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# THE EXTRAORDINARY GAMMA-RAY FLARE OF THE BLAZAR 3C 454.3

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## ABSTRACT

We present the gamma-ray data of the extraordinary flaring activity above 100 MeV from the flat spectrum radio quasar 3C 454.3 detected by *AGILE* during the month of 2009 December. 3C 454.3, which has been among the most active blazars of the FSRQ type since 2007, has been detected in the gamma-ray range with a progressively rising flux since 2009 November 10. The gamma-ray flux reached a value comparable with that of the Vela pulsar on 2009 December 2. Remarkably, between 2009 December 2 and 3, the source more than doubled its gamma-ray emission and became the brightest gamma-ray source in the sky with a peak flux of $F_{\gamma,p} = (2000 \pm 400) \times 10^{-8}$ ph cm$^{-2}$ s$^{-1}$ for a 1 day integration above 100 MeV. The gamma-ray intensity decreased in the following days with the source flux remaining at large values near $F_\gamma \simeq (1000 \pm 200) \times 10^{-8}$ ph cm$^{-2}$ s$^{-1}$ for more than a week. This exceptional gamma-ray flare dissipated among the largest ever detected intrinsic radiated power in gamma-rays above 100 MeV ($L_{\gamma,\mathrm{source,peak}} \simeq 3 \times 10^{46}$ erg s$^{-1}$, for a relativistic Doppler factor of $\delta \simeq 30$). The total isotropic irradiated energy of the month-long episode in the range 100 MeV–3 GeV is $E_{\gamma,\mathrm{iso}} \simeq 10^{56}$ erg. We report the intensity and spectral evolution of the gamma-ray emission across the flaring episode. We briefly discuss the important theoretical implications of our detection.

*Key words:* gamma rays: galaxies – quasars: individual (3C 454.3)

*Online-only material:* color figures

## 1. INTRODUCTION

Blazars (a special class of Active Galactic Nuclei with the relativistic jet pointing toward the Earth) show variability across their emitted spectrum on timescales of days, months, and years. Rarely are intense gamma-ray flares detected from blazars with fluxes reaching values near that of the Vela pulsar (i.e., the brightest steady gamma-ray source in the sky with a flux of $F_{\gamma,\mathrm{Vela}} \simeq 900 \times 10^{-8}$ ph cm$^{-2}$ s$^{-1}$ above 100 MeV). Even more rarely does a blazar gamma-ray "super-flare" reach intensities substantially larger than $F_{\gamma,\mathrm{Vela}}$, as in the case of the 1995 June flare from PKS 1622−29 (Mattox et al. 1997). On these rare occasions, the gamma-ray sky is remarkably dominated by a single transient source.

In this paper, we report the observations by the *AGILE* satellite of the most recent gamma-ray super-flare from the blazar 3C 454.3 during the period 2009 mid-November/mid-December. During a one month period, this source repeatedly reached a flux near $F_{\gamma,\mathrm{Vela}}$ for about two weeks, and then produced a very intense super-flare on 2009 December 2–3, with $F_\gamma > 2F_{\gamma,\mathrm{Vela}}$. This flare turns out to be even more intense than that detected from PKS 1622−29 (Mattox et al. 1997), which qualifies it as the most intense gamma-ray flare ever observed from a cosmic source at energies above 100 MeV.

The blazar 3C 454.3 (PKS 2251+158; $z = 0.859$) has been extensively studied over the last two decades. A wealth of multifrequency observations were especially obtained after the EGRET detections above 100 MeV in the range $F_\gamma =$

