Rapid Gamma-Ray Variability of NGC 1275

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Abstract

We report on a detailed analysis of the γ-ray light curve of NGC 1275 using the Fermi Large Area Telescope data accumulated during 2008–2017. Major γ-ray flares were observed in 2015 October and 2016 December/2017 January when the source reached a daily peak flux of $(2.21 \pm 0.26) \times 10^{-6}$ photon cm$^{-2}$ s$^{-1}$, achieving a flux of $(3.48 \pm 0.87) \times 10^{-6}$ photon cm$^{-2}$ s$^{-1}$ within 3 hr, which corresponds to an apparent isotropic γ-ray luminosity of $\approx 3.84 \times 10^{45}$ erg s$^{-1}$. The most rapid flare had an e-folding time as short as $1.21 \pm 0.22$ hr, which had never been previously observed for any radio galaxy in γ-ray band. Also, γ-ray spectral changes were observed during these flares: in the flux versus photon index plane, the spectral evolution follows correspondingly a counterclockwise and a clockwise loop inferred from the light curve generated by an adaptive binning method. On 2016 December 30 and 2017 January 1 the X-ray photon index softened $(\Gamma_X \approx 1.75–1.77)$ and the flux increased nearly $\approx 3$ times as compared with the quiet state. The observed hour-scale variability suggests a very compact emission region ($R_e \approx 5.22 \times 10^{15} (\delta/4$ km), implying that the observed emission is most likely produced in the subparsec-scale jet if the entire jet width is responsible for the emission. During the active periods, the γ-ray photon index hardened, shifting the peak of the high-energy spectral component to $>\text{GeV}$, making it difficult to explain the observed X-ray and γ-ray data in the standard one-zone synchrotron self-Compton model.

Key words: galaxies: active – galaxies: individual (NGC 1275) – galaxies: jets – gamma rays: galaxies – radiation mechanisms: non-thermal – X-rays: galaxies

1. Introduction

Due to its proximity ($z = 0.0176$, $\approx 75.6$ Mpc) and brightness, the radio galaxy NGC 1275 has been a target for observations in almost all energy bands. Core-dominated asymmetrical jets at both kpc (Pedlar et al. 1990) and pc scales (Asada et al. 2006) have been detected in the radio band with characteristics more similar to those of Fanaroff and Riley type I sources (Fanaroff & Riley 1974). The emission in the X-band is mostly dominated by the thermal emission from the cluster, although a nonthermal component in the energy range $0.5–10$ keV with a photon index of $\Gamma_X \approx 1.65$ has been observed (Churazov et al. 2003; Fabian et al. 2011). High Energy (HE; $>100$ MeV) γ-rays from NGC 1275 had already been detected by Fermi Large Area Telescope (Fermi-LAT) using the data obtained during the first four months of observations (Abdo et al. 2009b). Then, using the data accumulated for longer periods, γ-ray flux and photon index variation on month timescales were detected (Kataoka et al. 2010). However, the γ-ray emission is variable also in shorter (a few days) timescales (Brown & Adams 2011). Very High Energy (VHE; $>100$ GeV) γ-ray emission with a steep spectral index of $4.1 \pm 0.7$ was detected by the Major Atmospheric Gamma Imaging Cherenkov Telescopes (MAGIC) using the data accumulated between 2010 August and 2011 February (Aleksić et al. 2012). No hints of variability above 100 GeV were seen on month timescales.

Even if the observed γ-ray variability allowed the exclusion of the Perseus cluster as the main source of γ-ray emission, the exact mechanisms responsible for the broadband emission from NGC 1275 are still unclear. The multiwavelength Spectral Energy Distribution (SED) hints at a double-peaked SED with the peaks around $10^{12}$ Hz and $10^{23}–10^{24}$ Hz (Aleksić et al. 2014a). Within a “classical” misaligned BL Lac scenario, a one-zone synchrotron/Synchrotron Self-Compton (SSC) interpretation of the SED can well explain the HE peak constrained by Fermi-LAT and MAGIC data, but it has difficulties explaining the low-energy data. It requires that the jet should be more aligned than it is estimated, e.g., $30°–55°$ (Walker et al. 1994). Therefore, additional assumptions on the jet properties and/or more complex scenarios for inverse-Compton scattering should be made.

