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Does the gamma-ray flux of the blazar 3C 454.3 vary on subhour time-scales?

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ABSTRACT

In the early days of 2010 April, the blazar 3C 454.3 ($z = 0.859$) underwent a strong γ-ray outburst, reaching fluxes ($E > 100$ MeV) in excess of 10^{-5} photon cm^{-2} s^{-1}. The *Fermi Gamma-ray Space Telescope* performed a 200 ks long pointed observation starting from 2010 April 5 19:38 UTC. This allowed us to try probing the variability of the γ-ray emission on time-scales of hours or less. We found the variability on a few hours time-scale. On subhour time-scale we found no evidence of significant variability, although the present statistics is not yet conclusive and further observations are needed.

Key words: galaxies: jets – quasars: individual: 3C 454.3 – gamma-rays: galaxies.

1 INTRODUCTION

Blazars are one type of active galactic nuclei with relativistic jet. The small viewing angle of the jet makes it possible to observe strong effects of the special relativity, such as a boosting of the emitted power and a shortening of the characteristic time-scales. Although the variability in blazars has been observed at all the frequencies (see e.g. the reviews by Ulrich, Maraschi & Urry 1997; Wagner 2008), the part at high energies deserves a specific interest, since most of the bolometric power of these sources is emitted at γ-rays.

The shortest time-scales measured by the Energetic Gamma-ray Experiment Telescope (EGRET) onboard the *Compton Gamma-ray Observatory* are ∼4 h for PKS 1622−29 (Mattox et al. 1997) and 8 h for 3C 279 (Wehrle et al. 1998). Early results from the Large Area Telescope (LAT) onboard the *Fermi Gamma-ray Space Telescope* (hereafter *Fermi*) indicated similar results: from about half-day for PKS 1454−354 (Abdo et al. 2009a) and PKS 1502+106 (Abdo et al. 2010a) to 5–6 h in the cases of 3C 454.3, PKS B1510−089 (Tavecchio et al. 2010) and 3C 273 (Abdo et al. 2010b).

These time-scales are in agreement with the common paradigm that the characteristic spatial scale of the emitting region is of the order of the gravitational radius $r_{\rm g} = GM/c^2$ of the central space–time singularity (Begelman, Fabian & Rees 2008). The zone where most of the dissipation occurs is located at distances greater than $\Gamma^2 r_{\rm g}$, where Γ is the bulk Lorentz factor (for most blazars $\Gamma \sim 10$; see Ghisellini et al. 2010). The size of the emitting region is in turn linked to the variability time $t_{\rm var}$ by the relationship $R < ct_{\rm var}\delta\,(1 + z)$ (where δ is the Doppler factor). Obviously, it is expected that $R > r_{\rm g}$. Moreover, the emitting region must be optically thin and sufficiently far from the central black hole to allow the γ-rays to escape, otherwise they convert into electron–positron pairs.

An order-of-magnitude estimation of the above parameters results in an overall agreement with the observed variability on scales of days–hours. However, the recent detection by the ground-based Cerenkov telescopes (HESS and MAGIC) of fast variability (minutes time-scale) at γ-rays in some TeV BL Lac objects severely threatens the above scenario. In 2006, during an exceptional outburst (average flux seven Crab with peaks of more than 14 Crab), PKS 2155−304 displayed variability with doubling flux time-scale of about 200 s (Aharonian et al. 2007). In 2005, Mrk 501 changed its flux within a few minutes (Albert et al. 2007). Given the masses of these two blazars of the order of 10^9 M$_\odot$, the measured variability is more than one order of magnitude smaller than the minimum allowed. Several solutions have been proposed, from a ‘simple’ increase of the Doppler factor ($\delta > 50$) to invoking an internal structure of the jet (Begelman, Fabian & Rees 2008; Ghisellini & Tavecchio 2008; Giannios, Uzdensky & Begelman 2009).

