FERMI GAMMA-RAY SPACE TELESCOPE OBSERVATIONS OF GAMMA-RAY OUTBURSTS FROM 3C 454.3 IN DECEMBER 2009 AND APRIL 2010

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Abstract. The flat-spectrum-radio-quasar 3C 454.3 underwent an extraordinary outburst in December 2009 when it became the brightest gamma-ray source in the sky for over one week. Its daily flux measured with the *Fermi* Large Area Telescope at photon energies $E > 100$ MeV reached $F_{E>100\ \mathrm{MeV}} = 22 \pm 1 \times 10^{-6}$ ph cm^{-2} s^{-1}, representing the highest daily flux of any blazar ever recorded in high-energy γ rays. It again became the brightest source in the sky in April 2010, triggering a pointed-mode observation by *Fermi*. The γ-ray temporal and spectral properties during these exceptional events are presented and discussed.

Keywords: Galaxies: active, quasars: individual: 3C 454.3, gamma rays: observations

1 Introduction

The radio source 3C 454.3 is a well-known flat spectrum radio quasar (FSRQ) at redshift $z = 0.859$. It entered a bright phase starting in 2000, and has shown remarkable activity in the past decade.

First observations of 3C 454.3 with the *Fermi* Large Area Telescope (LAT) began in July 2008 during *Fermi*'s commissioning period, when the source was found at a high flux state with $F_{E>100\ \mathrm{MeV}} \cong 10 \times 10^{-6}$ ph cm^{-2} s^{-1} Abdo et al. (2009). Observations revealed a timescale less than 2 days for the flux to decline by a factor of 2. The spectrum showed a spectral break around 2 GeV with a spectral steepening from $\Gamma_1 = 2.3$ to $\Gamma_2 = 3.5$. Such a break has now been found to be a common feature in bright FSRQs and in some low-synchrotron peaked BL Lacs as well (Abdo et al. 2010c). Based on weekly light curves, a very moderate "harder when brighter" effect has also been observed, with the photon index obtained with a single power-law fit varying by less than 0.3 for flux ratios varying by >7 (Abdo et al. 2010c).

The continuous monitoring by the *Fermi* LAT showed that the source activity faded continuously in early 2009 and then rose back up from June onwards. It underwent an exceptional outburst in November 2009 - January 2010 when it became the brightest gamma-ray source in the sky for over a week, reaching a record daily flux level in the GeV band (Escande & Tanaka 2009). At the same time it also showed strong activity at several other frequencies. The source remained active afterwards with a slowly decaying flux around 2×10^{-6} ph cm^{-2} s^{-1} until early April 2010 when it brightened up again to a flux level of 16×10^{-6} ph cm^{-2} s^{-1}, prompting the first *Fermi*-LAT target-of-opportunity (ToO) pointed observation beginning on 2010 April 5 lasting for 200 ks.

These two major events offer a unique opportunity to probe intraday variability and the associated spectral changes in the gamma-ray band.More details can be found in Ackermann et al. (2010).

2 Observations and analysis

The *Fermi*-LAT is a pair-conversion gamma-ray telescope sensitive to photon energies greater than 20 MeV. It is particularly suited to blazars observation since it scans the sky constantly: with its field of view of about 2.4 sr, it covers 20% of the sky at any time and permits an all-sky coverage in 3 hours. The data presented here

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were collected from 2009 August 27 to 2010 April 5 in survey mode, except for a 200 ks period starting on April 5 at 19:38 UT where the pointed mode was used, resulting in a gain of accumulation of exposure by about a factor of 3.5 over survey mode. Standard cuts were applied to the data. More details concerning the analysis can be found in Ackermann et al. (2010).

