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MINUTE-TIMESCALE >100 MeV $\gamma$-RAY VARIABILITY DURING THE GIANT OUTBURST OF QUASAR 3C 279 OBSERVED BY FERMI-LAT IN 2015 JUNE


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ABSTRACT

On 2015 June 16, *Fermi*-LAT observed a giant outburst from the flat spectrum radio quasar 3C 279 with a peak >100 MeV flux of ∼3.6 × 10^{-5} photons cm^{-2} s^{-1}, averaged over orbital period intervals. It is historically the highest γ-ray flux observed from the source, including past EGRET observations, with the γ-ray isotropic luminosity reaching ∼10^{45} erg s^{-1}. During the outburst, the *Fermi* spacecraft, which has an orbital period of 95.4 minutes, was operated in a special pointing mode to optimize the exposure for 3C 279. For the first time, significant flux variability at sub-orbital timescales was found in blazar observations by *Fermi*-LAT. The source flux variability was resolved down to 2-minute binned timescales, with flux doubling times of less than 5 minutes. The observed minute-scale variability suggests a very compact emission region at hundreds of Schwarzschild radii from the central engine in conical jet models. A minimum bulk jet Lorentz factor (Γ) of 35 is necessary to avoid both internal γ-ray absorption and super-Eddington jet power. In the standard external radiation Comptonization scenario, Γ should be at least 50 to avoid overproducing the synchrotron self-Compton component. However, this predicts extremely low magnetization (∼5 × 10^{-4}). Equipartition requires Γ as high as 120, unless the emitting region is a small fraction of the dissipation region. Alternatively, we consider γ rays originating as synchrotron radiation of γ_e ∼ 1.6 × 10^6 electrons, in a magnetic field B ~ 1.3 kG, accelerated by strong electric fields E ~ B in the process of magnetoluminescence. At such short distance scales, one cannot immediately exclude the production of γ-rays in hadronic processes.

Key words: galaxies: active – galaxies: jets – gamma rays: galaxies – quasars: individual (3C 279) – radiation mechanisms: non-thermal

1. INTRODUCTION

Among all high-luminosity blazars—which are active galaxies dominated by Doppler-boosted emission from relativistic jets pointing toward our line of sight—3C 279 is one of the most extensively studied objects. This flat spectrum radio quasar (FSRQ; z = 0.536) has been detected in essentially all accessible spectral bands; in particular, strong and variable γ-ray emission was detected by *Compton*/EGRET (Hartman et al. 1992; Kniffen et al. 1993), and it was the first FSRQ detected above 100 GeV (Albert et al. 2008). The γ-ray emission dominates the apparent luminosity of the source, and the nature of γ-ray variability and its relationship to that measured in other bands provide the strongest constraints on the total energetics, as well as the emission processes operating in the jets of luminous blazars (e.g., Maraschi et al. 1992; Sikora et al. 1994).

Due to the all-sky monitoring capability of the *Fermi* Large Area Telescope (LAT; Atwood et al. 2009), we have a continuous γ-ray flux history of 3C 279 for more than 7 years. 3C 279 underwent several outbursts in the past, having flared with a peak γ-ray flux (E > 100 MeV) ∼10^{-2} photons cm^{-2} s^{-1}, in 2013 December and 2014 April, with fluxes above three times greater than the peak during the first 2 years of *Fermi*-LAT observations (Hayashida et al. 2012, 2015). During the flaring epoch in 2013 December, the γ-ray spectrum hardened (Γ_e ≳ 1.7 in dN/dE ∝ E^{-1.7}) and rapid hour-scale flux variability was observed. The γ-ray flux strongly dominated the flux in any other band, indicating a very high “Compton dominance” (the ratio of the total inverse-Compton luminosity over the total synchrotron luminosity) of a factor of 100. This in turn suggests extremely low jet magnetization, with a level of 10^{-5}. Those results motivated, e.g., the stochastic acceleration model, which could reproduce the hour-scale variability and the hard spectrum of the flare event (Asano & Hayashida 2015).

