Long-term $\gamma$-ray and multi wavelength observations of 3C 454.3 (a.k.a. the Crazy Diamond)

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Abstract. During the period July 2007 - January 2009, the AGILE satellite, together with several other space- and ground-based observatories monitored the activity of the flat-spectrum radio quasar 3C 454.3, yielding the longest multi-wavelength coverage of this $\gamma$-ray quasar so far. The source underwent an unprecedented period of very high activity above 100 MeV, a few times reaching $\gamma$-ray flux levels on a day time scale higher than $F = 400 \times 10^{-8}$ photons cm$^{-2}$ s$^{-1}$, in conjunction with an extremely variable behavior in the optical $R$-band, even of the order of several tenth of magnitude in few hours, as shown by the GASP-WEFT light curves. We present the results of this long term multiwavelength monitoring campaign, with particular emphasis on the study of possible lags between the different wavebands, and the results of the modeling of simultaneous spectral energy distributions at different levels of activity.

1. Introduction

Among active galactic nuclei (AGNs), blazars show intense and variable $\gamma$-ray emission above 100 MeV (Hartman et al. 1999), and the variability time scale can be as short as a few days, or last a few weeks. They emit across several decades of energy, from the radio to the TeV energy band and their spectral energy distributions (SEDs) are typically double humped with a first peak occurring in the IR/optical band in the flat-spectrum radio quasars (FSRQs) and low-energy peaked BL Lacs (LBLs), and at UV/X-rays in the high-energy peaked BL Lacs (HBLs). This peak is commonly interpreted as synchrotron radiation from high-energy electrons in a relativistic jet. The second SED component is commonly interpreted as inverse Compton (IC) scattering of soft seed photons by relativistic electrons, and peaks in the MeV–GeV and in the TeV energy bands in the FSRQs/LBLs and in the HBLs, respectively. A recent review of the blazar emission mechanisms and energetics is given in Celotti & Ghisellini (2008).

The FSRQ 3C 454.3 (PKS 2251+158; $z = 0.859$) is certainly one of the most active extragalactic sources at high energy. In the EGRET era, it was detected in 1992 during an intense $\gamma$-ray flaring episode (Hartman et al. 1992, 1993) when its flux $F_{E > 100\text{MeV}}$ was observed to vary within the range $(0.4 - 1.4) \times 10^{-6}$ photons cm$^{-2}$ s$^{-1}$. In 1995, a 2-week campaign detected a $\gamma$-ray flux < 1/5 of its historical maximum (Aller et al. 1997).

Figure 1 shows the $\gamma$-ray light curve for $E > 100$ MeV as observed by EGRET in the period 1991–1995.
Figure 1. EGRET 3C 454.3 light curve for $E > 100\,\text{MeV}$ in the period 1991-1995. The downward arrow represents a 2$\sigma$ upper-limit. Data from Hartman et al. (1999).

In 2005, 3C 454.3 underwent a major flaring activity in almost all energy bands (see Giommi et al. 2006). In the optical, it reached $R = 12.0\,\text{mag}$ (Villata et al. 2006) and it was detected by INTEGRAL at a flux level of $\sim 3 \times 10^{-2} \,\text{photons cm}^{-2} \,\text{s}^{-1}$ in the 3–200 keV energy band (Pian et al. 2006). Since the detection of the exceptional 2005 outburst, several monitoring campaigns were carried out to follow the source multifrequency behavior (Villata et al. 2006, 2007; Raiteri et al. 2007, 2008a,b). During the last of these campaigns, 3C 454.3 underwent a new optical brightening in mid July 2007, which triggered observations at all frequencies, including the AGILE one. In the following, we briefly describe the AGILE satellite, and we discuss the various campaigns triggered on 3C 454.3.

2. The AGILE Satellite

The AGILE satellite (Tavani et al. 2009) is a mission of the Italian Space Agency (ASI) devoted to high-energy astrophysics, operative since April 2007. The scientific instrument combines four active detectors yielding broad-band coverage from hard X-rays to $\gamma$-ray: a Silicon Tracker (ST; Prest et al. 2003, 30 MeV–30 GeV), a co-aligned coded-mask hard X-ray imager, Super–AGILE (SA; Feroci et al. 2007, 18–60 keV), a non-imaging CsI Mini–Calorimeter (MCAL; Labanti et al. 2009, 0.3–100 MeV), and a segmented Anti-Coincidence System (ACS; Perotti et al. 2006). The Gamma-Ray Imaging Detector (GRID) reaches a 5-$\sigma$

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1 Assuming a Crab-like spectrum.
sensitivity of about \((1 - 2) \times 10^{-6} \text{ cm}^{-2} \text{s}^{-1}\) above 100 MeV for an integration time of 2 days, sources positioned 30 degrees off-axis, an Earth occultation fraction of 20\% and near the Galactic Plane (high \(\gamma\)-ray background). The hard X-ray monitor on-board AGILE, Super-AGILE (SA), reaches a sensitivity of about 15 mCrab at 5-\(\sigma\) in the energy range 18–60 keV in a one-day observation.