3 Results

Figure 1 displays the daily light curves (red points) from MJD 55070 to 55307 (27 August 2009 to 21 April 2010) for fluxes above 100 MeV. The periods showing the fastest flux variations during the December flare, with fluxes changing by more than a factor of 2 in amplitude, are enlarged in the insets, with the $E > 100$ MeV fluxes averaged over a daily, 6-hour, and 3-hour binning shown by the red, open blue and green data points, respectively. The error bars are statistical only. Three flares displaying a flux variation greater than a factor of 2 over less than a day (MJD 55167, 55170 and 55195) have been studied extensively during this period. It is the first time that, in the gamma-ray band, we can study a source over such short periods. The flares were fitted with the function (Abdo et al. 2010a):

$$F = 2F_0(e^{(t_0-t)/T_r} + e^{(t-t_0)/T_f})^{-1} + F_{bgd}(t), \tag{3.1}$$

where T_r and T_f are the rising and falling times, F_0 is the flare flux amplitude and $F_{bgd}(t)$ is a (slowly varying) background flux. The shortest variability time scale is found to be shorter than 3 hours. The lightcurve of the

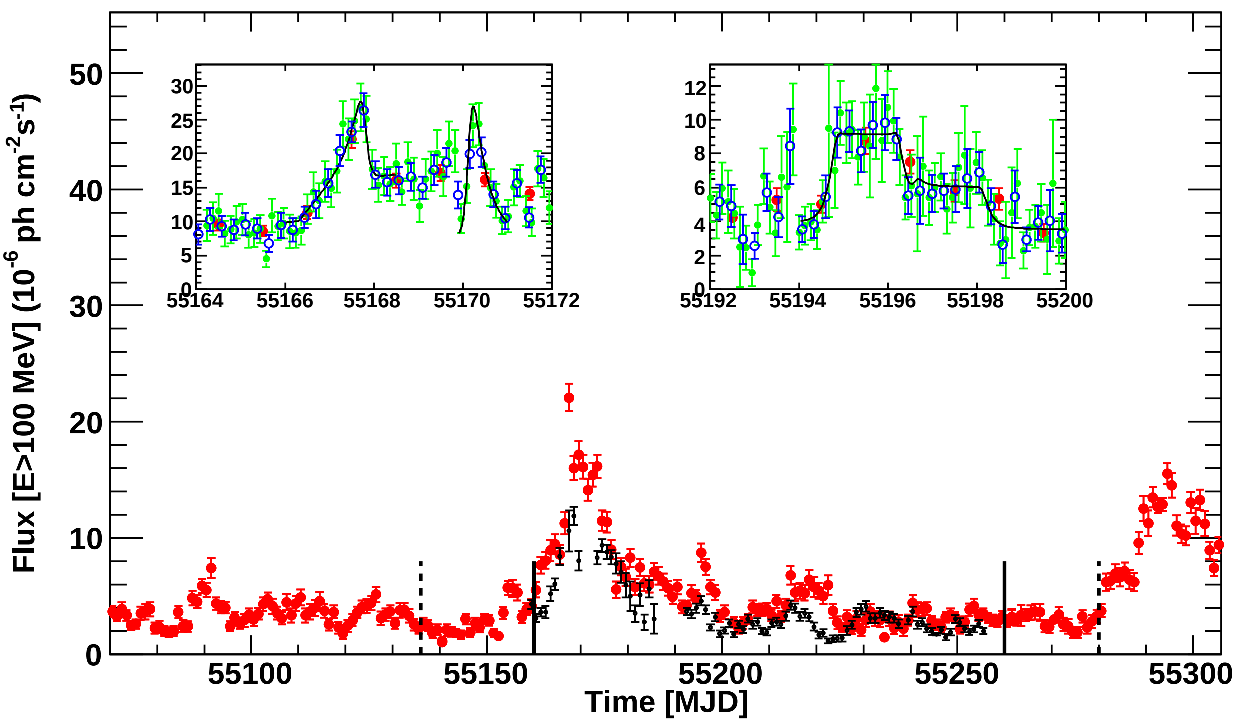

Fig. 1. Lightcurve of 3C 454.3 in the 100MeV-200GeV band (red). The lightcurve of the July-August 2008 flare, shifted by 511 days, is shown for comparison. The insets show blow-ups of the two periods when the largest relative flux increases took place. The red, blue, and green data points in the insets correspond to daily, 6hr, and 3hr averaged fluxes respectively. The fit results discussed in the text are displayed as solid curves.

