Radio Flaring Activity of 3C 345 and its Connection to γ-Ray Emission

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Abstract. 3C 345 is one of the archetypical active galactic nuclei, showing structural and flux variability on parsec scales near a compact unresolved radio core. During the last 2 years, the source has been undergoing a period of high activity visible in the broad spectral range, from radio through high-energy bands. We have been monitoring parsec-scale radio emission in 3C 345 during this period at monthly intervals, using the VLBA at 15, 24, and 43 GHz. Our radio observations are compared with gamma-ray emission detected by Fermi-LAT in the region including 3C 345 (1FGL J1642.5+3947). Three distinct gamma-ray events observed in this region are associated with the propagation of relativistic plasma condensations inside the radio jet of 3C 345. We report on evidence for the gamma-rays to be produced in a region of the jet of up to 40 pc (de-projected) in extent. This suggests the synchrotron self-Compton process as the most likely mechanism for production of gamma-rays in the source.

1. Introduction

The quasar 3C 345 is one of the best studied “superluminal” radio sources, with its parsec-scale radio emission monitored over the past 30 years. Substantial variability of the optical (Babadzhanyants & Belokon 1984; Kidger & Takalo 1990) and radio (Aller et al. 1996; Terasranta et al. 1998; Lobanov & Zensus 1999) emission has been observed, with a possible periodicity of 3.5–4.5 years and major flares occurring every 8–10 years. A new cycle of such enhanced nuclear activity began in early 2008 (Larionov et al. 2009).

3C 345 has also been known as a prominent variable source at high energies up to the X-ray band and only in the γ-ray regime had it not been clearly detected (Casandjian & Grenier 2008), possibly due to the low spatial resolution of previous γ-ray instruments and a lack of space instruments during periods of high source activity. The launch of the GLAST satellite (now Fermi) equipped with the Large Area Telescope (LAT) survey instrument (Atwood et al. 2009) enabled continuous monitoring of γ-ray emission originating from the vicinity of 3C 345.

This paper presents first results from an analysis of Fermi/LAT γ-ray monitoring data, combined with monthly radio observations made at 43.2 GHz (7 mm wavelength) with very long baseline interferometry (VLBI), using the VLBA facility.

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Throughout this paper, a flat ΛCDM cosmology is assumed, with $H_0 = 71 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and $\Omega_M = 0.27$. At the redshift $z = 0.593$ (Schneider et al. 2007) of 3C 345, this corresponds to a luminosity distance $D_L = 3.47 \text{ Gpc}$, a linear scale of 6.64 pc mas$^{-1}$, and a proper motion scale of 1 mas year$^{-1}$ corresponding to 34.5 c.

2. Observations & Data Processing

2.1. Fermi/LAT

The 11-month all-sky γ-ray monitoring by the Fermi/LAT instrument lists a strong detection of a γ-ray emitter in the region 1FGL J1642.5+3947 (Abdo et al. 2010a), which lies in the close vicinity of the three quasars 3C 345 (~6.4′ away from γ-ray localization) CLASS J1641+3935 (~17′ away) and NRAO 512 (~31′ away). The three month bright AGN list mentions the source 0FGL J1641.4+3939 (Abdo et al. 2009a) as being associated with the faint blazar CLASS J1641+3935 with low probability. However, the 1FGL source is now more convincingly associated with 3C 345 and not the faint CLASS source, albeit still formally at a low-probability.

The angular resolution (at a 68% confidence) of the Fermi/LAT instrument is about 0.8′ for single photons at 1 GeV energy and it is worse at other energies (Atwood et al. 2009), thus making it difficult to obtain a significant association with any source in this particular field, based on the γ-ray data alone. The statistical analysis shows that a majority of the received photons are located closer to 3C 345 than to the other two sources. Contribution by the other two candidates seems to be minor. A firm association of 1FGL J1642.5+3947 with 3C 345 can only be established with the inclusion...
of multi-wavelength observations. A detailed description of the maximum likelihood analysis as well as a thorough discussion of the γ-ray data will be given in a forthcoming Fermi/LAT collaboration paper on the γ-ray detection and multi-wavelength identification of 3C 345 (Schinzel et al. 2010).