In the HE γ-ray band, frequent flaring activities are known for NGC 1275 (Baghmanyan 2017). A substantial increase of the γ-ray flux in the HE and VHE γ-ray bands was detected in 2015 October and 2017 January (Pivato & Buson 2015; Lucarelli et al. 2017; Mirzoyan 2017; Mukherjee & VERITAS Collaboration 2017). In 2015 October, 25 Fermi-LAT detected a bright flare with a deep peak flux of $(1.6 \pm 0.2) \times 10^{-6}$ photon cm$^{-2}$ s$^{-1}$ (Pivato & Buson 2015). Then, in the night between 2016 December 31 and 2017 January 1, a major flare was detected in the VHE γ-ray band when the flux was 60 times higher than the mean flux (Mirzoyan 2017). Also, the flux $>100$ MeV was about 12 times higher than the most significant flux observed with Astro-Rivelatore Gamma a Immagini Leggero (AGILE; Lucarelli et al. 2017). Besides, Swift observations during this major γ-ray active period provided data in the UV and X-ray bands, providing a unique chance to investigate the flaring activity of NGC 1275 in the multiwavelength context.

The goal of this paper is to have a new look on the γ-ray emission from NGC 1275 in the last $\sim 8.7$ years in general and during the major flaring periods in particular. The larger data set allows the investigation of the γ-ray flux evolution in time with improved statistics in shorter timescales, while a detailed analysis of recently observed exceptional flares will provide an insight into the particle acceleration and emission processes.
This paper is organized as follows. The Fermi-LAT data reduction and temporal analyses are presented in Section 2. The spectral analyses of Fermi-LAT and Swift data are described in Section 3. We present our results and discussion in Section 4. A summary is given in Section 5.

2. Fermi-LAT Observations and Data Analysis

The Large Area Telescope on board the Fermi satellite is a pair-conversion telescope sensitive to γ-rays in the energy range of 20 MeV–500 GeV (Atwood et al. 2009). We used the publicly available data accumulated during the last ~8.7 years of Fermi-LAT operation (from 2008 August 4 to 2017 March 15). The data were analyzed with the standard Fermi Science Tools v10r0p5 software package released on 2015 May 18. The most recent reprocessed PASS eight events and spacecraft data were used with P8R2_SOURCE_V6 instrument response function. Only the events with a higher probability of being photons (evclass = 128, evtype = 3) in the energy range of 100 MeV–500 GeV were analyzed. In the analysis, we selected different radii (9°, 10°, 12° and 15°) of the region of interest (ROI) to ensure that the selected ROI is an accurate representation of the observation. This yielded essentially the same results within statistical uncertainties, so a radius of 12° was used and the photons from a 16.9° × 16.9° square region centered at the location of NGC 1275, (R.A., decl.) = (49.96, 41.51), were downloaded. The recommended quality cuts, (DATA_QUAL==1)&&(LAT_CONFIG==1) and a zenith angle cut at 90° to eliminate the Earth limb events were applied with gtselect and gmktime tools. We binned photons with gbin tool with an Aitoff projection into pixels of 0°.1 × 0°.1 and into 37 equal logarithmically spaced energy bins. Then, with the help of gtlike tool, a standard binned maximum likelihood analysis is performed. The fitting model includes diffuse emission components and γ-ray sources within the ROI. The model file was created based on the Fermi-LAT third source catalog (3FGL) (Acero et al. 2015) and the Galactic background component was modeled using the Fermi-LAT standard diffuse background model gll_eim_v06 and iso_P8R2_SOURCE_V6_v06 for the isotropic γ-ray background. The normalization of background models as well as fluxes and spectral indices of sources within 12° are left as free parameters. As in 3 FGL, the γ-ray spectrum of NGC 1275 was modeled using a log-parabola spectrum.

Using the data accumulated for a time period almost two times longer than in 3 FGL can result in new γ-ray sources in the ROI which are not properly accounted for in the model file. To probe for additional sources, a test statistics map of the ROI (TS defined as TS = 2(log L – log L0), where L and L0 are the likelihoods when the source is included or is not) is created with gttsmap tool using the best-fit model of 0.1–500 GeV events. To identify the coordinates of the excess hot spots with TS > 25 (5σ), we used the find_source iterative source-finding algorithm implemented in Fermipy. In the TS map, it identifies the peaks with TS > 25 and adds a source at each peak starting from the highest TS peak. The sources position is obtained by fitting a 2D parabola to the log-likelihood surface around the maximum. Alternatively, the sources position was calculated by hand using the pixels surrounding the highest TS (similar to the method used in Macias-Ramirez et al. 2012). Both methods resulted in similar values. For each given point, we sequentially added a new point source with a conventional spectral definition (power law) and performed binned likelihood analysis with gtlike. For further analysis, we used the model file with the new additional point-like sources to have better representation of the data.

