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Fermi observations of gamma-ray outbursts from 3C 454.3 in December 2009 and April 2010

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Summary. — 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 $E > 100\,\mathrm{MeV}$ reached $22 \pm 1 \times 10^{-6}\,\mathrm{ph\,cm^{-2}\,s^{-1}}$. 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.

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PACS 98.54.-h – Quasars; active or peculiar galaxies, objects, and systems.
PACS 95.85.Pw – γ-ray.

1. – Introduction

The radio source 3C 454.3 is a well-known flat spectrum radio quasar (FSRQ) at redshift $z = 0.859$ which entered a bright phase starting in 2000.

First observations of 3C 454.3 with the *Fermi* Large Area Telescope (LAT) began in July 2008 [1]. Observations revealed a timescale less than 2 days for the flux to decline by a factor of 2. The spectrum showed a break around 2 GeV with a steepening of the photon index 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 [2]. Based on weekly light curves, a very moderate "harder when brighter" effect has also been observed [2]. The source activity faded continuously in early 2009 and then increased once more back up from June onwards. It underwent an exceptional outburst between November 2009 and 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 as

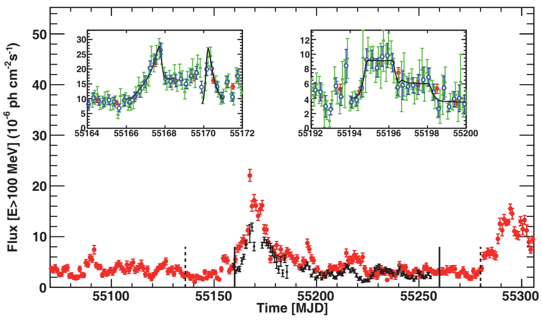

Fig. 1. – (Color online) Lightcurve of 3C 454.3 in the 100 MeV–200 GeV band (red). The lightcurve of the July-August 2008 flare, shifted by 511 days, is shown for comparison. The insets show blow-ups of the two periods when the largest relative flux increases took place. The red, blue, and green data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

seen by the LAT and AGILE [3, 4]. At the same time it also showed strong activity at several other frequencies. After a slowly decaying activity, it again became the brightest source in the sky in April 2010 with a flux level of $16 \times 10^{-6}\,\mathrm{ph\,cm^{-2}\,s^{-1}}$, 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 regarding the analysis can be found in [5].

2. – Results

Figure 1 displays the daily lightcurve (red points) from MJD 55070 to 55307 (27 August 2009 to 21 April 2010) of fluxes above 100 MeV. The error bars are statistical only. The three more rapid flares (MJD 55167, 55170 and 55195) were fitted with the function [6]: $F = 2F_0(e^{(t_0-t)/T_r} + e^{(t-t_0)/T_f})^{-1} + F_{\mathrm{bgd}}(t)$, where T_r and T_f are the rising and falling times, F_0 is the flare flux amplitude and $F_{\mathrm{bgd}}(t)$ is a (slowly varying) background flux. The shortest variability time scale is found to be shorter than 3 hours. Very limited variation of the photon spectral index measured for this source is in agreement with the results found from the July 2008 flare and the first 6 months of LAT data [1, 2]. Nevertheless, there is a suggestion that a progressive hardening over several weeks precedes a major outburst, but observations of more such events are required to establish whether this behavior is typical. The evolution of the source spectrum in the phase space of flux and photon index was examined for evidence of loops during the most rapid flares. Instead of finding a universal behavior, 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 hours and 3 hours for the survey and pointed modes, respectively. As expected from 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,

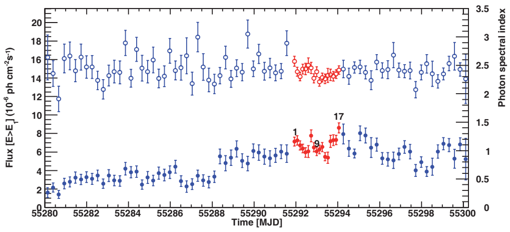

Fig. 2. – (Color online) Flux (filled data points; left-hand axis) and photon index (open data points; right-hand axis) as a function of time in the period surrounding the ToO pointing.

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.* [7].

In order to study the evolution of the position of the spectral break of 3C 454.3, integrated spectra were computed over four different periods. 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 fig. 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.

3. – Discussion

As a result of 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 $F_{E>100\,\mathrm{MeV}} = 22 \pm 1 \times 10^{-6}\,\mathrm{ph\,cm^{-2}\,s^{-1}}$ from 3C 454.3 at $z = 0.859$ implies an apparent isotropic γ-ray luminosity above 100 MeV of $L_\gamma \cong 3.8 \pm 0.2 \times 10^{49}\,\mathrm{erg\,s^{-1}}$.

Several parameters of the source can be constrained from these data. The first is the minimum Doppler factor $\delta_{\rm min}$, 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 estimated from the expression $\delta_{\rm min} \cong \left[(\sigma_T d_L^2 (1+z)^2 f_{\hat\epsilon} \epsilon_1)(4 t_{\rm var} m_e c^4)\right]^{1/6}$. 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

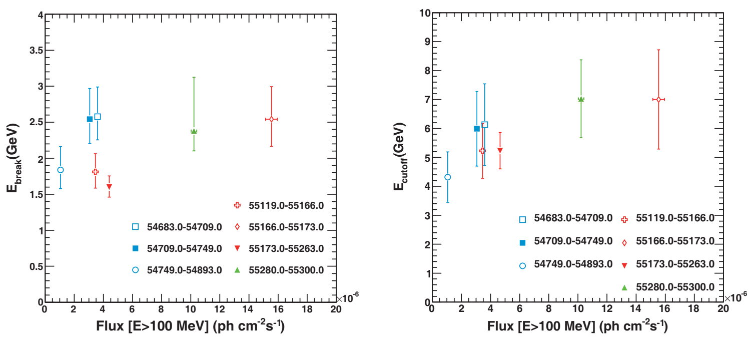

Fig. 3. – Evolution of $E_{\rm break}$ and $E_{\rm cutoff}$ with flux.

variability time $t_{\mathrm{var}} = t_{\mathrm{var,d}}$ day are measured. The νF_ν flux f_ϵ 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 $\delta_{\min} \approx 13$.

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 $r < 2c\Gamma_b^2 t_{\mathrm{var}}/(1+z) \approx 0.2\Gamma_{15}^2 t_{\mathrm{var,d}}$ pc; *i.e.*, towards the outer parts of the BLR. This conclusion tends to disfavor models in which the high-energy emission results from Inverse-Compton up-scattering of photons from the torus or further in the jet.

The near constancy of the position of the break observed in the spectrum could be explained by the 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 being in the Thomson regime occurs for $E_C(\mathrm{GeV}) < 12/E_\star(\mathrm{eV})$, 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 Ly α photons at 10.2 eV. This possibility was tested (see [5]) and the difficulty to fit the sharp spectral break with a single power law electron distribution shows, as already mentioned in [1], that this break reflects a complex electron spectrum [8].

4. – Conclusions

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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