From the available Fermi/LAT data, a weekly light curve was constructed for the first 14 months of LAT observations using the Fermi Science Tools software package release v9r15p2 (08/08/2009). The procedures applied were similar to the one described in Abdo et al. (2009a) using the current instrument response function P6_V3, isotropic background model v02, and Galactic diffuse background models as discussed in Abdo et al. (2009b). The sources Mrk 501 and 4C +38.41 have been included in the source model for the region of interest using a powerlaw spectral fit with photon spectral energy index of around 1.79 and 2.66 respectively. For the target source 3C 345, a fixed photon index of 2.46 was applied to obtain weekly averaged flux values from the modelfits. The resulting 0.1–300 GeV lightcurve of 3C 345 is shown in the top panel of Fig. 1.

2.2. VLBA

Following the onset of a new period of flaring activity in 2008, we initiated a dedicated monthly VLBA monitoring of radio emission from 3C 345 at 43.2, 23.8, and 15.4 GHz (VLBA project codes: BS193, BS194). In this paper only the 43.2 GHz observations are discussed, while the analysis of 15.4 and 23.8 GHz data is continued. The observations were made with a bandwidth of 32 MHz (total recording bit rate 256 Mbit s⁻¹). The total of 12 VLBA observations have been completed, with about 4.5 hours at 43.2 GHz spent on 3C 345 during each observation. Scans on 3C 345 were interleaved with observations of J1310+3233 (amplitude check, EVPA calibrator), J1407+2827 (D-term calibrator), and 3C 279 (amplitude check, EVPA calibrator). The VLBA data were correlated at the NRAO VLBA processor. Analysis was done with the NRAO Astronomical Image Processing System (AIPS) and Caltech Difmap (Shepherd et al. 1995) software for imaging and modeling. Corrections were applied for the parallactic angle and for Earth orientation parameters used by the VLBA correlator. Fringe fitting was applied to calibrate the observations for group delay and phase rate. A summary of all the observations is presented in Table 1. The data from the first 10 epochs of the projects BS193 and BS194 are complemented with 14 VLBA observations from the blazar monitoring program of Marscher et al. (VLBA project codes BM256, BM303, S1136) available online. The combined data (see Table 1) were made with a bandwidth of 32 MHz (total recording bit rate 256 Mbit s⁻¹) and 32 MHz (total recording bit rate 256 Mbit s⁻¹).

The brightness distribution of the radio emission was model-fitted by multiple Gaussian components, providing positions, flux densities and sizes of distinct emitting regions in the jet. Fig. 2 illustrates the observed radio structure and its Gaussian model fit representation. Compact emission in the nuclear region (≤0.15 mas from the VLBI core) was modelled using two circular Gaussians providing the optimal ratio of \(\chi^2\) to the number of model parameters for all epochs.

We interpret the eastern-most component, hereafter labeled Q0, as the base (or “core”) of the radio jet at 43.2 GHz, whereas the other features can signify perturbations or shocks developing in the jet. Locations and proper motions of other jet features are then determined with respect to Q0.

3. Results

3.1. Evolution of the radio emission in the nuclear region

A new moving emission region, labeled Q9, was first detected with the VLBA observation on June 16, 2008, followed by detections of another new component on January 24, 2009 (Q10) and a third one on July 27, 2009 (Q11). In the following, the components Q9, Q10, and Q11 observed within a distance of ≤0.3 mas from the core Q0 are referred to as the “jet”.

The flux density evolution of the jet is plotted in the lower part of Fig. 1 together with the flux densities of the core and the sum of jet and core. During 2009, the jet (average flux density: 3.6 Jy) was stronger than the core (average flux density: 1.5 Jy) by a factor of 2.4.