In 2015 June, 3C 279 became very active again, with fluxes exceeding the 2013/2014 level (Cutini 2015; Paliya 2015), and prompting a target of opportunity (ToO) pointing of *Fermi*, resulting in a ∼2.5 times greater exposure. The measured γ-ray flux in daily bins reached ∼2.4 × 10^{-5} photons cm^{-2} s^{-1} on 2015 June 16, allowing an unprecedented investigation of variability on timescales even shorter than one *Fermi* orbit. In this Letter, we report and offer an interpretation of the minute-scale variability observed by *Fermi*-LAT for the first time in any blazar.

2. FERMI-LAT GAMMA-RAY OBSERVATIONS

We analyzed the LAT data following the standard procedure53, using the LAT analysis software Science-Tools v10r01p01 with the P8R2_SOURCE_V6 instrument response functions. Events with energies of 0.1–300 GeV were extracted within a 15” acceptance cone region of interest (ROI) centered at 3C 279 (R.A. = 195°047, decl. = −5°789, J2000). Gamma-ray spectra were derived by an unbinned maximum likelihood fit with gtlike. The background model included sources from the third LAT catalog (3FGL: Acero et al. 2015) inside the ROI and which showed TS > 25 based on an analysis of 1 month of LAT data, for 2015 June. Their spectral parameters were fixed by the fitting results from the 1-month data analysis. Additionally, the model included the isotropic and Galactic diffuse emission components55 (Acero et al. 2016), with fixed normalizations during the fitting. Note that the contribution of background components to the 3C 279 flux determinations in short-term binned light curves during the outburst is negligible.

53 http://fermi.gsfc.nasa.gov/ssc/data/analysis/54 “TS” stands for the test statistic from the likelihood ratio test (see Mattson et al. 1996).
55 Liso_P8R2_SOURCE_V6_v06.txt and gll_iem_v06.fits.
2.1. Light Curve

Figure 1 shows light curves of 3C 279 measured by Fermi-LAT between 2015 June 14 12:00:00 and June 18 00:00:00 UTC, including the most intense outburst observed on June 16. ToO observations were conducted from 2015 June 15 17:31:00 through 2015 June 23 16:19:00, during which LAT switched from its normal survey mode to a pointing mode targeting 3C 279. For data taken during the normal observing mode, the data were binned at twice the orbital period so that individual bins could have more uniform exposure times. Beginning with the ToO observation, the data were binned orbit by orbit. The $\gamma$-ray fluxes and photon indices were derived using a simple power-law model. The hardness ratio in the 5th panel of Figure 1 was defined as the ratio between the hard-band ($>$1 GeV) and the soft-band (0.1–1 GeV) fluxes; $F_{>$1 GeV}/F_{0.1-1 GeV}$. Here we define the outburst phase to be between 2015 June 15 22:17:12 and June 16 15:46:36 (MJD 57188.92861 and 57189.65736), as indicated in Figure 1: it comprises 11 one-orbit bins designated Orbit “A” through “K,” respectively.

The greatest flux above 100 MeV was recorded during Orbit C, centered at 2015 June 16 02:15:42 (MJD 57189.90424), reaching $(3.6 \pm 0.2) \times 10^{-5}$ photons cm$^{-2}$ s$^{-1}$. It exceeds the largest 3C 279 flares previously detected by Fermi-LAT on 2013 December 20, 2014 April 4 (Hayashida et al. 2015; Paliya et al. 2015), and those detected by EGRET in 1996 (Wehrle et al. 1998) $(\sim 1.2 \times 10^{-5}$ photons cm$^{-2}$ s$^{-1}$), making it historically the largest $\gamma$-ray ($>$100 MeV) flare of 3C 279. It
is the second-greatest flux among blazars observed by Fermi-LAT after the 3C 454.3 outburst in 2010 November (Abdo et al. 2011a). During Orbit C we found $\Gamma_\gamma = 2.01 \pm 0.05$, which was not as hard as the $\Gamma_\gamma \sim 1.7$ that was observed on 2013 December 20. The hardest spectrum during this outburst was $\Gamma_\gamma = 1.91 \pm 0.07$ in Orbit B.

