THE $\gamma$-RAY EMISSION REGION IN THE FANAROFF–RILEY II RADIO GALAXY 3C 111

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Received 2012 February 29; accepted 2012 April 3; published 2012 April 30

ABSTRACT

The broad-line radio galaxy 3C 111, characterized by a Fanaroff–Riley II (FRII) radio morphology, is one of the sources of the misaligned active galactic nucleus sample, consisting of radio galaxies and steep spectrum radio quasars, recently detected by the Fermi Large Area Telescope (LAT). Our analysis of the 24 month $\gamma$-ray light curve shows that 3C 111 was only occasionally detected at high energies. It was bright at the end of 2008 and faint, below the Fermi-LAT sensitivity threshold, for the rest of the time. A multifrequency campaign of 3C 111, ongoing in the same period, revealed an increase of the millimeter, optical, and X-ray fluxes in 2008 September–November, interpreted by Chatterjee et al. as due to the passage of a superluminal knot through the jet core. The temporal coincidence of the millimeter–optical–X-ray outburst with the GeV activity suggests a cospatiality of the events, allowing, for the first time, the localization of the $\gamma$-ray dissipative zone in an FRII jet. We argue that the GeV photons of 3C 111 are produced in a compact region confined within 0.1 pc and at a distance of about 0.3 pc from the black hole.

Key words: galaxies: active – galaxies: jets

Online-only material: color figures

1. INTRODUCTION

The Large Area Telescope (LAT) on board the Fermi $\gamma$-ray satellite (Atwood et al. 2009) has recently detected a handful of misaligned active galactic nuclei (MAGNs), i.e., radio galaxies (RGs) and steep spectrum radio quasars (Abdo et al. 2010a). In spite of their small number, these $\gamma$-ray emitters are extremely appealing sources, as they offer a different perspective to approach the high-energy phenomena.

For example, the study of the spectral energy distribution (SED) of misaligned FRI RGs such as NGC 1275 (Abdo et al. 2009a), M87 (Abdo et al. 2009b), and NGC 6251 (Migliori et al. 2011) has clearly evidenced the difficulty of the one-zone homogeneous synchrotron self-Compton model (SSC) in describing the jet emission within the AGN unified scheme. The SED modeling required low Lorentz factors ($\Gamma \lesssim 3$), implying bulk velocities of the RG jets much lower than typical values found in BL Lac objects (BLs). This is in contrast with the idea that blazars and MAGNs are the same kind of source, only characterized by a different inclination angle of the jet (Urry & Padovani 1995). As suggested by several authors (Georganopoulos & Kazanas 2003; Ghisellini et al. 2005; Giannios et al. 2010), this difficulty can be resolved if the hypothesis of a one-zone homogeneous emitting region is relaxed and a structured jet is assumed. In these models, an efficient (radiative) feedback between different zones at different velocities can reconcile the apparent FRI–BL discrepancy. In the MAGN sample detected by the Fermi-LAT, there is a clear predominance of nearby RGs with FRII morphology. High power radio sources (i.e., FRIIs) with GeV emission are rare. 3C 111 is indeed the only FRII RG of the sample with a secure $\gamma$-ray association. The rarity of $\gamma$-ray counterparts of FRIIs could be due to intrinsic jet differences (Grandi 2011).

The exact localization of the $\gamma$-ray emitting region is however still an open problem. Fast GeV flux variations, observed on timescales of hours to days (Abdo et al. 2010c), have unambiguously attested to the compact nature (but not the localization) of the $\gamma$-ray source in blazars. Very recently, Agudo et al. (2011a, 2011b) claimed that multiwavelength outbursts, observed in two BLs, i.e., OJ 287 and AO 0235+164, can occur in different zones along the jet, in the stationary core as well as in knots, even at larger distances (>14 pc) from the black hole. Furthermore, in the flat-spectrum radio quasar PKS 1510–089, the complexity of the radio to $\gamma$-ray variability was interpreted as being due to different events occurring along the jet as a knot propagates (Marscher et al. 2010). Constraining the black hole–$\gamma$-ray source distance is a critical issue. Indeed, it has a strong impact on the physical models invoked to explain the high-energy emission (Tavecchio et al. 2011).