As noted by Begelman et al. (2008), while these explanations could fit reasonably with BL Lac subclass of blazars, the same is not appropriate for flat-spectrum radio quasars (FSRQ) subclass. Indeed, these type of blazars generate γ-rays by inverse Compton on a population of seed photons external to the jet (external Compton). Therefore, the pair photosphere can be at fairly large distances ($>10^4 r_{\rm g}$), which in turn means that the blob has a size so large to determine an insufficient energy density to develop strong and fast flares.

It is evident that the search for subhour time-scales in FSRQ can have a strong impact on the current knowledge. If measured, such very short variability would call for a strong revision of the present day models and understanding of relativistic jets. What we need is a strong outburst – like those occurred in the BL Lac objects PKS 2155−304 and Mrk 501 – and a highly performing instrument.

To date, the shortest time-scale observed at high energies in a FSRQ is ∼2000 s, but in the hard X-rays. It is the case of NRAO 530 as observed by *INTEGRAL* (20–40 keV energy band) during an

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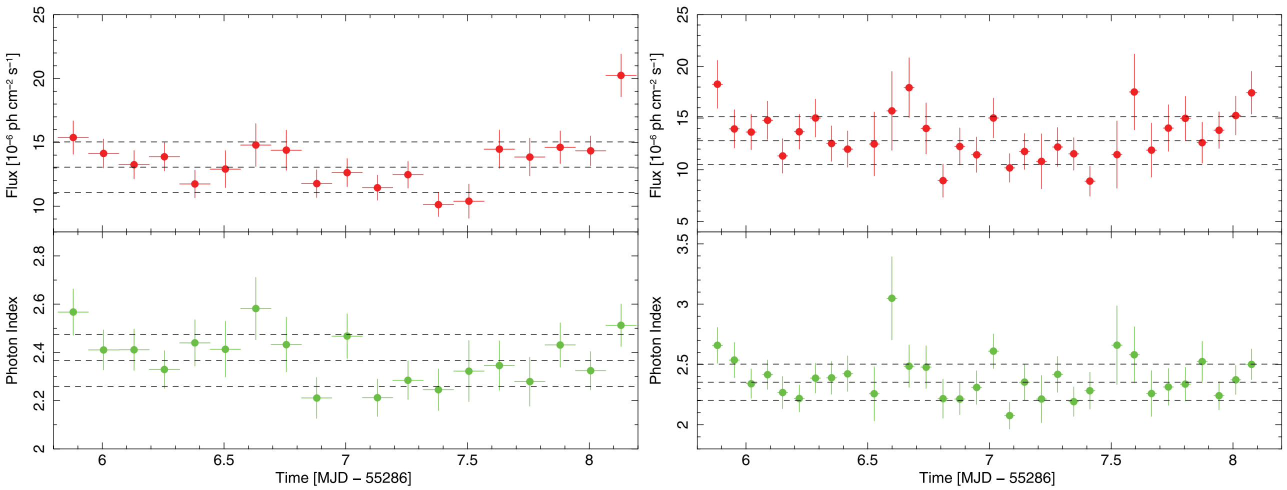

Figure 1. Light curves of 3C 454.3 ($E > 100$ MeV) with 3 h (left-hand panel) and 1 h (right-hand panel), respectively. Time starts on 2010 March 31 (MJD 55286), so that the number of the days corresponds also to days of April. The horizontal dashed lines in each panel correspond to the weighted average ±1 standard deviation.

exceptional flare in 2004 February (Foschini et al. 2006). Despite the good performance of *INTEGRAL*, that episode consists of a single 5σ detection, while the source is below the detection limit of the instrument during the remaining of the time. No multiwavelength observations were possible at that time and, specifically, no γ-ray satellites were operating. Therefore, this remains an isolated exceptional case and, as for every exceptional claim without a strong observational support, there is always a ‘halo’ of doubts.