$(40–140) \times 10^{-8}$ ph cm$^{-2}$ s$^{-1}$ during the 1990s (Hartman et al. 1992; Aller et al. 1997). The source entered an active phase in 2000, and was very active in 2005–2006. During the 2005 May–June period, the source in 2005 May showed the strongest optical flare ever recorded, and reached the optical magnitude $R \simeq 12$ (Villata et al. 2006; Fuhrmann et al. 2006). X-ray (Giommi et al. 2006) and hard X-ray observations (Pian et al. 2006) covering this active phase in 2005 detected large fluxes between 10 and 100 mCrab. 3C 454.3 has been subsequently monitored very extensively at all wavelengths (Villata et al. 2006, 2007, 2009b; Raiteri et al. 2007, 2008a). Starting with the 2007 July *AGILE* detection above 100 MeV (Vercellone et al. 2008), 3C 454.3 has been very active in gamma-rays, and certainly it can be referred to as the most active blazar during the last two and a half years. A series of papers describe the *AGILE* gamma-ray observations in 2007–2009 as showing repeated flares that usually coincide with periods of intense optical and enhanced X-ray activity (Vercellone et al. 2008, 2009a, 2010; Donnarumma et al. 2009); see also the 1AGL catalog (Pittori et al. 2009). The multi-year optical evolution of 3C 454.3 has been presented in Raiteri et al. (2008b). *Fermi* has also detected several gamma-ray flaring episodes above 100 MeV (Hill 2009; Tosti et al. 2008), and determined an average spectrum for the 2009 August–September period in the range of 200 MeV–10 GeV showing a distinct break in the power-law spectrum at energies of 2–3 GeV (Abdo et al. 2009, 2010).

## 2. *AGILE* AND THE EXCEPTIONAL GAMMA-RAY FLARE OF 2009 DECEMBER 2

The *AGILE* mission, operating since 2007 April (Tavani et al. 2009), is characterized by a very compact instrument consisting of a Gamma-Ray Imager Detector (GRID, sensitive to energy between 30 MeV and 30 GeV) and a hard X-ray imager (Super-*AGILE*, sensitive in the energy range 18–60 keV). A non-imaging calorimeter (sensitive in the range 0.4–100 MeV) and an anticoincidence system complete the instrument. The *AGILE* detectors are characterized by large field of views (2.5 sr for GRID and 1 sr for Super-*AGILE*), optimal angular resolution, and good gamma-ray sensitivity especially in the energy range 100 MeV–1 GeV.

During the period 2007 April until the end of 2009 October, *AGILE* operated in a fixed-pointing mode covering about 1/5 of the entire sky. Due to a re-configuration of the satellite attitude control system, in early 2009 November *AGILE* changed its scientific operation mode into a "spinning mode," with the instrument boresight axis sweeping the sky with the angular speed of about $1^\circ \mathrm{s}^{-1}$. All instrument units maintained their functionality, and in particular the GRID detector can access about 80% of the sky in the spinning mode. The observations reported in this *paper* were obtained with *AGILE* operating in the spinning mode.

Because of the *AGILE* new pointing strategy, the FSRQ 3C 454.3 has been constantly monitored with no gaps since early 2009 November, with a typical 2 day exposure value of $\sim 10^7$ cm$^2$ s at 100 MeV. All the gamma-ray fluxes reported in this paper were obtained with a maximum likelihood analysis using our FM3.119 calibrated filter. We used a standard event selection procedure that takes into account the South Atlantic Anomaly (SAA) passage and a standard Earth albedo photon filtering procedure.

Figure 1 shows in the upper panel the $2\frac{1}{2}$ year gamma-ray light curve of 3C 454.3 obtained by integrating all available *AGILE* gamma-ray data since 2007 July. The lower panel of Figure 1 shows the detailed *AGILE*–GRID gamma-ray light curve of 3C 454.3 obtained for the period from 2009 November 7 until 2010 January 9. Integrating from 2009 November 10 (MJD = 55,145.7) until 2009 December 2 (MJD = 55,167.7), the source shows an increasing flux above 100 MeV from a value of $F_{\gamma,1} \simeq 100 \times 10^{-8}$ ph cm$^{-2}$ s$^{-1}$ up to a Vela–PSR like flux, $F_{\gamma,2} \simeq 1000 \times 10^{-8}$ ph cm$^{-2}$ s$^{-1}$. During the same period (2009 November 21 and December 1–2), a gradual optical flux increase of more than 1 mag in the $R$ band was reported (Villata et al. 2009a), with a maximum intensity reaching $R = 14.1$ on December 1–2.