The highest-energy photon, 56 GeV, was detected\(^{56}\) at 2015 June 16 14:58:12 UTC, almost at the end of the outburst phase (Figure 1, bottom), corresponding to $\sim 15.1$ hr since the outburst began, and $\sim 12.7$ hr later than the center of the highest-flux time bin. Interestingly, in the 2010 November flare of 3C 454.3, the highest-energy photon (31 GeV) also arrived during the decay part of the main flare (Abdo et al. 2011a).

### 2.2. Sub-orbital Scale Variability

The very high $\gamma$-ray flux state and the ToO observations provided a sufficiently large number of photons in each bin to resolve light curves with shorter timescales than the Fermi orbital period. Figure 2(a) shows light curves above 100 MeV for integration times of 5 minutes (red) and 3 minutes (green) for Orbits B–J, where the orbit-averaged flux exceeded $2 \times 10^{-3}$ photons cm$^{-2}$ s$^{-1}$. The spacecraft location and attitude data with 1-s resolution were used for analysis of those short-timescale light curves. To investigate flux variability at sub-orbital periods, we fitted a constant value to each orbit for both time bins, and calculated a probability ($p$-value) from $\chi^2$ in each orbit. While many orbits resulted in $p$-values consistent with constant fluxes, we found significant indications of variability on a sub-orbital timescale for Orbit C: ($p$, $\chi^2$/dof) = (0.0015, 19.62/5) and (0.00047, 29.8/9) for 5-minute and 3-minute bins respectively, and Orbit D: ($p$, $\chi^2$/dof) = (0.067, 11.79/6) and (0.068, 18.65/11) for 5-minute and 3-minute bins, respectively (see details in Table 1).

Enlarged views of light curves above 100 MeV for Orbits C and D are in Figure 2(b); those figures show integration times of 3 and 2 minutes. In those time bins, the flux reached $\sim 5 \times 10^{-3}$ photons cm$^{-2}$ s$^{-1}$ at the highest, and showed the most rapid variations. In the 3-minute binned light curve, the flux doubled even from the third to the fourth bins, and decreased by almost a half from the sixth to the seventh bins. Although defining the characteristic timescale of the variability

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\(^{56}\) Probability of association with 3C 279 as estimated by gtsrcprob is >99.99%.
is difficult, the flux doubling time is conservatively less than 10 minutes, and plausibly ~5 minutes or shorter.

2.3. Power Density Spectrum

The available LAT data allow us to study the power density spectrum (PDS) on different timescales. Results for three different frequency ranges are shown in Figure 3. Two lower-frequency (<0.1 day⁻¹) PDSs were calculated, each from a 3-day binned light curve covering one half of the 7 year LAT data (MJD 54683–55950 and 55950–57254, respectively). The PDS for intermediate frequencies is based on a light curve for the active period in 2015 June. The PDS for the second 3.5 year interval shows a higher relative variability and a flatter spectrum (slope: −0.06 ± 0.06) compared to the first interval (slope: −1.24 ± 0.15), as well as a break around 0.1 day⁻¹.

2.4. Gamma-Ray Spectra

Gamma-ray spectra measured by Fermi-LAT, extracted for each orbit during the outburst, were fitted to simple power-law (PL) and log-parabola (LP: \( dN/dE \propto (E/E_0)^{-\alpha - \beta \log(E/E_0)} \)) with \( E_0 = 300 \text{ MeV} \) models (see Table 1). The peak energy \( E_{\text{peak}} \) of the spectral energy distribution (SED) was derived from a fit with the LP model. Generally, the LP model is more favored than the PL model to describe the spectral shape. The fitting results suggest that \( E_{\text{peak}} \) ranges between ~300 MeV and ~1 GeV during the outburst. At the beginning and end of the outburst, the spectra appear relatively hard, with SED peaks at...
The SED peaks were located at significantly higher energies than for the usual states of 3C 279, when the peak is located below the Fermi-LAT band (<100 MeV), but lower than $E_{\text{peak}}$ observed in the 2013 December 20 flare ($\gtrsim$3 GeV).