July-August 2008 flare, shifted by 511 days, is shown for comparison.These two lightcurves exhibit a similar profile : a major outburst which lasts for about 10 days then followed by a long tail of fairly high activity upon which are superimposed minor flares lasting for a few days.

The 1 GeV daily lightcurve (not shown here) closely resembles the 100 MeV one, hinting a little spectral variability. This behavior is confirmed by the very limited variation of the photon spectral index measured for this source. The near constancy of the spectrum is in accord with the results found from the July 2008 flare and the first 6-months of LAT data (Abdo et al. 2009, 2010c). The variation of the amplitude of the weekly photon indices is only $\Delta\Gamma$=0.35 (varying between 2.35 and 2.7) during the period under consideration, but the variation is statistically significant. There is a suggestion that a progressive hardening over several weeks precedes a major outburst, but more such events will be needed to establish whether this behavior is typical. The correlation between index and flux provides insight into acceleration and cooling processes. Loop patterns were looked for during the most rapid flares to reveal a possible universal behavior. Indeed, what is expected after a flare is a softening of the source (cooling effect). But instead of a well-defined, universal pattern, a variety of patterns is found such as a weak hardening during the flux decrease which constitutes an indication of a "hard-lag", linked to acceleration processes. Figure 2 shows the flux and photon spectral index as a function of time in the period around (blue) and during (red) the time of the ToO when the *Fermi*-LAT was in pointed mode (MJD 55291.82-55294.13). The binning is 6 hour and 3 hour for the survey and pointed modes respectively. As expected by the 3.5 fold increase in exposure per unit time during the ToO, the statistical accuracy in the measurement of both parameters improves significantly. Although in a high state, the source was unfortunately fairly steady during this period. No indication for variability more rapid than that observed during the giant outburst is found during the ToO period, as already noted by Foschini et al. (2010). The reduced χ^2 for a constant fit of the photon index is 18.52/16, indicating that the data are consistent with a constant value.

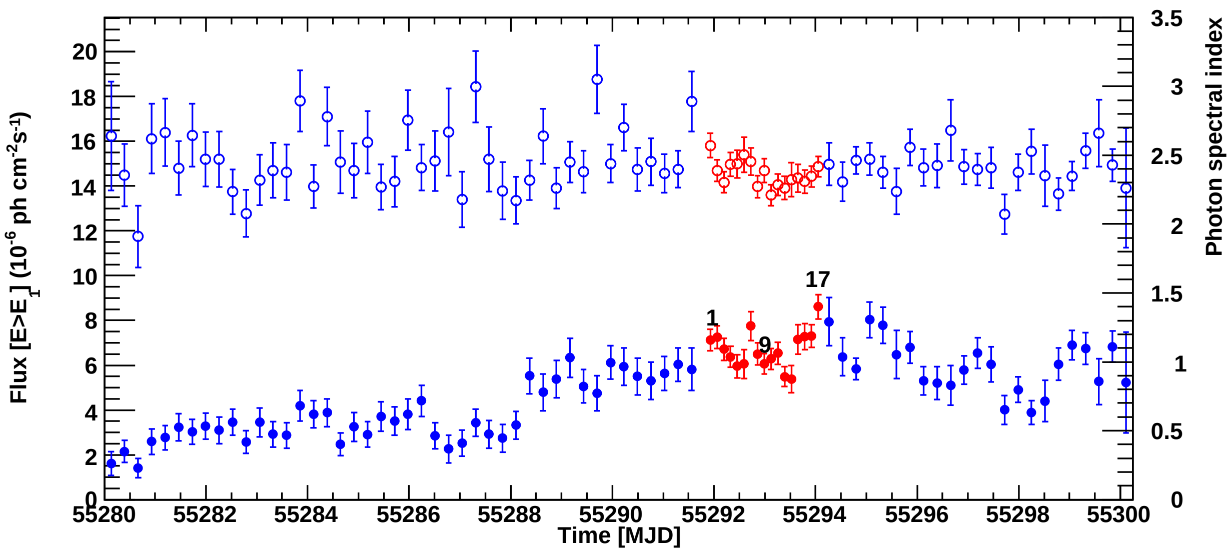

Fig. 2. Flux (filled data points; left-hand axis) and photon index (open data points; right-hand axis) as a function of time in the period surrounding the ToO pointing. Data collected in survey mode (6-hr binning) are in blue, those collected in pointed mode are in red (3-hr binning).