After an intense and prolonged gamma-ray activity above 100 MeV detected during the last days of 2009 November and early days of 2009 December (Striani et al. 2009a), an exceptional 1 day gamma-ray emission was detected by *AGILE* from 3C 454.3 during the time interval UT 2009 December 2 06:30 to UT 2009 December 3 06:30 (Striani et al. 2009b) with a peak flux of $F_{\gamma,p} = (2000 \pm 400) \times 10^{-8}$ ph cm$^{-2}$ s$^{-1}$ ($E > 100$ MeV). During this time interval, 3C 454.3 became the brightest gamma-ray source in the sky with a flux above 100 MeV $F_{\gamma,p} > 2\,F_{\gamma,\mathrm{Vela}}$. This flux exceeded that of the previous day, showing a rapid increase (about 80%) within 24 hr. Integrating from 2009 November 29 19:00 until 2009 December 01 17:00 (MJD 55,164.8–55,166.7), we obtain the 2 day averaged gamma-ray flux $F'_\gamma(2\,\mathrm{day}) = (688 \pm 160) \times 10^{-8}$ ph cm$^{-2}$ s$^{-1}$. Integrating from 2009 December 1 17:00 until 2009 December 3 17:00 (MJD 55,166.7 – 55,168.7), we obtain the flux $F_{\gamma,p}(2\,\mathrm{day}) = (1680 \pm 240) \times 10^{-8}$ ph cm$^{-2}$ s$^{-1}$. The statistical significance of the 2 day averaged flux variability turns out to be above $3\sigma$. Following the super-flare episode, the source flux decreased to an average value close to $1000 \times 10^{-8}$ ph cm$^{-2}$ s$^{-1}$ ($E > 100$ MeV) during the following 10 days, and later decreased to an average flux of $400 \times 10^{-8}$ ph cm$^{-2}$ s$^{-1}$ ($E > 100$ MeV).

Multifrequency observations in the IR, optical, X-ray, and $\gamma$-ray bands have been reported for this extraordinary gamma-ray flaring activity including those by *Fermi*/LAT (Escande & Tanaka 2009), *Swift*/XRT (Sakamoto et al. 2009), *Swift*/BAT (Krimm et al. 2009), SMARTS/ANDICAM (Bonning et al. 2009), and the Kanata telescope (Sasada et al. 2009), and during the following days by *INTEGRAL*/IBIS (Vercellone et al. 2009b), MIRO (Baliyan et al. 2009), and ARIES (Gupta et al. 2009).

In order to study the gamma-ray emission in the *AGILE* main spectral bands, we plot in Figure 2 the 1 day integrated light curves in two energy ranges, a "soft" band with 100 MeV $< E <$ 400 MeV (blue curve), and a "hard" band with 400 MeV $< E <$ 3 GeV (red curve). The shape of the light curves in the two energy bands shows a possible hint that the source emission hardens across the super-flare episode. Figure 2 shows, indeed, a substantial increase of the "hard" flux, while a flattening is present in the "soft" light curve. The full band light curve reported in Figure 1 seems to be more influenced by the behavior of the hard band emission across the super-flare episode.

We carried out a time-resolved spectral analysis of 3C 454.3 dividing the period of exceptional gamma-ray activity in three time intervals. Figure 3 shows our results for: (1) a 25 day integrated period before the super-flare (interval-1), (2) the super-flare episode integrated over 2 days (interval-2), and (3) the following 3 days (interval-3). The 3- and 25-day integrations are chosen to provide a good statistical sample.