In RGs, the situation is even more complicated. Time variability is difficult to detect at GeV energies because of poor statistics. In addition, the discovery of $\gamma$-ray emission from the radio lobes of Centaurus A shows that GeV photons can also originate from extended structures (Abdo et al. 2010d). In only one case, the FRI RG NGC 1275, flux variations on timescales of months were clearly detected in the LAT light curves (Abdo et al. 2010a; Kataoka et al. 2010) allowing the compact nature (but not the localization) of the $\gamma$-ray emitting region to be asserted. Only in the case of the FRII RG M87, some clues on the location were provided by the very high energy (VHE) photons, detected by the ground-based Cherenkov telescopes (Aharonian et al. 2003, 2006; Aìcari et al. 2008; Albert et al. 2008). The TeV flare in 2005 was simultaneous to a strong X-ray burst associated with the innermost knot in the jet (Harris et al. 2006). In 2008, the coincidence of the VHE and radio flares, monitored with the Very Long Baseline Array (VLBA), confined the VHE photon production within 10 Schwarzschild radii (Aìcari et al. 2009). A subsequent TeV flare in 2010 was related to a flux increase of the core in X-rays (Raue et al. 2011). The difficulty in the data interpretation does not allow an unequivocal spatial identification of the emitting region.

In this Letter, we present the first localization of a $\gamma$-ray flare in an FRII RG. The source, 3C 111, was observed by Fermi in
Figure 1. Left panel: LAT light curve of 3C 111 covering the first 2 years of survey (from 2008 August 4 to 2010 August 4), considering a bin time of 2 months. The source was only detected in 2008 October–November. Right panel: 1 month light curve from 2008 August to 2009 January (lower box) and corresponding test statistic for each time interval (upper box). The source is detected with a $\text{TS} = 9.7 \sim 3\sigma$ only in 2008 October.

Figure 2. Millimeter (230 GHz), optical (R), X-ray (2.4–10 keV), and $\gamma$-ray (0.1–100 GeV) light curves. The original millimeter–optical–X-ray data are from CH11. A detailed study of the correlation among the different light curves is also presented in the same paper. The black arrow indicates the time when the radio knot was ejected by the core. (A color version of this figure is available in the online journal.)

2. THE 3C 111 $\gamma$-RAY FLARE

2.1. The Source

3C 111 ($z = 0.0491$; Eracleous & Halpern 2004), optically classified as a broad-line radio galaxy (BLRG), shows a typical FRII morphology. It exhibits radio lobes, a strong core and a prominent 120$''$ one-sided jet, terminating in the hot spot of the northeast lobe (Linfield & Perley 1984). At a distance of 196 Mpc, the linear extension of the jet is 114 kpc ($1'' = 948$ pc) in projection, assuming $H_0 = 71$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.27$, and $\Omega_\Lambda = 0.73$. VLBA observations reveal a one-sided core–jet structure characterized by an intrinsic half opening angle $\phi \sim 3^\circ$ and an inclination angle $\theta \sim 18^\circ$ (Jorstad et al. 2005). The milliarcsecond (mas) jet contains multiple superluminal components with apparent velocities $\beta_{\text{app}} = 2$–6 (Kadler et al. 2008), ejected approximately every 5 months from the core (Jorstad et al. 2005). The accretion disk of this source is very efficient in converting gravitational power into radiation, as attested by the presence of an iron K$\alpha$ line detected by several X-ray satellites (Lewis et al. 2005; CH11; Ballo et al. 2011).

3C 111 was one of the few sources in the MAGN sample proposed as a possible $\gamma$-ray counterpart of an EGRET detection (Hartman et al. 2008 and references therein) and subsequently confirmed by Fermi. In the first LAT catalog of AGNs (1LAC; Abdo et al. 2010b), based on 11 months of data, the source was associated with the low-latitude $\gamma$-ray source 1FGL J0419.0+3811 (detection significance $\sigma = 4.3$) with a high probability ($P = 87\%$). 3C 111 was still detected with a similar significance after 15 and 24 months of survey (Abdo et al. 2010a; Kataoka et al. 2011). It is not listed in the second LAT AGN catalog (Ackermann et al. 2011), where only sources with a detection $\geq 5\sigma$ are included. Indication of possible time variability was first suggested by Hartman et al. (2008). They noted that the source only occasionally became bright ($F_{100} > 10^{-7}$ phot cm$^{-2}$ s$^{-1}$) and detectable by EGRET, suggesting a low duty cycle for the $\gamma$-ray emission. The Fermi light curve, based on 15 months of data, revealed a similar behavior. 3C 111 was detected with a significance larger than $3\sigma$ only in 2008 August–November (Abdo et al. 2010a).