Figure 4 shows the $\gamma$-ray SED as measured by Fermi-LAT for each orbit. In these plots, Orbits F and G and Orbits H and I were combined because they showed similar spectral fitting results and fluxes. The spectra in the "pre-outburst" and "post-flare" periods as defined in Figure 1 were also extracted for comparison. The spectral peaks are apparently located within the LAT energy band during the outburst. The peak SED flux reaches nearly $10^{-8}$ erg cm$^{-2}$ s$^{-1}$, corresponding to an apparent luminosity of $10^{49}$ erg s$^{-1}$.

3. DISCUSSION

For the first time, Fermi-LAT detected variability of $>100$ MeV $\gamma$-ray flux from a blazar on timescales of $t_{\text{var,obs}} \sim 5$ minutes or shorter. These timescales are comparable to the shortest variability timescales detected above 100 GeV in a handful of blazars and a radio galaxy by ground-based Cherenkov telescopes (PKS 2155–304, Aharonian et al. 2007; Mrk 501, Albert et al. 2007; IC 310, Aleksic et al. 2014). Moreover, this is only the second case when such timescales have been reported for an FSRQ blazar, after PKS 1222+216 (Aleksic et al. 2011), while Fermi-LAT had only ever detected variability as short as hour timescales in some FSRQs (e.g., Abdo et al. 2011a; Saito et al. 2013; Hayashida et al. 2015). This observational result imposes very stringent constraints on the parameters of the $\gamma$-ray emitting region.

Emitting region size: the observed variability timescale constrains the characteristic size of the emitting region radius $R_e < Dct_{\text{var,obs}}/(1 + z) \sim 10^{-4}(D/50)\text{pc}$, where $D$ is the Doppler factor. With such an extremely short variability timescale, we may consider a significantly larger dissipation...
Jet energetics: the total jet power required to produce a synchrotron self-Compton emission performed during OI1. The jet power needed to reach a soft photon flux of $10^{-11}$ erg cm$^{-2}$ s$^{-1}$ for a hard photon index of $-2$, which resulted in a high-energy electron flux of $2 	imes 10^{-12}$ cm$^{-2}$ s$^{-1}$, is $L_{\gamma\nu} = 10^{46}$ erg s$^{-1}$ (from the 0.15-15 keV band). Based on the observed synchrotron photon energy limit to comfort, the minimum Doppler factor corresponding to $\Gamma = \infty$ has been adopted. The minimum Doppler factor $\Gamma = \infty$ is $L_{\nu\nu} = 10^{46}$ erg s$^{-1}$.

The synchrotron cooling timescale is $\simeq \lambda_{\nu}^{2} / \nu_{\nu}^{3}$. The radiative cooling timescale $\tau_{\nu}$ is calculated as $\tau_{\nu} \propto \nu_{\nu}^{-2} / \lambda_{\nu}^{2}$.

A dedicated study of the jet power required to produce a synchrotron self-Compton emission performed during OI1. The jet power needed to reach a soft photon flux of $10^{-11}$ erg cm$^{-2}$ s$^{-1}$ for a hard photon index of $-2$, which resulted in a high-energy electron flux of $2 	imes 10^{-12}$ cm$^{-2}$ s$^{-1}$, is $L_{\gamma\nu} = 10^{46}$ erg s$^{-1}$ (from the 0.15-15 keV band). Based on the observed synchrotron photon energy limit to comfort, the minimum Doppler factor corresponding to $\Gamma = \infty$ has been adopted. The minimum Doppler factor $\Gamma = \infty$ is $L_{\nu\nu} = 10^{46}$ erg s$^{-1}$.

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4. SUMMARY

In this Letter, we reported the first minute-timescale γ-ray flux variability observed by Fermi-LAT in an FSRQ blazar, 3C 279. In the standard ERC scenario with conical jet geometry, the minute-scale variability requires a high Γ (>50) and extremely low magnetization, even at the jet base (~100 R_S) or Γ ~ 120 under equipartition. The high Γ and/or low magnetization at the jet base pose challenges to standard models of electromagnetically driven jets. We also discuss an alternative, synchrotron origin for the GeV γ-ray outburst, which would work in a magnetically dominated jet, but requires higher electron energies and still implies Γ ~ 25 at the jet base.

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