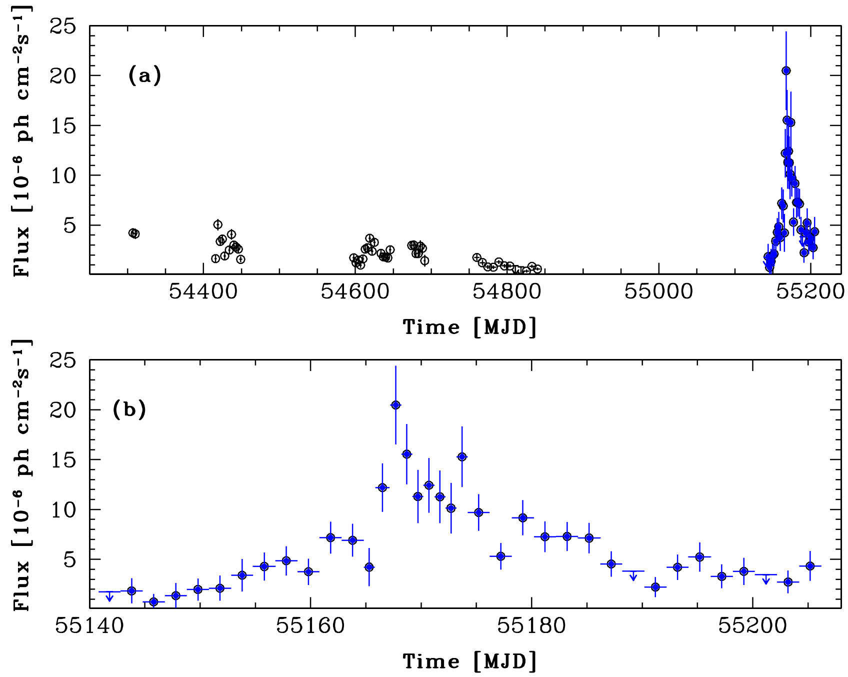


**Figure 1.** Gamma-ray emission above 100 MeV from 3C 454.3 as monitored by *AGILE*. Upper panel: the $2\frac{1}{2}$ year flux light curve covering the period from 2007 July to 2009 December. The black data points are obtained with *AGILE* in the pointing mode (see Vercellone et al. 2010); the blue data points were collected in spinning mode. Lower panel: gamma-ray light curve obtained for the period 2009 November 7 and 2010 January 9 (spinning mode). All flux values are obtained with the *AGILE* standard maximum likelihood analysis, using the FM3.119 calibrated filter, with standard event selection that takes into account the SAA passage and the Earth albedo photons. The temporal bin for the blue data points is 2 days, except for the 9 day interval centered around the peak, for which a 1 day integration was performed. Data obtained with a maximum off-axis angle $\theta_m = 60^\circ$.

(A color version of this figure is available in the online journal.)

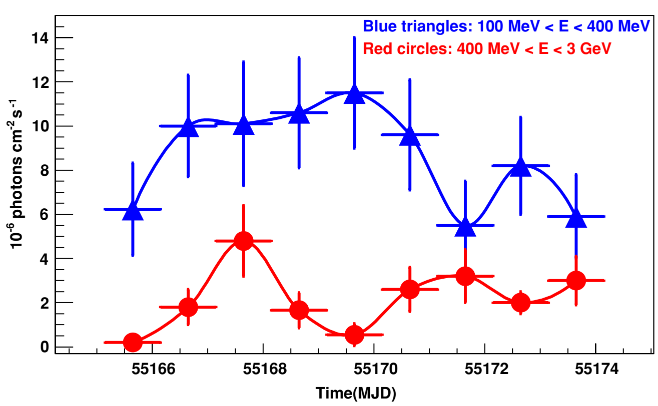


**Figure 2.** One day gamma-ray light curve of the 3C454.3 between 2009 November 30 and December 8 in different spectral bands. Blue curve and data points: light curve for photon energies 100 MeV $< E <$ 400 MeV. Red curve and data points: light curve for photon energies 400 MeV $< E <$ 3 GeV. The super-flare episode occurred on 2009 December 2–3 (MJD = 55,167.7). Data obtained with a maximum off-axis angle $\theta_m = 40^\circ$.

(A color version of this figure is available in the online journal.)

The spectral behavior during these three intervals seems to confirm the hardening deduced by the "soft" and "hard" gamma-ray properties of the source emission during the super-flare. The super-flare spectrum is well fitted between 100 MeV and 1 GeV by a single power law with photon index $\alpha = 1.66 \pm 0.32$ (statistical error only, defined as $dN_\gamma/dE \propto E^{-\alpha}$). A single power-law fit for the pre- and post-flare spectra gives $\alpha = 1.85 \pm 0.26$ (interval-1) and $\alpha = 2.04 \pm 0.26$ (interval-3), respectively.[19] The pre- and post-super-flare spectra show a curvature with a peak energy $E_p$ of the $\nu F_\nu$ spectrum, $E_p \simeq$ 300 MeV.