2.1. Temporal Variability

The γ-ray light curve is calculated using the unbinned likelihood analysis method implemented in the gtlike tool. (0.1–500) GeV photons are used in the analysis with the appropriate quality cuts applied in the previous section. Different model files are used to ensure that the possible contribution from sources within the ROI are properly accounted for. In the model file obtained from the whole-time analysis, the photon indices of all background sources are first fixed to the best-guess values to reduce the uncertainties in the flux estimations, then those of the sources within the ROI are considered as free parameters. In addition, we analyzed the data accumulated during the one-month periods covering the major flares (2016 October 1–30 and December 15–2017 January 15). Then, we fixed the spectral parameters of all background sources as in Ackermann et al. (2016). All approaches yielded essentially the same results. We used the latter model as the rising and decaying times of the first flare can be evaluated better. Given shorter periods are considered, the spectrum of NGC 1275 has been modeled using a power-law function with the index and normalization as free parameters. Since no variability is expected for the background diffuse emission, the normalization of both background components is also fixed to the values obtained for the whole time period.

Figure 1 (upper panel) shows the γ-ray light curve with three-day bin size. Despite the fact that the flux sometimes exceeded the averaged value presented in 3FGL (∼2.0 ± 10−7 photons cm−2 s−1), pronounced flaring activities were detected in 2015 October (hereafter Flare 1 [F1]) and in 2016 December/2017 January (hereafter Flare 2 [F2]). Starting from 2015 October 22, the daily averaged flux of NGC 1275 was above 10−6 photons cm−2 s−1 and remained high for five days with a daily averaged maximum of (1.48 ± 0.20) × 10−6 photons cm−2 s−1 observed on 2015 October 24. Another substantial increase in the γ-ray flux was observed on 2016 December 31 when the flux increased from about (4 ± 5) × 10−7 photons cm−2 s−1 to (2.21 ± 0.26) × 10−6 photons cm−2 s−1 within a day with a detection significance of ∼21.5σ.

The photon statistics allowed us to study these flares with denser time sampling (sub-day) for the first time. The shortest bin sizes have been chosen to ensure that (i) the flare rise and decay periods are well constrained and (ii) the detection significance for each bin exceeds the ∼5σ limit. The statistics allowed to use bins with 8 hr intervals for F1 and 3 hr bins for F2. For example, from MJID 57317 to MJID 57322, the detection significance varied between 5.1σ and 13.1σ, and from MJID 557753 to MJID 57754 it was between 5.3σ and 10.4σ. The corresponding light curves are shown in the middle panels of Figure 1. To check if the likelihood fit has converged in each time bin, the plot of Npred/√Npred versus Flux/ΔFlux is shown in the lower panels of Figure 1 for 8 hr (left) and 3 hr (right) bins. We verified that the fit has converged in the surrounding bins as well. As one can see, it seems there is a linear correlation without any declination, so the errors are an accurate representation of the observation.

Footnote

http://fermipy.readthedocs.io/en/latest/
Furthermore, the γ-ray flux and photon index variations are investigated using a light curve generated by an adaptive binning method (Lott et al. 2012). In this method, the time bin widths are flexible and were chosen to produce bins with a constant flux uncertainty. This method allows a detailed investigation of the flaring periods, as at times of a high flux, the time bins are narrower than during lower flux levels, therefore rapid changes of the flux can be found. To reach the necessary relative flux uncertainty, the integral fluxes are computed above the optimal energy (Lott et al. 2012), which in this case is \( E_0 = 208.6 \text{ MeV} \). Also, to improve the accuracy of the method, the flux of bright sources that lie close to NGC 1275 have been taken into account. This is done by providing the parameters of confusing sources during the adaptive binning light curve calculations. The light curve calculated assuming a constant 15% uncertainty is shown in Figure 2 (upper panels) for the period covering the large flares.

3. Spectral Analysis

3.1. Fermi Data

The changes in the γ-ray photon index are investigated by analyzing the data from the following four periods.

(i) Overlapping with the observation of Swift on 2016 December 30. Even if the Swift observations lasted \( \sim 960 \text{ s} \), to increase the statistics, the γ-ray spectrum has been extracted for the period MJD 57752.75–57753.25 where the source has a comparable flux as revealed from the light curve with a 6 hr binning (Figure 1, middle right panel).

(ii) MJD 57754.00–57755.75, when the flux is relatively constant and it coincides with the observations of Swift on 2017 January 01.

(iii) At the peak of F2 (MJD 57753.81), using the data accumulated for 3 hr.