In order to study the evolution of the position of the spectral break of 3C 454.3, integrated spectra were computed over four periods : Period 1, MJD 55121-55165, Period 2, MJD 55166-55173 (week of the giant outburst), Period 3, MJD 55174-55262 and Period 4 MJD 55280-55300. It is the first time that the position of the break can be determined with such a short period of time integration (one week for the giant outburst). The distributions were fitted with a broken power law and a power law with exponential cutoff functions, which are difficult to discriminate for these periods. The variation of break energy (cutoff energy) with flux is displayed in the left (right) panel in Figure 3 for different observing periods. No strong evolution of either the break energy or the cutoff energy is found, but there is some indication of a slight hardening with flux.

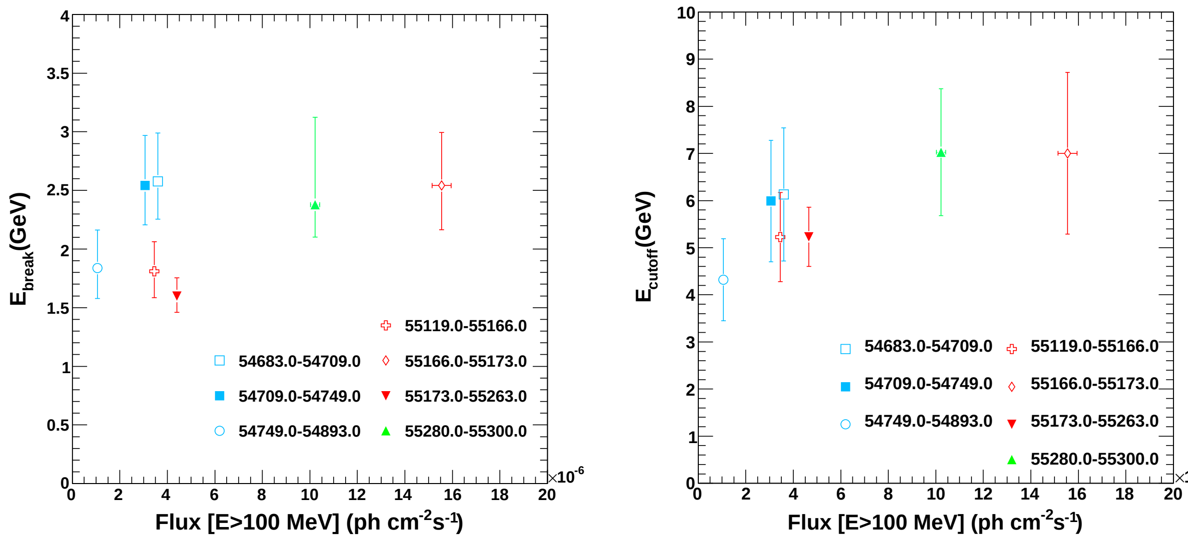

Fig. 3. Evolution of E_{break} and E_{cutoff} with flux.