We also performed a refined temporal analysis of the super-flare episode and studied the gamma-ray light curve with temporal bins of different durations (24 hr, as well as 12–6–3 hr). We extracted gamma-ray photons from a radius of 2° for the period 55,165–55,173 MJD, and obtained the corresponding light curves with different binning. Restricting the analysis to the super-flare period (55,166–55,169 MJD) and to the 6 hr bin light curve above 100 MeV, we detect a $3\sigma$ peak (above a 2 day average) during the 6 hr period between UT 2009 December 2 10:30 and UT 2009 December 2 16:30. This sharp increase (for *AGILE*, this is due essentially to photons above 400 MeV) is in temporal agreement with the 6 hr increase also reported by *Fermi* (Escande & Tanaka 2009).

## 3. DISCUSSION

3C 454.3 turns out to be the brightest and most active gamma-ray blazar detected above 100 MeV since the beginning of operations of the new generation gamma-ray instruments (*AGILE* and *Fermi*). Many gamma-ray flares have been detected from this source in the last two years, and the most recent flaring at the end of 2009 is the culmination of a very active phase. The gamma-ray super-flare of early 2009 December is remarkable for many reasons.

1. It reaches the strongest ever gamma-ray flux detected from a blazar, with an apparent (isotropic) 1 day peak luminosity of $L_{\gamma,\mathrm{iso},p} \simeq 6 \times 10^{49}$ erg s$^{-1}$ above 100 MeV. We note that for a 3C 454.3 black hole mass of $M \simeq 2 \times 10^9\, M_\odot$ (Woo & Urry 2002), the observed isotropic gamma-ray luminosity is apparently strongly super-Eddington. However, taking

[19] However, note that these values are all consistent within the $1\sigma$ level.

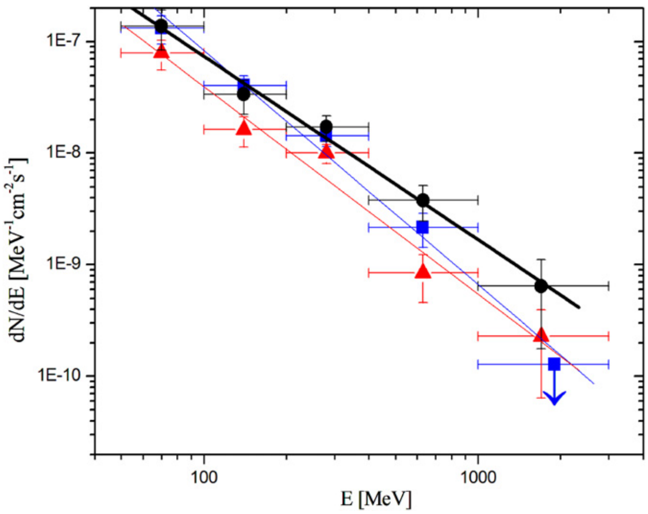


**Figure 3.** Photon number differential energy spectra of 3C 454.3 before, during, and after the 2009 December 2–3 super-flare. Red triangles: the 25 day spectrum integrated for the period between UT 2009 November 6 05:00 and UT 2009 December 1 01:00. Black circles: the 2 day spectrum integrated for the period between UT 2009 December 1 12:00 and UT 2009 December 3 17:00. Blue squares: the 3 day spectrum integrated for the period between UT 2009 December 3 17:00 and UT 2009 December 6 16:00. Solid lines show the spectral slopes discussed in the main text. Data obtained with a maximum off-axis angle $\theta_m = 40°$.

(A color version of this figure is available in the online journal.)

into account the radiation pressure of a fraction of spherical surface for a jet opening angle $\phi \sim 5°$ (Gopal-Krishna et al. 2004), we obtain an observed radiated luminosity on the order of 1/10 of the Eddington limit obtained for spherical accretion ($L_E \simeq 3 \times 10^{47}$ erg s$^{-1}$). For an efficiency near 10% of kinetic energy conversion into gamma-ray radiation and maximal extraction of accretion power into jet kinetic power, the deduced accretion rate can reach the Eddington limit during the super-flare episode. By rescaling the peak luminosity value with the relativistic beaming and Doppler factors, we obtain the intrinsic peak luminosity $L_{\gamma,\mathrm{source},p} = L_{\gamma,\mathrm{iso},p}\,\Gamma^2\,\delta^{-4}$ (e.g., Maraschi & Tavecchio 2003). There are uncertainties for the value of the Doppler factor $\delta = \Gamma^{-1}\,(1 - \beta\,\cos\theta)^{-1}$ (with $\Gamma = (1-\beta^2)^{-1/2}$, and $\beta$ the bulk jet velocity), for which values between 20 and 40 are found in the literature. We adopt here, for consistency with other recent investigations (e.g., Vercellone et al. 2010), the value $\delta \simeq 30$ (also see Savolainen et al. 2010). The corresponding values of the bulk Lorentz factor and the angle $\theta$ between the jet axis and line of sight are in the approximate ranges $15 < \Gamma < 20$, and $1° < \theta < 3°$. We adopt the values $\Gamma = 20$ and $\theta = 1.°2$, and obtain $L_{\gamma,\mathrm{source},p} \simeq 3 \times 10^{46}$ erg s$^{-1}$.