(iv) MJD 57442.32–57444.45, which corresponds to the quiet (steady) state in the X-ray and γ-ray bands.

The γ-ray spectrum of NGC 1275 has been modeled using a power-law function \( (dN/dE) \sim N_0 E^{-\Gamma} \), where the normalization \( (N_0) \) and power-law index (\( \Gamma \)) are considered as free parameters. The best matches between the spectral models and events are obtained with an unbinned likelihood analysis implemented in gtlike. The spectral fitting results are summarized in Table 1. After analyzing the data for each considered period, the SEDs are obtained by freezing the NGC 1275 photon index in the model file and separately running gtlike for smaller energy bins of equal width in log scale. The SED for each period is shown in Figure 3. Although some features can be noticed, it is hard to make any conclusion because of large uncertainties in the estimated parameters.

We separately analyze the Fermi-LAT data to determine the energy of the highest-energy photon detected from NGC 1275...
using gtsrcprob tool and the model file obtained from the likelihood fitting. All spectral parameters of the sources within the ROI are first fixed to the best fitting values obtained in the whole-time analysis and then are left free. Both yielded identical results. In this case, additional care must be taken since IC 310, which is known to be a strong emitter in the VHE $\gamma$-ray band (Aleksić et al. 2014b), is only at a distance of $\theta = 0.623$. Therefore, both sources are considered to estimate the probability whether the photon belongs to NGC 1275 or to IC 310. The highest-energy photons detected during the four periods mentioned above are presented in Table 1.

### 3.2. Swift UVOT/XRT Data

During F2, Swift (Gehrels et al. 2004) had observed NGC 1275 three times (see Table 1). Unfortunately, there were no observations overlapping with F1. In addition to these observations, the Swift data of 2016 February 25, corresponding to a relatively stable state in the X-ray band have been analyzed. The XRT data were analyzed with the XRTDAS software package (v.3.3.0) distributed by HEASARC along with the HEASoft package (v.6.21). The source region was defined as a circle with a radius of 10.6 pixels (25′) at the center of the source, while the background region as an annulus centered at the source with its inner and outer radii being 20 ($\approx 47′$) and 30 pixels ($\approx 71′$), respectively. Such selections allowed us to minimize the possible contribution from the cluster emission. For PC mode observations (Obsid 87312001, 87311001), the count rate was above 0.5 count s$^{-1}$, being affected by the piling-up in the inner part of the PSF. This effect was removed, excluding the events within a four-pixel radius circle centered on the source position. All spectra were re-binned to have at least 20 counts per bin, ignoring the channels with energy below 0.3 keV, and fitted using Xspec v12.9.1a. The results of the fit are presented in Table 1.

In the analysis of Swift UVOT data, the source counts were extracted from an aperture of 5′ radius around the source. The background counts were taken from the neighboring circular source-free region with a radius of 20′. The magnitudes were computed using the uvotsource tool (HEASOFT v6.21) corrected for extinction according to Roming et al. (2009),...
Table 1
Parameters of Spectral Analysis

| Period         | Date            | Flux\(^a\) | Photon Index\(^b\) | Test Statistic | Highest Photon Energy\(^c\) |
|---------------|-----------------|------------|--------------------|----------------|-----------------------------|
| 57442.32–57444.45 | 2016 Feb (24–26) | 4.18 ± 0.85 | 1.93 ± 0.14        | 123            | 10.39                       |
| 57752.75–57753.25 | 2016 Dec (30–31) | 8.56 ± 2.30 | 1.79 ± 0.17        | 106            | 34.77                       |
| 57753.81       | 2016 Dec 31     | 34.82 ± 8.67 | 1.93 ± 0.19        | 102            | 5.84                        |
| 57754.00–57755.75 | 2017 Jan (01–02) | 6.27 ± 1.20 | 1.67 ± 0.11        | 178            | 4.18                        |

| Swift XRT     | Obsid.          | Date            | Exp. Time | Photon Index\(^d\) | Unabsorbed Flux\(^c\) | \(\chi^2_{\text{red}}\) (dof) |
|---------------|-----------------|-----------------|-----------|--------------------|-------------------------|-----------------------------|
|               | 34380005        | 2016 Feb 25     | 2750      | 1.52 ± 0.08        | 3.10 ± 0.19             | 1.04 (75)                  |
|               | 87312001        | 2016 Dec 30     | 939       | 1.75 ± 0.12        | 8.64 ± 0.76             | 0.74 (24)                  |
|               | 87311001        | 2017 Jan 01     | 619       | 1.77 ± 0.17        | 10.57 ± 1.26            | 1.15 (15)                  |
|               | 31770011        | 2017 Jan 01     | 984       | 1.77 ± 0.08        | 10.29 ± 0.55            | 0.95 (173)                 |