The launch of *Fermi*/LAT in 2008 June could give more opportunities to search for subhour variability. The LAT (Atwood et al. 2009) could have the necessary sensitivity to probe into the shortest time-scales at γ-rays in quasars. If we consider a flux of 10^{-5} photon cm^{-2} s^{-1} ($E > 100$ MeV) and an effective area of $\sim$5000 cm^2 (see fig. 14 of Atwood et al. 2009, by taking into account the 0.1–100 GeV energy range), it results that for normal incidence there are about 15 photons per 5 min (about a 4σ detection, by assuming that on such short time-scales the background is almost absent). However, LAT operates almost always in scanning mode. This, in turn, has the great advantage to offer an efficient monitoring of all the sky (a complete coverage every 3 h or two orbits), but it hampers the possibility to probe time-scales shorter than 3 h (the source is not always at the boresight of the instrument and, therefore, the effective area is smaller).

A first tentative to bypass this issue has been recently made by performing a pointed observation during the giant outburst of 3C 454.3 ($z = 0.859$) which occurred in early 2010 April (Wallace et al. 2010), when the source reached fluxes in excess of 10^{-5} photon cm^{-2} s^{-1} ($E > 100$ MeV). Such flux levels were already reached by 3C 454.3 during the first 10 d of 2009 December (see Bonnoli et al. 2010 and references therein), but it was not possible at that time to perform a pointed observation and hence to search for subhours time-scales.

Here we report the study of the variability of the γ-ray emission of 3C 454.3 as observed by *Fermi*/LAT during the pointed observation performed from 2010 April 5 to 8 .

2 DATA ANALYSIS

Data of *Fermi*/LAT (Atwood et al. 2009) have been downloaded from the publicly accessible web site of High Energy Astrophysics Science Archive Research Center (HEASARC)[1] and analysed by means of the public software package LAT SCIENCE TOOLS, v. 9.15.2, including the calibration files (instrument response file, IRF P6_V3_DIFFUSE), the maps of the spatial diffuse background and the spectrum of the isotropic (cosmic and instrumental) background.

We retrieved the photon list with $E > 100$ MeV and spacecraft data from 2010 April 5, 19:38 UTC to 2010 April 8, 03:12 UTC (MJD 55291.8180–55294.1333) corresponding to an elapsed time of about 200 ks (see Fig. 1). Events of class 3 (diffuse) inside a radius of 7° centred on the coordinates of 3C 454.3 (RA $= 22^{\mathrm{h}}\,53^{\mathrm{m}}\,57\overset{\mathrm{s}}{.}7$; Dec. $= +16^{\circ}\,08'\,53''$, J2000) and coming within 105° of the zenith angle have been selected. This data set has been further filtered to exclude the events outside the good-time intervals and within 8° of the Earth limb. Livetime and exposure maps have been calculated, as well as the diffuse background.

An unbinned likelihood algorithm (Cash 1979; Mattox et al. 1996), implemented in the GTLIKE task, has been used to extract the flux and the photon index of the source emission. A single power-law model in the form $F(E) \propto E^{-\Gamma}$, where Γ is the photon index, was used to fit the energy flux distribution of the blazar. It is known that the γ-ray spectrum of 3C 454.3 displays a break at a few GeV (Abdo et al. 2009b; Finke & Dermer 2010), but since we want to probe the shortest time-scales (hence, lower statistics), it is better to adopt a single power-law model. The broken power-law model has been used to fit the data of the whole observation (see the next section). The backgrounds (spatial diffuse and isotropic) measured during this fit are kept fixed during the processing of the light curves with hours time bins or less, since we do not expect strong changes of the background in such short time-scales.

A first run with the optimizer DRMNFB is done to grossly estimate the spectral parameters. Then, the output of this process is used as input for a second run with the NEWMINUIT optimizer to assess better the measurement errors. In the following, only statistical errors are displayed. The use of the P6_V3_DIFFUSE response file guarantees that systematics affect the results by a value of less than 20 per cent (Rando et al. 2009). However, since this work is based only on LAT data, with no comparison with other instruments at other

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[1] http://fermi.gsfc.nasa.gov/

wavelengths, there is no need of absolute flux calibration. Hence, systematics are not applied.