4 Discussion

Thanks to this series of outbursts observed with the *Fermi*-LAT, a much more accurate picture of the behavior of 3C 454.3 in flaring states has been obtained. A photon flux of $F_{E>100 \text{ MeV}} = 22 \pm 1 \times 10^{-6}$ ph cm^{-2} s^{-1} from 3C 454.3 at $z = 0.859$ implies an apparent isotropic γ-ray luminosity above 100 MeV of $L_\gamma \cong 3.8 \pm 0.2 \times 10^{49}$ erg s^{-1}. This is ~ 3 times larger than the luminosity of the $z = 1.839$ blazar PKS 1502+106 during its August 2008 flare (Abdo et al. 2010b), but still lower than the luminosity of PKS 1622-297 ($\sim 5.1 \times 10^{49}$ erg s^{-1} with the current cosmological model) during the 1995 flare (Mattox et al. 1997). Several parameters of the source can be constrained from these data. The first one is the minimum Doppler factor δ_{min}, defined by the condition that the optical depth $\tau_{\gamma\gamma}(\epsilon_1)$ of a photon with energy $E_1 = \epsilon_1 m_e c^2$ to the $\gamma\gamma$ pair-production process is $\tau_{\gamma\gamma}(\epsilon_1) = 1$. It can be estimate thanks to the expression

$$\delta_{min} \cong \left[\frac{\sigma_T d_L^2 (1+z)^2 f_{\hat{\epsilon}} \epsilon_1}{4 t_{var} m_e c^4} \right]^{1/6} \tag{4.1}$$

Here f_ϵ is the νF_ν spectrum of 3C 454.3 measured at frequency $\nu = m_e c^2 \epsilon / h$. To estimate $\delta_{\rm min}$, the photon with maximum energy E_1 is used during the period in which f_ϵ and variability time $t_{\rm var} = t_{\rm var,d}$ day are measured. The νF_ν flux f_ϵ in eq. (4.1) is evaluated at $\epsilon = \hat{\epsilon} = 2\delta^2/(1+z)^2 \epsilon_1$ from the pair-production threshold condition. Swift XRT observations contemporaneous with the time that the 20 GeV photon was detected lead to $\delta_{\rm min} \approx 13$. The location of the emission region compared to the black hole can also been constrained. For a conical geometry of opening angle 2 $\theta_j > R/r \sim 1/\Gamma_b$, the location of the emitting region for the December flare is constrained to be at distance $r < 2c\Gamma_b^2 t_{\rm var}/(1+z) \approx 0.2 \Gamma_{15}^2 t_{\rm var,d}$ pc; i.e., towards the outer parts of the BLR. This conclusion tends to disfavor the models in which the Inverse Compton is made on photons from the torus or further in the jet. Several hypotheses can be made concerning the near constancy of the position of the break observed in the spectrum of 3C 454.3 despite very different flux level exhibited by the source. One possibility is related to scattering of a target photon field in the Klein-Nishina regime. Compton scattering takes place in the Thomson limit when the energy of the photon to be scattered is (in $m_e c^2$ units) $\epsilon'' < 1/4$ in the electron rest-frame, denoted by the double primes on quantities. The scattering is in the Thomson regime occurs for $E_C(\text{GeV}) < 12/E_\star(\text{eV})$, independent of the Doppler factor. If the break energy observed in 3C 454.3 at ≈ 2 GeV is due to the transition to scattering in the KN regime, then the underlying target photon energy $E_\star \approx 6$ eV is close to the energy of the Ly α photon at 10.2 eV. We have tested this possibility by comparing the Compton-scattered spectrum from a power-law electron distribution with a monochromatic Ly α photon source with the *Fermi* LAT data. The spectrum we obtained (not shown here) is too hard to fit the data, and treatment of KN effects on cooling (Dermer & Atoyan 2002) or the addition of other soft photon sources will reduce the sharpness of the break.

The difficulty to fit the sharp spectral break with a single power-law electron distribution is in accord with the conclusion of Abdo et al. (2009) that this break reflects a complex electron spectrum.

5 Summary

The correlated spectral and temporal properties of 3C 454.3 during two very strong flaring episodes, when the source was the brightest object in the γ-ray sky, have been studied. An important result of the present work is that the significant spectral break between $\approx 2-3$ GeV in γ-ray spectrum of 3C 454.3 is very weakly dependent on the flux state, even when the flux changes by an order of magnitude. Flux variations of a factor of 2 have been observed over time scales as short as three hours, though only weak variability was observed during the time of the Target of Opportunity pointing of the *Fermi* Telescope towards 3C 454.3.

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