Notes.
\(\text{a}\) Integrated \(\gamma\)-ray flux in the 0.1–100 GeV energy range in units of \(10^{-7}\) photon cm\(^{-2}\) s\(^{-1}\).
\(\text{b}\) \(\gamma\)-ray photon index from likelihood analysis.
\(\text{c}\) Photon energy in GeV.
\(\text{d}\) Photon index from X-ray data analysis.
\(\text{e}\) X-ray flux in the energy range 0.3–10 keV in units of \(10^{-11}\) erg cm\(^{-2}\) s\(^{-1}\) (corrected for the Galactic absorption).

Figure 3. Multiwavelength SED for the periods presented in Table 1.

using \(E(B – V) = 0.14\) from Schlafly & Finkbeiner (2011) and zero points from Breeveld et al. (2011) converted to fluxes, following Poole et al. (2008). The corresponding spectra are shown in Figure 3.

4. Results and Discussions

The \(\gamma\)-ray emission from one of the brightest radio galaxies in the MeV/GeV band—NGC 1275—has been investigated using the Fermi-LAT data accumulated during the last \(\sim 8.7\) years. The \(\gamma\)-ray light curve appears to be quite complex, with many peaks and flaring periods. The highest fluxes were detected in 2015 October and 2016 December/January, when the daily averaged peak \(\gamma\)-ray fluxes \((\sim 1.48–2.21) \times 10^{-6}\) photons cm\(^{-2}\) s\(^{-1}\) integrated above 100 MeV were detected. It reached its maximum of \((3.48 \pm 0.87) \times 10^{-6}\) photon cm\(^{-2}\) s\(^{-1}\) on 2016 December 31, within 3 hr, which is the highest \(\gamma\)-ray flux observed from NGC 1275 so far; it exceeds the averaged flux by a factor of \(\sim 15.4\). The apparent isotropic \(\gamma\)-ray luminosity at the peak of the flare, \(L_\gamma \sim 3.84 \times 10^{45}\) erg s\(^{-1}\) (using \(d_L = 75.6\) Mpc), exceeds the averaged \(\gamma\)-ray luminosity of other radio galaxies detected by Fermi-LAT (usually \(\lesssim 10^{45}\) erg s\(^{-1}\) (Abdo et al. 2010c)); it is more comparable with the luminosity of BL Lac blazars.

This is quite impressive, considering the large Doppler boosting factors of blazars \((\delta > 10)\) as compared with the value of \(\delta \sim (2–4)\) usually used for the radio galaxies. Yet, at \(\delta = 4\) the total power emitted in the \(\gamma\)-ray band in the proper frame of the jet would be \(L_{\gamma,\text{em}} \sim L_\gamma \delta^2 \sim 1.2 \times 10^{44}\) erg s\(^{-1}\). It is of the same order as the kinetic energy of the NGC 1275 jet \((L_\gamma \approx (0.6–4.9) \times 10^{44}\) erg s\(^{-1}\)) estimated from broadband SED modeling (Abdo et al. 2009b). This implies that during the discussed flaring period a substantial fraction of the total jet power, \((L_{\gamma,\text{em}})/L_\gamma \lesssim 1\), is converted into \(\gamma\)-rays. These assumptions are in a strong dependence with \(\delta\), which is highly unknown. However, it seems that \(\delta = 4\) is already a limiting case, and larger decrease of \(L_{\gamma,\text{em}}\) is not expected.

The \(\gamma\)-ray spectrum estimated during the peak flux appeared as a nearly flat one (cyan data in Figure 3), though the photon index estimation uncertainty is large \((\Gamma \approx 1.93 \pm 0.19)\). This is similar with the spectrum measured in a quiet state (Figure 3, gray data), although with a significantly increased flux. The \(\gamma\)-ray photon index measured before and after the peak flux hints at spectral hardening (see Table 1 and Figure 3, blue and red data). However, large uncertainties in the photon index estimations do not allow us to make strong conclusions on the spectral hardening or softening. Although, as compared with the quiet state, it is clear that during the active states the \(\gamma\)-ray flux increases and the spectrum shifts to higher energies.

