \\
K\gamma_{\text{br}}^{-p_1 - p_2 \gamma^{-p_2}} & \gamma_{\text{br}} < \gamma \leq \gamma_{\text{max}}.
\end{cases}
\]

The model parameters include R, the magnetic field strength B, electron break energy γ_br, the minimum and maximum energies, γ_min and γ_max, of the radiating electrons, the normalization of the particle number density K, and the indices p_1,2 of the broken power-law particle distribution. The synchrotron self-absorption and the Klein–Nishina effect in the IC scattering are properly addressed in our calculations. The χ^2-minimization method is used to obtain the best-fitting input parameters. Specially, the B and δ are constrained at the 1σ confidence level, based on the fit probability \( p \propto e^{-\chi^2/2} \) where χ^2 values are calculated for wide ranges of B and δ. A similar SED modeling strategy has been adopted in previous studies (e.g., Zhang et al. 2012; Liao et al. 2014).

Simultaneous Planck, Swift, and Fermi observations for III Zw 2 at the beginning of July in 2010 provide the best coverage of its electromagnetic emission (Giommi et al. 2012). In addition, WISE performed a simultaneous complementary infrared observation at MJD 55381.6 (Wright et al. 2010). Moreover, infrared colors are given as \( w_1 - w_2 = 0.93 \) and \( w_2 - w_3 = 2.53 \), suggesting that III Zw 2 falls into the WISE
blazar stripe and the jet emission is significant in the infrared bands (Massaro et al. 2012). Together with the co-instantaneous V-band UVOT observation, the peak frequency of the synchrotron bump can be constrained in the optical/near-infrared range (see Figure 8). However, despite the well-sampled data from radio to X-rays, there is no significant simultaneous γ-ray detection. Based on our γ-ray temporal analysis, this multiwavelength campaign is performed several tens of days after the violent variability in MJD 55340. Due to its rapid variability, it is reasonable to assume that III Zw 2 was then under the detection threshold of Fermi-LAT. Nevertheless, the 7-year average γ-ray spectrum is believed to be a good approximation and is used instead of the simultaneous γ-ray upper limit. Note that in our modeling, several data points have been excluded. The UV emission is likely dominated by the accretion disk emission. The W4 band WISE infrared flux clearly deviates from the smooth non-thermal emission. For the Planck radio data, due to the significant spectral break around 200 GHz, only two data at 353 and 545 GHz are included. On the other hand, thanks goes to the optical observations by Yunnan Observatories, which allowed the SED of III Zw 2,
including simultaneous optical and γ-ray detections, to be obtained for the first time. However, coverage of the jet emission is rather limited. The OVRO 15 GHz and Yunnan Observatories B-band data are not considered in the SED modeling. Due to the lack of simultaneous submillimeter/ infrared and X-ray data, the locations of the synchrotron and IC peaks are unknown, which makes the SED input parameters highly unconstrained in this case. Nevertheless, because the γ-ray doubling time of 0.9 day is then detected, the Doppler factor is set as 6, and the radius of the emission blob can be highly unconstrained in this case. Nevertheless, because the peaks are unknown, which makes the SED input parameters obtained for the extended radio luminosities and intrinsic bolometric luminosities thus adopted since it is not significant and does not suffer from the Doppler beaming effect. Recently, 1.4 GHz VLA extended radio luminosities and intrinsic bolometric luminosities of 128 2FGL FSRQs (Nolan et al. 2012) were provided in Nemmen et al. (2012). For III Zw 2, its 1.4 GHz VLA observation gives an extended radio flux density of 17 mJy (Cooper et al. 2007), with a corresponding luminosity of 5.3 × 10^{39} erg s^{-1}. The intrinsic bolometric luminosity of III Zw 2, derived from the isotropic bolometric luminosity by the modeling of the SED in 2010, is \( L_{\text{bol}} = (1 - \cos(1/\Gamma))L_{\text{iso}} \simeq 3 \times 10^{44} \text{ erg s}^{-1} \), where \( \Gamma = 3 \) is the Lorentz factor based on our SED modeling study. Then III Zw 2 is plotted into the \( L_{\text{bol}} - L_{\text{radio}}^\text{ext} \) diagram; see Figure 9. Interestingly, although III Zw 2 shares a similar \( L_{\text{bol}} \) to those FSRQs, the \( L_{\text{radio}}^\text{ext} \) of III Zw 2 is generally lower than that of the FSRQs. A radio spectral and spatial evolution study of III Zw 2 indicates that it shares the same physical processes with young radio sources (Brunthaler et al. 2005). And in addition to its weak radio lobe emission reaching up to 20–30 kpc (e.g., Falcke et al. 1999; Brunthaler et al. 2005), III Zw 2 could be a case of recurrent core jet activity in conjunction (e.g., Yuan & Wang 2012) with a relic radio lobe. Since extended radio emission is widely accepted as originating from accumulated old-age low-energy electrons, it is reasonable that the \( L_{\text{radio}}^\text{ext} \) of III Zw 2 is generally lower in comparison with that of the FSRQs, due to its recently active core.