2.2. The 24 Month $\gamma$-Ray Light Curve

Taking advantage of the recent improvement of the instrument response functions (IRFs) and the background models, we produced a new 0.1–100 GeV light curve of 3C 111 from 2008 August to 2010 August using a bin time of 2 months. The
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Figure 3. VLBA images (43 GHz) at four epochs, mapping the emergence of a new knot from the radio core. The different jet components are shown as crosses (delta profile), circles (circular Gaussian profile), and ellipses (elliptical Gaussian profile). The sequence shows the appearance of a new component (blue filled circle) in 2008 November that is clearly separated from the core (red filled circle) in 2008 December and 2009 January.

(Fermi-LAT ScienceTools software (version v9r23p1) was used with the P7SOURCE_V6 set of IRFs. The time intervals when the rocking angle of the LAT was greater than 52° were rejected and a cut on the zenith angle of γ-rays of 100° was applied. The model for which we calculated a binned likelihood is the combination of point-like and diffuse sources located within a region of interest (RoI) having a radius of 15° and centered on 3C 111. For each point-like source the spectral slope was frozen to the best-fit value provided by the Fermi-LAT Second Source Catalog (2FGL; Nolan et al. 2012). The RoI model also includes sources falling between 15° and 20° from the target source, which can contribute to the total counts observed in the RoI due to the energy-dependent size of the point-spread function of the instrument. For these additional sources, normalizations were also fixed to the values of the 2FGL catalog. The spectral model used for 3C 111 is a power law \( F = kE^{-\Gamma} \) with the spectral slope fixed to the value reported in the 1LAC paper, \( \Gamma = 2.6 \pm 0.2 \). Note that the \( \Gamma \) uncertainties have very negligible effect on the flux calculation. A Galactic emission model (gal_2yearp7v6_v0.fits) and an extragalactic and instrumental background (isotrop_2year_P76_source_v0.txt) were used to model the background. We evaluated the significance of the detection given by the test statistic (TS) = 2Δlog (likelihood) between the models with and without the source (Mattox et al. 1996). When the TS was less than 10, the bin flux value at \( F > 0.1 \text{GeV} \) was replaced by a 2σ upper limit, calculated by finding the point at which 2Δlog (likelihood) = 4 when increasing the flux from the maximum-likelihood value.

The 24 month light curve confirms the high state of 3C 111 in late 2008 (Figure 1, left panel): the source appears to spend not more than 2 months flaring and then drops below the LAT sensitivity threshold. In order to better constrain the γ-ray flare shape, a denser LAT time sampling from 2008 August to December was then performed. A light curve was...
generated by dividing the time interval into bins of 1 month duration and repeating the likelihood analysis for each interval (Figure 1, right panel). The source is detected with a significance of \( \sim 3\sigma \) (TS = 9.7) only on one occasion, indicating that the GeV flare peaked between October 4 and November 4. It is probable that the major \( \gamma \)-ray activity was at the beginning of October. A likelihood analysis performed using a sampling of only 15 days shows that the largest test statistic value (TS = 7) is observed between October 4 and 19.