The photon spectral index \(\alpha\) is defined as \(F(E) \propto E^{-\alpha}\), where \(F(E)\) is the γ-ray photon flux as function of energy \(E\).
Table 1. Summary of 43 GHz VLBA Observations.

| Date       | S^\text{tot}_D | D      | Beam (bpa)          | Ref. |
|------------|----------------|--------|---------------------|------|
| 2008-01-17 | 1.90           | 2300   | 0.31\times10^{-19} (27) | 1    |
| 2008-02-29 | 2.02           | 1600   | 0.37\times10^{-21} (29) | 1    |
| 2008-06-12 | 2.44           | 2100   | 0.38\times10^{-16} (28) | 1    |
| 2008-07-06 | 2.23           | 800    | 0.33\times10^{-15} (17) | 1    |
| 2008-08-16 | 3.78           | 2700   | 0.41\times10^{-19} (30) | 1    |
| 2008-09-10 | 3.67           | 4300   | 0.37\times10^{-19} (33) | 1    |
| 2008-11-16 | 4.43           | 300    | 0.37\times10^{-33} (1.5) | 1    |
| 2008-12-21 | 2.91           | 5500   | 0.39\times10^{-17} (17) | 1    |
| 2009-01-24 | 5.04           | 8900   | 0.31\times10^{-17} (21) | 1    |
| 2009-02-19 | 3.55           | 2200   | 0.37\times10^{-20} (19) | 1    |
| 2009-02-22 | 4.63           | 8800   | 0.35\times10^{-15} (19) | 1    |
| 2009-03-16 | 6.01           | 2400   | 0.43\times10^{-30} (9.3) | 2    |
| 2009-04-01 | 5.67           | 8000   | 0.33\times10^{-16} (19) | 1    |
| 2009-04-21 | 5.78           | 2600   | 0.33\times10^{-22} (17) | 2    |
| 2009-05-27 | 7.00           | 3500   | 0.33\times10^{-15} (15) | 2    |
| 2009-05-30 | 8.65           | 6900   | 0.32\times10^{-16} (20) | 1    |
| 2009-06-21 | 5.04           | 6500   | 0.38\times10^{-16} (11) | 1    |
| 2009-06-29 | 6.43           | 2600   | 0.29\times10^{-16} (12) | 2    |
| 2009-07-27 | 7.63           | 2900   | 0.38\times10^{-31} (31) | 1    |
| 2009-09-26 | 6.58           | 2000   | 0.32\times10^{-17} (25) | 2    |
| 2009-10-01 | 6.67           | 2300   | 0.22\times10^{-18} (22) | 2    |
| 2009-11-07 | 6.38           | 1400   | 0.32\times10^{-15} (15) | 2    |
| 2009-11-30 | 5.53           | 2000   | 0.29\times10^{-16} (17) | 2    |
| 2009-12-28 | 4.95           | 2400   | 0.31\times10^{-16} (8.1) | 2    |

Notes: S^\text{tot}_ = total flux density recovered in VLBA image; D = dynamic range measured as a ratio of the image peak flux density to the r.m.s. noise; Beam (bpa) = beam size, major axis vs minor axis with position angle of ellipse in parenthesis; References: 1 = blazar monitoring Marscher et al. (VLBA project code BM256, BM303, S1136); 2 = dedicated monitoring (VLBA project codes BS193, BS194). † = not used for the flux density analysis due to gain calibration problems and bad weather conditions at some of the VLBA antennas.

Relative positional offsets of components Q10, Q9, and Q8 are measured with respect to the base of the jet at component Q0. All three features follow a similar trajectory; however, curiously, the recently detected Q11 shows a northward offset of 0.025 mas (~1/7th of the beamsize) in its trajectory, compared to the previous features. This should be verified by continued radio monitoring of the jet.

All newly ejected jet features show similar apparent acceleration from about 2 - 10 c over a distance of 0.2 mas.

3.2. γ-Ray Emission

The weekly binned light curve plotted in Fig. 1a., shows six distinct events above 2.4 \times 10^{-7} \text{ph cm}^{-2} \text{s}^{-1}.

The six events are split into two sub-categories according to their duration. Long events, with durations of 40 - 60 days, are labeled with roman capitals; shorter events, with durations of 20 - 35 days, are labeled with arabic numbers. These sub-categories can also be distinguished by their peak fluxes: the long events had peak flux values of (3.86 - 5.19) \times 10^{-7} \text{ph cm}^{-2} \text{s}^{-1}, whereas short events ended up with a lower range of (2.48 - 3.19) \times 10^{-7} \text{ph cm}^{-2} \text{s}^{-1}.