Finally, let us jump out from the frame of the radio-loud AGN alone. Recently, accumulated evidence has suggested that galaxies convolved with their central SMBHs (e.g., Kormendy & Ho 2013; Heckman & Best 2014). Radio jets likely play a unique role in AGN feedback (e.g., Fabian 2012). The galaxy merger phenomenon is believed to be a possible path for generating the radio-loud AGNs (e.g., Hopkins et al. 2008; Lagos et al. 2009). Galaxy mergers may lower the specific angular momentum of gas in the galaxy and thus drive the gas toward the center, and another effect of mergers is spin-up and an increase to the mass of the SMBH (Chiaberge et al. 2015). The spin of a BH is believed to be a crucial factor for generating a strong radio jet; this is the so-called spin paradigm (Blandford et al. 1990). For III Zw 2, tentative evidence of a broad Fe Kα emission line may be indicative of the fast spin of its central BH (Jiménez-Bailón et al. 2005), confirming the existence of a strong jet based on strong γ-ray emission and rapid and large-amplitude γ-ray variability. Besides these parameters, the magnetic flux threading the SMBH is also proposed as a dominant factor for launching powerful jets (Sikora & Begelman 2013). And the radio activity of RIQs is associated with the fluctuating magnetic field of jets, such as the magnetic reconnection. Interestingly, rapid γ-ray variability, with a doubling time of nearly 2 hr that was detected for III Zw 2, could correspond to such a physical process. Moreover, III Zw 2 is hosted by a merging galaxy and considering the evidence of a rejuvenation radio core, it is likely to be an ideal target to provide insights into the fueling and triggering of the activity in radio-loud AGNs. Further simultaneous multiwavelength observations are urgently needed to study III Zw 2.

### Table 3

| Epoch     | \( p_1 \) | \( p_2 \) | \( \gamma_{\text{ew}} \) | \( \gamma_{\text{min}} \) | \( K (\text{cm}^{-3}) \) | \( B (\text{Gauss}) \) | \( \delta \) | \( R (\text{cm}) \) |
|-----------|--------|--------|--------------------|--------------------|-----------------|-----------------|--------|--------|
| 2009 Nov  | 2.5    | 4.5    | \( 3.6 \times 10^3 \) | 40                | \( 1.6 \times 10^4 \) | 10^3            | 6      | \( 1.3 \times 10^{16} \) |
| 2010 Jul  | 2.5    | 6.4    | \( 3.2 \times 10^3 \) | 40                | \( 4.9 \times 10^3 \) | 5.6 ± 0.6       | 3.0 ± 0.1 | \( 1.7 \times 10^{16} \) |

**Notes.**

- A detailed description of the parameters is provided in Section 4.
- \( \gamma_{\text{max}} \) is set as a hundred times \( \gamma_{\text{ew}} \).
- In this case, the SED data is so limited that further constraints on the uncertainties of \( B \) and \( \delta \) cannot be given.
Ray Zw 2 and the 2009 November strongly support an association between III Kunming 1 m telescopes. Funding for these telescopes has been referee, which led to substantial improvement of this work. We triggering of activity in radio-loud AGNs. this making it a valuable target for investigating the fueling and (High Energy Astrophysics Science Archive Research Center Province. This research has made use of data obtained from the ray localization and coincident signals in 2009 November and 2010 May are all above 25 and of III Zw 2. On the other hand, considering its radio core that is relativistic powerful jet is likely similar to those of blazars. This indicates that the central engine that generates the moderate-7-year average of III Zw 2 are adopted as 0.25 and 0.7 dex, i.e., the sample average values found in Nemmen et al. (2012).

In summary, we present the results of radio to γ-ray observations of III Zw 2 and report the discovery of its γ-ray emission. Although significant γ-ray emission is not detected from the 7-year averaged Fermi-LAT data, III Zw 2 exhibits strong γ-ray emission in the short term. The TS values of γ-ray signals in 2009 November and 2010 May are all above 25 and the joint analysis gives a TS value as high as 83. Results of γ-ray localization and coincident γ-ray and optical variations in 2009 November strongly support an association between III Zw 2 and the γ-ray source. Moreover, violent γ-ray variability with a doubling timescale of 2.5 hr was detected in another γ-ray flare in 2010 when the 3-hr γ-ray flux was 250 times the 7-year average flux. Such an extreme variability behavior indicates that the central engine that generates the moderate-relativistic powerful jet is likely similar to those of blazars. This scenario is also supported by modeling the simultaneous SEDs of III Zw 2. On the other hand, considering its radio core that is similar to young radio sources and its relic radio lobe extending to 20–30 kpc, III Zw 2 likely harbors a recurrent activity core, making it a valuable target for investigating the fueling and triggering of activity in radio-loud AGNs.