2.3. Localization of the \( \gamma \)-Ray Dissipation Region

As a multiwavelength campaign of 3C 111 (CH11) was ongoing in the same period monitored by LAT, it was possible to compare the \( \gamma \)-ray data with millimeter–optical–X-ray light curves (Figure 2). The simultaneity of the flare is impressive: the source luminosity was increasing from millimeter to X-ray frequencies exactly when the greatest flux of \( \gamma \)-ray photons occurred. This is a clear indication of the cospatiality of the event. As attested by the TeV-radio campaigns organized for the RG M87 (Acciari et al. 2009), a fruitful approach to identify the zone where high-energy photons are produced is to follow the jet dynamics at mas scales. We therefore investigated the VLBA images at 43 GHz made available by the blazar research group at Boston University\(^3\) and discussed in CH11. Looking at Figure 6 of CH11, it appears evident that a deep modification of the core–jet system took place in late 2008. As deduced by the same authors, on October 29 (with an uncertainty of \( \sim 26 \) days) a new component was ejected from the stationary core. In order to quantify the jet dynamics, we analyzed the VLBA images at four epochs, before (2008 September) and after (2008 November–December, 2009 January) the appearance of the new blob. To minimize the free parameters, the model fitting of the \((u, v)\) data were performed with DIFMAP (Shepherd 1997) using the simplest models (i.e., delta, circular Gaussian, elliptical Gaussian). The model components were added to the residual images with a restored beam size of 0.1 mas (Figure 3). This is the angular resolution in the direction of the jet propagation, obtained with a suitable weighting of the visibilities. The brightest component was identified as the stationary core, while the westernmost component, at a distance of \( \sim 0.1 \) mas from the core, was associated with a possible counterjet. The new knot was emerging in November and appears clearly separated from the core in the successive epochs. It is beyond the aim of this Letter to attest to the real nature of the westernmost feature. However, we note that our analysis of eight epochs, from 2008 June to 2009 February, indicates that the candidate counterjet does not show any significant systematic displacement. In the assumption that the counterjet is stationary with respect to the core, we can estimate the position errors from its position scatter. Using the mentioned eight epochs, the scatter is 0.005 mas. The flux densities of the different jet components, when close to each other, are difficult to disentangle even with the model fitting procedure used here. For this reason, we preferred to follow the core evolution, considering the variation of the total flux density, including the contribution of the stationary feature, the counterjet and, when separated, the new ejected knot. In 2009 January, a small component between the head of the ejected blob and the core is evident. Its flux was also included, given the difficulty in establishing its nature. It could be a new emerging knot or simply a disruption/elongation of the component ejected in 2008 (see also Großberger et al. 2012). The speed of the knot, considering the blob–core distance at three different epochs (2008 November–2009 January), is 1.07 ± 0.05 mas yr\(^{−1}\) (\( \beta_{\text{app}} = 3.3c \)) and the ejection time, obtained by extrapolating the linear (core–knot distance versus time) fit, is \( T_0 = 2008.80 ± 0.01 \). Our \( T_0 \) is in agreement, within the uncertainties, with the value of CH11, while our \( \beta_{\text{app}} \) is smaller, because we considered only three epochs closest to the ejection. It is interesting to note that, assuming an inclination angle of 18\(^{\circ}\) and apparent velocity \( \beta_{\text{app}} = 3.3c \), the arm length ratio\(^4\) is about 20. As a consequence, the observed approaching components extending \( \sim 2 \) mas from the core (Figure 3) should be compressed to \( \sim 0.1 \) mas on the receding side. This latter value is consistent with the unresolved size of the counterjet in the VLBA images.

The light curve of the core is shown in Figure 4. The brightness increases from August to November, following the evolution of the multiwavelength flare (Figure 2), then decreases when the new radio component becomes visible (Figure 3).

Finally, we note that two other knots could have been ejected by the core at the beginning of 2009 (CH11). These minor events caused no significant amplification of the GeV radiation. It seems that only exceptional jet perturbations can boost the gamma-ray flux above the LAT sensitivity threshold.

3. CONCLUSIONS

Marscher et al. (2002) in an enlightening paper on the RG 3C 120 noted that a dip in the X-ray light curve is generally associated with an expulsion of a bright superluminal radio knot. It was suggested that, as in microquasars, the inner regions of an efficient accretion disk could be accelerated, causing a shock front streaming along the jet.

3C 111 is quite similar to 3C 120. They are both BLRGs probably hosting a disk–corona system (Haardt & Maraschi 1991). CH11, exploring the radio, optical, and X-ray light curves of 3C 111 noted, also for this source, a strong suppression of X-rays followed by the appearance of a new component in the high-resolution radio maps. They interpreted the flux

\[ Q = d_1/d_2 = (1 + \beta \cos(\theta))/(1 - \beta \cos(\theta)), \]

where \( \beta \) is the bulk jet velocity in units of the speed of light (Longair & Riley 1979).