Flare III has been reported on previously in the form of two Astronomers Telegrams by the Fermi/LAT (Reyes & Cheung 2009) and GASP collaborations (Larionov et al. 2009), reporting on mm-wavelength (230 GHz SMA), optical (R-Band) and γ-ray (GeV) activity.

3.3. Radio/γ-ray Correlation

A first look at the γ-ray light curve (Fig. 3a) gives the impression of a rising underlying trend in the γ-ray emission similar to the one observed in radio.

The radio and γ-ray light curves were “de-trended” using cubic spline interpolations with 0.5 year bins (Press et al. 1992). Remarkably, as shown in Fig 3, the jet matches the long-term trend of the γ-rays. A mismatch of the first 0.5 year results from the absence of γ-ray data before 2008.6 and a secondary weaker γ-ray flare after 2008.7 (see Fig. 1b) which contributes to the flux level at 2008.8 causing a slightly higher starting flux. The core showed no to little variation in flux density over this time period, with an average value around 1.5 Jy.

A discrete correlation as described by Edelson & Krolik 1988 was applied to the re-scaled with their respective average values and de-trended light curves with the obtained cubic splines fits. No strong correlation is evident, either for the jet or for the core, after de-trending. However, the jet shows a weak correlation with a coefficient of 0.6 ± 0.3 at timelag 3 ± 15 days and a weak anti-correlation in the following bin of −0.6 ± 0.3.

Sparse sampling of the radio data makes it difficult to obtain firm specific localizations of individual events in the radio jet. Nonetheless, the similarity of the long-term
Fig. 3. Long-term trends of the radio jet, radio core flux densities and the γ-ray flux relative to their respective mean values (jet: 3.6 Jy, core: 1.5 Jy, γ: 1.9 \times 10^{-7} \text{ ph cm}^{-2} \text{ s}^{-1})). The trend has been obtained using splines with 0.5 year bins. γ-ray and radio light curves between 2009.8 and 2010.0 have been re-scaled. The 0 value represents the mean value of 3.60 Jy for the radio flux density of the jet of an apparent size of \lesssim 2 pc (excluding the core), 1.5 Jy for the flux density of the core of an apparent size of \sim 0.3 pc and 1.9 \times 10^{-7} \text{ ph cm}^{-2} \text{ s}^{-1} for γ-rays.

The trends observed in the lightcurves provides good evidence for correlated underlying emission between the radio flux density of the jet and the γ-ray flux.

4. Summary & Conclusions

We have found a correspondence between the long-term Fermi-LAT lightcurve of the region 1FGL J1642.5+3947 and the radio emission of 3C 345, establishing the detection of γ-ray emission from 3C 345 by comparison of radio and γ-ray variability.

More importantly, we find γ-ray emission to be related to the pc-scale jet of the source of up to 2 pc (\sim 40 pc de-projected adopting a viewing angle of \theta \sim 2.7\degree; Jorstad et al. 2005). We have been able to trace back the ejection of new superluminally moving and apparently accelerating features in the jet to be linked to γ-ray production. Even though a correspondence between the jet and γ-ray emission was found, there is no evidence for correlation between γ-ray emission and radio core flux density at 43 GHz. The observed radio properties of these features together with the observed γ-ray variability question existing jet models and suggest the synchrotron self-Compton (SSC) process as the most likely mechanism driving the production of γ-ray photons in the source. This conclusion is supported by the spectral energy distribution of 3C 345 being compatible with SSC exhibiting an IC to synchrotron peak ratio of only \sim 5 (for the Oct. 2009 flare).

Continued monitoring and more densely sampled VLBI observations could provide better confirmation of our results and provide an opportunity to localize more accurately the sites of individual flares in the jet. At this writing, the nuclear region of 3C 345 remains at high flux density and γ-ray flux levels are still elevated. The characteristics of the long-term activity of the source as observed over the last 30 years suggest that this continued activity may last for at least another year, giving a unique opportunity to trace this active state.

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