2. The peak gamma-ray emission is characterized by a very short rise time (6–12 hr) and shows a spectral evolution with a hard spectral component that modifies the pre- and post-peak spectra (see Figures 2 and 3).
3. The total isotropic irradiated energy in the range 100 MeV–3 GeV during the 2 month period from 55,146–55,205 MJD is $E_{\gamma,\mathrm{iso}} \simeq 10^{56}$ erg. This implies an intrinsic total radiated energy above 100 MeV of $E_{\gamma,\mathrm{source}} = E_{\gamma,\mathrm{iso}}\,\Gamma^2\,\delta^{-4} \simeq 5 \times 10^{52}$ erg $\simeq 1/40\,M_\odot$. For comparison, the total energy irradiated in the gamma-ray band by PKS 1622−29 (at $z \simeq 0.8$, assuming the same parameters as 3C 454.3) during the flare in 1995 was $E_{\gamma,\mathrm{source}} \simeq 3 \times 10^{52}$ erg.

The 3C 454.3 super-flare phenomenon is intrinsically broad band in nature, and a satisfactory picture of the emission mechanism can be obtained only from a complete multifrequency account of the spectral evolution (see Pacciani et al. 2010). Here we briefly focus on the gamma-ray spectral features as shown in Figures 2 and 3. Among the possible mechanisms that can account for a spectral hardening and subsequent decay observed during and following the 3C 454.3 super-flare, we mention here one possibility: the injection of energetic electrons with an energy cutoff larger by a factor of ∼3 than the $\gamma_c$ applicable to the pre- and post-flare conditions. This extra-acceleration, which has to occur with a comoving timescale less than $\tau_a \simeq (1\,\mathrm{day})\,\delta\,(1+z)^{-1}$, influences the whole spectral energy distribution (SED), modifying the synchrotron, synchrotron self-Compton (SSC), and external inverse Compton components. The rapid spectral variation inferred from Figure 3 indeed argues for substantial cooling of the particle distribution function. The additional component of energized particles may be the manifestation of the drastic modification of the inner parts of the disk/jet system that produce the rapidly variable high-energy emission. Previous broadband SED determinations of 3C 454.3 for the gamma-ray activity detected by *AGILE* in 2007, 2008, and 2009 (Vercellone et al. 2008; Vercellone et al. 2009a; Donnarumma et al. 2009, also see Raiteri et al. 2007 for the detection of little and big blue bumps in the optical spectra) constitute an unprecedentedly constraining database from which further theoretical modeling can be developed.

## 4. CONCLUSIONS

3C 454.3 reveals itself as the most prolific gamma-ray blazar during the last three years and has been dominating the gamma-ray sky above 100 MeV since mid-2007. During 2009 December, the source showed dramatic activity, reaching and maintaining for several weeks a flux above 100 MeV comparable to or larger than the brightest persistent gamma-ray source such as the Vela pulsar. During the period 2009 December 2–3, 3C 454.3 produced a super-flare that has turned out to be the brightest blazar emission episode above 100 MeV ever detected. The *AGILE* satellite continuously followed the daily evolution of the flaring activity of 3C 454.3. Even though a comprehensive picture of the physical mechanism at work can be obtained only from a multifrequency collection of simultaneous data, restricting ourselves to the gamma-ray range in any case provides very important information on the physics of the source. For a detailed theoretical modeling and a broad spectral evolution of 3C 454.3's exceptional activity see Pacciani et al. (2010).

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