The broadband SED of NGC 1275 (Figure 3) shows that during the bright \(\gamma\)-ray states, the X-ray flux also has increased. The analysis of the Swift XRT data detected during F2 results in an unabsorbed flux of \(F_{\gamma} \sim 10^{-10}\) erg cm\(^{-2}\) s\(^{-1}\) which nearly three times exceeds the averaged flux observed in 2016 February. We note that the X-ray photon index measured during the quiet state is somewhat similar to the values measured by XMM-Newton (Churazov et al. 2003) and Swift BAT (Ajello et al. 2009), while during the active states, the X-ray photon index is steeper \((\sim 1.7)\). In the lower-energy band, the UV flux from UVOT observations is relatively stable when comparing the
quiescent and flaring states, albeit the data from all filters are not available to make definite conclusions.

4.1. γ-ray Photon Index Variation

The γ-ray photon index changes during ~8.7 years of Fermi-LAT observations are investigated with the help of an adaptively binned light curve. In Figure 2 (upper panels) the photon flux and index variation in time are shown for the time that covers only F1 and F2. In the course of ~8.7 years, the hardest photon index of $\Gamma = 1.62 \pm 0.13$ was observed on MJD 55331.51 for ~2.78 days, while the softest index of $\Gamma = 2.77 \pm 0.21$ was detected on MJD 56124.71. The lowest and highest fluxes (above 208.6 MeV) were $F_{\gamma} = (4.27 \pm 1.06) \times 10^{-8}$ photon cm$^{-2}$ s$^{-1}$ and $F_{\gamma} = (1.18 \pm 0.28) \times 10^{-6}$ photon cm$^{-2}$ s$^{-1}$, respectively. When the source is in active state, the data accumulated for a few hours is already enough to reach 15% flux uncertainty, while in the quiet states, the data should be accumulated for several days. Interestingly, in the first ~8.7 years of Fermi-LAT operation, the highest-energy photon with $E_{\gamma} = 241.2$ GeV has been detected on MJD 57756.62 (after F2) within a circle of 0.071 around the nucleus of NGC 1275 with the 3.36σ probability to be associated with it. Another events with $E_{\gamma} = 221.5$, 164.9, 125.6, 123.3 and 109.2 GeV have been observed on MJD 55402.39, 56760.82, 56610.75, 56578.00 and 57694.65, respectively. We note that the PSF of Fermi-LAT at energies >10 GeV is sufficient to distinguish the photons with high accuracy, so the highest-energy photons are most likely coming from NGC 1275. It appeared that the γ-ray spectra for the periods when the highest-energy photons were emitted, have mostly harder photon indexes (e.g., $\Gamma = 1.74 \pm 0.14$ when $E_{\gamma} = 241.2$ GeV photon was detected). Likewise, when photons with $E_{\gamma} = 221.5$, 164.9, 125.6, 123.3 and 109.2 GeV were detected, the photon indexes were $\Gamma = 1.81 \pm 0.15$, $1.93 \pm 0.15$, $1.79 \pm 0.13$, $1.94 \pm 0.14$ and $1.86 \pm 0.15$, respectively. This hardening is probably associated with the emission from reaccelerated or fresh electrons, which produce also the observed highest-energy photons.

The spectral changes observed in the photon-index-flux plane give us important information about the dynamics of the source and an insight into the particle acceleration and emission processes. The photon index $\Gamma$ as a function of the flux during F1 and F2 is shown in the bottom panels of Figure 2. A counterclockwise loop is observed during F1, while during F2 the spectral index and flux changes follow a clockwise path. Such loops are expected to occur as a consequence of diffusive particle acceleration at strong shocks and cooling of the radiating particles. As discussed in Kirk et al. (1998), it is expected to have a counterclockwise loop if the variability, acceleration and cooling timescales are similar, implying that during the flare, the spectral slope is controlled by the acceleration rather than by the cooling processes. Consequently, the occurrence of a flare propagates from lower to higher energies, so the lower-energy photons lead the higher-energy ones. Instead, if the spectral slope is controlled by synchrotron cooling or any cooling process that is faster at higher energies, a clockwise loop will be seen. The counterclockwise loop observed during F1 suggests that it is most likely that this flaring event is due to the acceleration of the lower-energy electrons. Note that such “harder-when-brighter” behavior was already observed during the previous flares of NGC 1275 (Kataoka et al. 2010; Brown & Adams 2011).

The clockwork loop observed during F2 indicates that during this flare the flux started to increase at low energies (HE radiating particles cool down and radiate at lower and lower energies) and then propagate to HE. This shows that HE electrons are playing a key role during F2, which also produce the highest-energy photons from NGC 1275 observed around F2.