This procedure is performed iteratively for each bin time within each good-time interval in order to generate the light curve. We discarded all the detections that have sufficiently no high test statistic (TS; see Mattox et al. 1996 for the definition), i.e. we considered only time bins with detection at $\sigma \sim \sqrt{\mathrm{TS}} > 5$. A light curve with 3 h time bin is displayed in Fig. 1, left-hand panel. The effective source ontime changes within the elapsed time bin, ranging from 10 to 98 per cent in the 30 min bin light curve. Therefore, we checked for a reasonable high TS even in the presence of a low source ontime. For example, the bin with the lowest source ontime (10 per cent of the elapsed time bin) has TS = 73.

We note that the average TS increased by a factor of ≈2.5 during the pointed observation, as expected from the increase of the instrument sensitivity when changing from scanning to pointed mode (the light curve in scanning mode is not shown).

3 DISCUSSION

The whole data set of 200-ks observation has been fitted with a broken power-law model in the form of $F(E) \propto (E/E_{\mathrm{break}})^{\Gamma_1}$ for $E < E_{\mathrm{break}}$ and $F(E) \propto (E/E_{\mathrm{break}})^{\Gamma_2}$ otherwise. This results in these parameters: the photon indices below and above the break energy are $\Gamma_1 = 2.22 \pm 0.04$ and $\Gamma_2 = 2.80 \pm 0.08$, respectively. The break energy is 0.9 ± 0.2 GeV and the flux integrated over the 0.1–100 GeV energy band is $(12.7 \pm 0.3) \times 10^{-6}$ photon cm^{-2} s^{-1}. The recorded counts are 3044 and TS = 10 592(>100σ). We compare these values with the early observations with *Fermi* referring to the first month of data (Abdo et al. 2009b). In 2008 August, the flux was about a factor of 4 smaller than in 2008 April, with a value of $(3.0 \pm 0.1) \times 10^{-6}$ photon cm^{-2} s^{-1}, the break energy was greater (2.4 ± 0.3 GeV), and the photon index above the break quite softer, with a value of $\Gamma_2 = 3.5 \pm 0.2$. Γ_1 is consistent within the measurement errors. It seems that the higher flux needs a harder spectrum.

The γ-ray emission of 3C 454.3 in Fig. 1 (left-hand panel) is variable on a few hours time-scale. A fit with a constant-flux line gave $\chi^2/\mathrm{dof} = \tilde{\chi}^2 \sim 2.7$ (with 18 dof, this means a chance probability of 0.99). However, we note that the last point, which is mainly driving the global variability of the light curve, is not a statistical fluctuation, but the beginning of a real flux increase. This is confirmed by the fact that on April 8, there was the peak of the γ-ray emission of the 2010 April outburst, with a day average of $\sim 16 \times 10^{-6}$ photon cm^{-2} s^{-1}. On the other hand, no strong variability of the photon index has been measured, although some trend is visible between April ∼6.5 and ∼7: Γ changed from 2.58 ± 0.13 on April ∼6.63 to 2.21 ± 0.08 (∼3σ significance) on April ∼ 6.88. Similar spectral changes have been observed in γ-ray blazars by EGRET (Nandikotkur et al. 2007) and LAT in the case of 3C 273 (Abdo et al. 2010b).

The light curve with 1 h time bin (Fig. 1, right-hand panel) has larger error bars and hence the slight variability seen in the 3 h bin curve is now smoothed. The fit with a constant-flux line gives $\tilde{\chi}^2 = 1.6$, but the visible trends are consistent with those observed in Fig. 1 (left-hand panel). The most significant trend is the drop in flux observed between April ∼6.7 and 6.8.

To evaluate the time-scales of these trends, we calculated the time of exponential rise or decay as defined by

$$F(t) = F(t_0)\exp[-(t - t_0)/\tau], \tag{1}$$

where $F(t)$ and $F(t_0)$ are the fluxes at the time t and t_0, respectively, and τ is the characteristic time-scale.