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\(^3\) http://www.bu.edu/blazars/

\(^4\) The arm length ratio is the ratio between the apparent length of the approaching (\( d_1 \)) and receding (\( d_2 \)) jets, defined as...
increase, quasi-simultaneously observed at millimeter–optical and X-ray frequencies after the dip, as the passage of a new knot through the jet stationary core (see also Bell & Comeau 2011 for a different interpretation). Incidentally, we note that the Suzaku X-ray satellite observed 3C 111 before the flare, during the dip, on 2008 August 22, and XMM-Newton observed it after the blob ejection in 2009 February 15 (Ballo et al. 2011; Torresi 2012). As expected, there is a difference in the 2–10 keV flux by about a factor two between the observations. An absorption blueshifted feature, associated with the resonant Fe XXVI Lya transition, was revealed by Suzaku but not by XMM-Newton. This absorption line could originate in a fast disk wind (Ballo et al. 2011 and references therein). If this detection will be confirmed, the episodic presence of hard X-ray absorption features could represent a signature of an ongoing disk–jet perturbation.

Our analysis of 24 months of Fermi data reveals that the production of GeV photons is related to these phenomena. First of all, the short time interval of 3C 111 detectability (Δt ∼ 30–60 days) by the LAT denotes the compactness of the emitting region. Causality arguments show that it cannot be larger than R < Δt/c < 0.1 pc, if a Doppler factor of δ ∼ 3 (Jorstad et al. 2005) is assumed. This immediately allows us to exclude the radio lobes as the main source of γ-rays. Note that assuming an extreme time variability of 15 days reduces the radial extent to 0.04 pc. In addition, 3C 111 was detected by the LAT exactly when the millimeter, optical, and X-ray fluxes were rising. The temporal coincidence of the millimeter–optical, X-ray, and γ-ray flares unambiguously implies a cospatiality of the event. Since the outburst of photons is directly connected to the ejection of a new radio knot, it is natural to localize the γ-ray source in the radio core region, the size of which cannot be larger than 0.3 pc, corresponding to the VLBA angular resolution of ~0.1 mas.

The distance between the stationary radio structure and the black hole (δbh−c) is unknown. However, a weak VLBA feature is seen at a distance of ~0.1 mas from the core (δc−q), just on the opposite side of the ejected bright knot. If this is the counterjet, as we suggest, the black hole necessarily lies within 0.1 mas (i.e., δbh−c < δc−q). As a consequence, the distance of the γ-ray dissipation region from the central engine has to be of the same order of magnitude or slightly larger depending on the position of the γ-ray source with respect to the counterjet. This black hole–γ-ray source distance (~0.1 mas corresponding to 0.3 pc) is surely a conservative upper limit. Indeed, a recent estimate of the separation between the black hole and the base of the jet in the RG M87 (Hada et al. 2011) indicates shorter distances between these components: the stationary core seems to be at not more than about 20 Schwarzschild radii from the central engine.

The Fermi-LAT Collaboration acknowledges generous on-going support from a number of agencies and institutes that have supported both the development and the operation of the LAT as well as scientific data analysis. These include the National Aeronautics and Space Administration and the Department of Energy in the United States; the Commissariat à l’Energie Atomique and the Centre National de la Recherche Scientifique/Institut National de Physique Nucléaire et de Physique des Particules in France; the Agenzia Spaziale Italiana and the Istituto Nazionale di Fisica Nucleare in Italy; the Ministry of Education, Culture, Sports, Science and Technology (MEXT), High Energy Accelerator Research Organization (KEK), and Japan Aerospace Exploration Agency (JAXA) in Japan; and the K. A. Wallenberg Foundation, the Swedish Research Council, and the Swedish National Space Board in Sweden.

Additional support for science analysis during the operations phase is gratefully acknowledged from the Istituto Nazionale di Astrofisica in Italy and the Centre National d’Études Spatiales in France.

The authors are very grateful to the blazar research group at the Boston University, who have made all the multwavelength data of the 3C 111 campaign available. The authors also thank D. Bastieri, G. Tosti, J. Finke, and M. Kadler for useful discussions. E.T. acknowledges the Italian Space Agency for financial support (contract ASI/GLAST/1/07/0).

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