The interpretation of the mechanism responsible for spectral evolution can be more complicated than it was discussed above. It has been already shown that depending on the change of the total injected energy, the dominance of synchrotron and Compton components can also vary, so that the trajectory in the photon index-flux plane evolves clockwise or counterclockwise, depending on the total energy and the observed energy bands (Li & Kusunose 2000; Böttcher & Chiang 2002). Thus, the observed spectral evolution is quite sensitive to various parameters in the model and it is hard to draw any firm conclusions. The discussions above are of first-order approximation and are generally meant to understand the dynamics of the system.

4.2. Minimum Flux Variability Period:

During F1 and F2, the flare time profiles are investigated by fitting them (Figure 1, middle panels, blue data) with double exponential functions in the following form (Abdo et al. 2010b)

$$F(t) = F_{\gamma} + F_0 \times (e^{-t/\tau_1} + e^{-t/\tau_2})^{-1}$$  (1)

where $t_0$ is the time of the maximum intensity of the flare ($F_0$) and $F_{\gamma}$ is the constant level present in the flare. $\tau_1$ and $\tau_2$ are the rise and decay time constants, respectively. The fitting parameters are summarized in Table 2 and the corresponding fit is shown in Figure 1 middle panels (red dashed line). The time profiles show asymmetric structures in both flares, showing a slow rise and a fast decay trend. The time peak of the flares calculated by $t_p = t_0 + t_1$ is 8.7 years of NGC 1275. The rise time is $32.49 \pm 7.20$ hr with a sudden drop within 2.22 ± 1.19 hr. The parameters of F2 are better estimated and are characterized with a shorter rise time, when within 8.03 ± 1.24 hr the flux reaches its maximum of $(4.20 \pm 0.48) \times 10^{-6}$ photon cm$^{-2}$ s$^{-1}$ on MJD 57753.79 and drops nearly four times in ~6 hr. The minimal e-folding time is $t_0 = 1.21 \pm 0.22$ hr, using the decay timescale of F2, and it is the most rapid γ-ray variability observed for NGC 1275. We note that even if the rise time of F2 is used, the flux e-folding time of about 8.03 ± 1.24 hr will still be shorter than any previously reported value.

The obtained shortest flux e-folding time, $t_0 = 1.21 \pm 0.22$ hr, is unusual for radio galaxies and has never been observed for any other radio galaxy so far. It is more similar to the rapid γ-ray variability detected from several bright blazars (Foschini et al. 2011, 2013; Brown 2013; Nalewajko 2013; Rani et al. 2013; Saito et al. 2015; Hayashida et al. 2015; Ackermann et al. 2016). Brown (2013) was the first to point out that during the γ-ray flares of PKS 1510-089 the flux doubling timescale was as short as 1.3 ± 0.12 hr which was the shortest variability timescales measured at MeV/GeV energies at that time. It is interesting that such rapid γ-ray variability is mostly observed from flat-spectrum radio quasars. The asymmetric profile of NGC 1275 flares can be explained if assumed that the accelerated particles (e.g., by shock acceleration) quickly cool down due to
the increase of the magnetic field (assuming the electrons dominantly lose energy by synchrotron cooling). To interpret the fast decay ($t_{\text{dec}} = 1.21 \pm 0.22 \text{ hr}$) as cooling of relativistic electrons ($t_{\text{cool}} = t_{\text{decay}}/\delta$; $t_{\text{cooling}} = 6 \pi m_e^2 c^3/\sigma_T B^2 E_e$) with $E_e = 100 \text{ GeV}$, the magnetic field should be $B \approx 478 \text{ mG} (\delta/4)^{-1/2} (t_{\text{dec}}/1.2 \text{ hr})^{-1/2} (E_e/100 \text{ GeV})^{-1/2}$ (where we assumed a moderate Doppler boosting factor of $\delta = 4$), which is not far from the typical values usually used in the modeling of emission from radio galaxies (Abdo et al. 2009a, 2010a). Even if the magnetic field is 10–100 times lower than this value, the shock acceleration timescales ($t_{\text{acc}} \approx 6 \tau_6 c/v_6^2$ (Rieger et al. 2007)) would be more than enough to accelerate the electrons >100 GeV within the observed rise time scale (8.03 ± 1.24 hr).