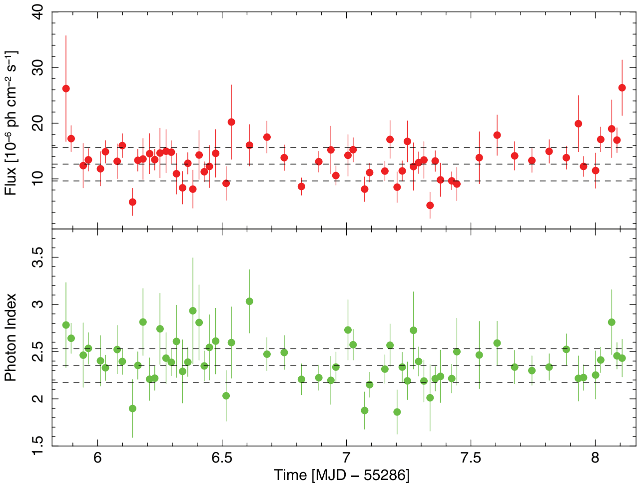

Figure 2. Top panel: flux light curve of 3C 454.3 ($E > 100$ MeV) with 30 min time bin. Bottom panel: photon index. Time starts on 2010 March 31 (MJD 55286), so that the number of the days corresponds also to days of April. The horizontal dashed lines in each panel correspond to the weighted average ±1 standard deviation.

In this case, the drop on April ∼6.7–6.8 visible in Fig. 1 (right-hand panel) has $\tau = 4.8 \pm 4.6$ h (significance of the flux variation 3.1σ). This value is confirmed in the 30 min time bin light curve shown in Fig. 2 ($\tau = 4.7 \pm 4.4$ h, 3.1σ). Moreover, the rise at the end of the curve between ∼8.0 and 8.1 has $\tau = 2.7 \pm 1.0$ h (3.3σ).

It is possible to estimate the minimum Doppler factor δ (e.g. Dondi & Ghisellini 1995; Mattox et al. 1997),[2] although during this pointed observation it was not possible to perform multiwavelength observations, because the blazar was too close to the Sun. Therefore, we adopted for the X-ray flux and spectrum, the values measured during the 2009 December outburst, when 3C 454.3 reached similar γ-ray fluxes: $\alpha = 0.4$ and $F_{1\,\mathrm{keV}} \sim 30$ μJy (Bonnoli et al. 2010). We obtained $\delta \geq 14$ for 1 GeV γ-rays and $\tau = 2.7$ h, a high value for a lower limit, but not unlikely (cf. Ghisellini et al. 2010).

We noted a few cases of sudden drop in the flux with ∼ 30 min time-scale on April ∼6.1–6.2 and ∼7.3. A closer inspection of the data revealed that these bins had small source ontime (∼25 per cent of the whole bin). Therefore, it is likely that it is a fake drop, caused by the not so good reconstruction of the flux in presence of a too few events, although sufficient for a high TS.

4 FINAL REMARKS

We presented the variability analysis of the γ-ray observation with *Fermi*/LAT of the blazar 3C 454.3 pointed during the outburst of early 2010 April. Contrary to the usual scanning mode, this time *Fermi* performed a 200 ks pointed observation (Wallace et al. 2010), which guarantees a higher sensitivity and a longer source ontime. These particular settings, together with the exceptionally high flux emitted by the blazar, enabled us to probe the shortest time-scales that we found to be in the range of ∼2–5 h, confirming the indications found by Bonnoli et al. (2010), Tavecchio et al. (2010) and in agreement with the current theories.

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[2] In the present work we used the most recent value for the Hubble–Lemaître constant $H_0 = 73$ km s^{-1} Mpc^{-1} (Freedman & Madore 2010).

Although the significance of the events is not very strong ($\sim 3\sigma$), the fact that it is present in the light curves with different time bins is an indication that the findings are well grounded. On the other side, we have not found significant evidence of sub-hour time-scales, but the present data set is not yet conclusive. We noted that the flux increased at the end of the pointed observations with $\tau \sim 2.7$ h. Therefore, we could expect (or reasonably hope) that hours or less time-scales may be effectively probed with *Fermi*/LAT under conditions of even greater fluxes, likely as occurred in 2009 December (Bonnoli et al. 2010).

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