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REFERENCES
Abdo, A. A., Ackermann, M., Ajello, M., et al. 2009a, ApJ, 699, 976
Abdo, A. A., Ackermann, M., Ajello, M., et al. 2009b, ApJ, 707, 1310
Abdo, A. A., Ackermann, M., Ajello, M., et al. 2010a, ApJ, 720, 912
Abdo, A. A., Ackermann, M., Ajello, M., et al. 2010b, ApJ, 709, L152
Acero, F., Ackermann, M., Ajello, M., et al. 2015, ApJS, 218, 23
Ackermann, M., Ajello, M., Allafort, A., et al. 2012, ApJ, 747, 104
Ackermann, M., Ajello, M., Atwood, W. B., et al. 2015, ApJ, 810, 14
Aharonian, F., Akhperjanian, A. G., Barres de Almeida, U., et al. 2008, A&A, 478, 387
Aller, H. D., Aller, M. F., Latimer, G. E., & Hodge, P. E. 1985, ApJS, 59, 513
Antonucci, R. 1993, ARA&A, 31, 473
Ark, H. 1968, ApJ, 152, 1101
Atwood, W., Albert, A., Baldini, L., et al. 2013, arXiv:1303.3514
Atwood, W. B., Abdo, A. A., & Ackermann, M. 2009, ApJ, 697, 1071
Bai, J. M., Xie, G. Z., Li, K. H., Zhang, X., & Liu, W. W. 1998, A&A, 13132, 83
Bai, J. M., Xie, G. Z., Li, K. H., Zhang, X., & Liu, W. W. 1999, A&A, 365, 455
Becker, R. H., White, R. L., & Helfand, D. J. 1995, ApJ, 450, 559
Begelman, M. C., Fabian, A. C., & Rees, M. J. 2008, MNRAS, 384, L19
Bessell, M. S. 2005, ARA&A, 43, 293
Best, P. N., Kauffmann, G., Heckman, T. M., et al. 2005, MNRAS, 362, 25
Blazewiowski, M., Sikora, M., & Moderski, R., & Madejski, G. M. 2000, ApJ, 545, 107
Blandford, R. D., Netzer, H., Woltjer, L., Courvoisier, T. J.-L., & Mayor, M. 1990, Active Galactic Nuclei, Vol. 280 (Berlin: Springer)
Blandford, R. D., & Rees, M. J. 1978, in Pittsburgh Conf. on BL Lac Objects, ed. A. M. Wolfe (Pittsburgh, PA: Univ. Pittsburgh Press), 328
Bottcher, U., Ury, C. M., Bailly, C., et al. 2012, ApJ, 756, 13
Brunthaler, A., Falcke, H., Bower, G. C., et al. 2000, A&A, 357, L45
Brunthaler, A., Falcke, H., Bower, G. C., et al. 2005, A&A, 435, 497
Cardelli, J. A., Clayton, G. C., & Mathis, J. S. 1989, ApJ, 345, 245
Celotti, A., & Ghisellini, G. 2008, MNRAS, 385, 283
Chen, L., Bai, J.-M., Zhang, J., & Liu, H.-T. 2010, A&A, 2010, 10, 707
Chen, L., Bai, J.-M., & Bai, J. M. 2012, ApJ, 748, 119
Chiaberge, M., Gilli, R., Lutz, J. M., & Norman, C. 2015, ApJ, 806, 147
Condon, J. J., Cotton, W. D., Greisen, E. W., et al. 1998, AJ, 115, 1693
Cooper, N. J., Lister, M. L., & Kochanek, C. S. 2007, ApJL, 171, 376
Croom, S. M., Smith, R. J., Boyle, B. J., et al. 2001, MNRAS, 322, L29
D'Auria, F. D., & Schlickeiser, R. 1993, ApJ, 416, 458
Djorgovski, S. G., Drake, A. J., Mahabal, A. A., et al. 2011, arXiv:1102.5004
Dondi, L., & Ghisellini, G. 1995, MNRAS, 273, 583
Drake, A. J., Djorgovski, S. G., Mahabal, A. A., et al. 2009, ApJ, 696, 870
Fabian, A. C. 2012, ARA&A, 50, 455
Falcke, H., Bower, G. C., Lobanov, A. P., et al. 1999, ApJL, 514, L17
Falcke, H., Patnaik, A. R., & Sherwood, W. 1996a, ApJ, 473, L13
Falcke, H., Sherwood, W., & Patnaik, A. R. 1996b, ApJ, 471, 106