4.3. The Origin of Emission

The observed short timescale variability of 1.21 ± 0.22 hr allows us to constrain the characteristic size of the emitting region radius to $R_s \leq \delta \times c \times \tau \approx 5.22 \times 10^{14} (\delta/4) \text{ cm}$. If the entire jet width is responsible for the emission, assuming the jet half-opening angle $\theta_j \approx 0.1^\circ$, the location of the emitting region along the jet will be $r \approx R_s/\theta_j \approx 0.1 (\delta/4) (\theta_j/0.1^\circ)^{-1} \text{ pc}$. This strongly suggests that the observed emission is most likely produced in the subparsec-scale jet. In principle, the jet can be much more extended and the emission is produced in a region smaller than the width of the jet. For example, multiple regions moving in a wider jet having different beaming factors can be an alternative possibility (Lenain et al. 2008). In this model, the emission is expected to take place in a broadened jet formation zone close to the central supermassive black hole where, even for a large jet angle, a few emission zones can move directly toward the observer and Doppler boost the emission. Here the emission region is very close to central source, again implying that the innermost jet (subparsec-scale) is responsible for the emission.

The SED presented in Figure 3 as well as that in Aleksić et al. (2014a), hint at a double-peaked SED similar to those of other GeV/TeV-emitting radio galaxies (Abdo et al. 2009a, 2010a) and blazars. This similarity allowed to model the SED of NGC 1275 within the one-zone synchrotron SSC scenario (Aleksić et al. 2014a). However, it failed to reproduce the required large separation of the two peaks (Figure 3, gray data) with small Doppler factors ($\delta = 2–4$) typical for radio galaxies. With the new data, the situation even worsened: even if the data are not enough to exactly identify the location of the peaks, clearly, the first peak is at $\approx (10^{14}–10^{15}) \text{ Hz}$ (unchanged) while the rising shape of the MeV/GeV spectrum indicates the second peak shifted to higher frequencies. Such large separation of the two SED peaks unavoidably requires a higher Doppler factor than that used previously. Moreover, if one-zone SSC emission dominates, usually it is expected to have correlated changes in the X-ray/γ-ray band, which are not observed here. One can avoid these difficulties by assuming that HE emission is produced in a local substructure of the jet, which is characterized by a higher boosting factor and/or smaller inclination angle. For example, the mini-jets generated by local reconnection outflows in a global jet (“jets in a jet” model (Giannios et al. 2009)) can have extra Lorentz boosting and the emission can be produced around these local reconnection regions. This successfully explains the fast TeV variability of M87 (Giannios et al. 2010) so that it also can be naturally considered in this case. In addition, two-zone SSC models, when different regions are responsible for low- and high-energy emissions, can be an alternative. In more complex-structured jet models, the seed photons for IC scattering can be of external origin (the emission region is the layer and external photons are from the spine, or vice versa (Tavecchio & Ghisellini 2014)), the energy of which is higher than that of synchrotron photons resulting in the shift of the emission peak to higher energies. However, these models involve additional parameters that cannot be constrained with the current data set and additional observations in the radio/optical and VHE γ-ray bands are required.

### 5. Summary

We report on the results of ~8.7 years’ γ-ray observations of NGC 1275 radio galaxy. The source displayed prominent flaring activities in 2015 October and 2016 December/2017 January with the 3 hr peak flux above 100 MeV of $(3.48 \pm 0.87) \times 10^{-6} \text{ photon cm}^{-2} \text{ s}^{-1}$ observed on 2016 December 31 corresponding to an apparent isotropic γ-ray luminosity of $L_\gamma \approx 3.84 \times 10^{45} \text{ erg s}^{-1}$. This luminosity is more typical for BL Lac blazars and corresponds to a large fraction of the kinetic energy of the NGC 1275 jet, implying that the γ-ray production efficiency is very high. During the major flares, the photon statistics allowed us to investigate the flare properties with as short as 3 hr intervals for the first time. This allowed to find very rapid variability with the flux e-folding time as short as 1.21 ± 0.22 hr, which is very unusual for radio galaxies. The γ-ray photon index of the source was evolving during the flaring periods, showing counterclockwise and clockwise loops in the photon-index-flux plane during the flares in 2015 October and 2016 December/2017 January, respectively. Also, some of the highest-energy γ-ray photons observed from the source during ~8.7 years arrived around the same active periods. Perhaps this rapid γ-ray flare was associated with effective particle acceleration that led to emission of these photons.

The observed hour-scale variability suggests that the emission is produced in a very compact emission region with $R_s \leq 5.22 \times 10^{14} (\delta/4) \text{ cm}$, and perhaps it is produced in a subparsec scale jet. During the γ-ray activity, the HE component not only increased but also shifted to higher energies. Considering this shift and the large γ-ray luminosity, it makes it very challenging to explain the observed X-ray and γ-ray data in the standard synchrotron/SSC models. Additional assumptions on the jet structure/emission processes are to be made.
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