3. The AGILE Campaigns

3.1. July 2007

At the epoch of the 3C 454.3 optical flare (2007 July 19–21) the closest pointing position allowed by the solar panel constraints ranged within 35°–40° from the source. Because of the remarkably large (\(\sim 3\) sr) field of view (FOV) of the GRID and the successful detection of the Vela pulsar at \(\sim 55°\) off-axis obtained during the science verification phase, AGILE could reliably study 3C 454.3 despite its large off-axis position. The observations were performed between 2007 July 24 14:30 UT and 2007 July 30 11:40 UT, for a total pointing duration of \(\sim 220\) ks. The source detection significance is 13.8\(\sigma\) as derived from a maximum likelihood analysis (Vercellone et al. 2008).

![Figure 2](image)

Figure 2. Panel (a): 3C 454.3 light curve in the period 2007 July 24–30. Panel (b): comparison between the long term EGRET and AGILE average fluxes. Adapted from Vercellone et al. (2008).

Figure 2 panel (a), shows the AGILE/GRID light curve for \(E > 100\) MeV during the \(\gamma\)-ray flare, while panel (b) shows the comparison with the historical EGRET flux values.
We note that 3C 454.3 is detected at a 4-σ level during almost the whole period on a 1-day timescale. The average γ-ray flux above 100 MeV for the whole period is $F_{E>100\text{ MeV}} = (280 \pm 40) \times 10^{-8}$ photons cm$^{-2}$ s$^{-1}$. The average γ-ray flux above 100 MeV for the whole period was the highest ever detected from this source, as shown in Figure 2 panel (b).

The source was not detected (above 5-σ) by the Super-AGILE Iterative Removal Of Sources (IROS) applied to the $Z$ image, in the 20–60 keV energy range. Assuming a power law spectral shape with photon index $\Gamma = 1.5$, we find a 3-σ upper limit of $2.3 \times 10^{-3}$ photons cm$^{-2}$ s$^{-1}$ on the average flux from 3C 454.3.

### 3.2. November 2007

In November 2007 AGILE began pointing 3C 454.3 at high off-axis angle (about 40°). Nevertheless, in a few days 3C 454.3 was detected at more than 5-σ, exhibiting variable activity on a day time-scale. Immediately after the source detection, a multiwavelength campaign started (Vercellone et al. 2009a). AGILE data were collected during two different periods, the first ranging between 2007-11-10 12:17 UT and 2007-11-25 10:57 UT and the second between 2007-11-28 12:05 UT and 2007-12-01 11:39 UT, for a total of about 592 ks. The three-day gap between them was due to a pre-planned GRID calibration activity. INTEGRAL data were collected during a dedicated ToO on revolutions 623 (between 2007-11-20 03:35 UT and 2007-11-22 08:46 UT) and 624 (between 2007-11-22 20:45 UT and 2007-11-24 15:50 UT), for a total of about 300 ks, while Swift/XRT data were obtained during several ToO pointings for a total of about 10 ks. WEBT data (radio to optical) as well as Swift/UVOT data were published in Raiteri et al. (2008a), while REM data were acquired following a ToO request. In both cases, optical data were acquired continuously during the whole AGILE campaign.

Figure 3 shows the multi wavelength light curves during the November 2007 observing campaign. We investigated the expected γ-optical flux correlation by means of the discrete correlation function (DCF). The DCF peak occurred at $\tau = 0$, and its value is $\sim 0.5$. This indicates a moderate correlation, with no significant time delay between the γ-ray and optical flux variations.

We fit the SEDs for two major γ-ray flaring episodes by means of a one-zone leptonic model, considering the contributions from synchrotron self-Compton (SSC), and from external seed photons originating both from the accretion disk and from the broad-line region (BLR). We note that during both flaring episodes, the external Compton scattering of direct disk radiation (ECD) contribution can account for the soft and hard X-ray portion of the spectrum, which show a moderate, if any, time variability. However, we note that the ECD component alone cannot account for the hardness of the γ-ray spectrum. We therefore argue that in the AGILE energy band a dominant contribution from the external Compton scattering of the BLR clouds (ECC) seems to provide a better fit of the data during the γ-ray -ray flaring states.

### 3.3. December 2007

In December 2007 AGILE began a multi wavelength campaign involving Spitzer, Swift, Suzaku, the WEBT consortium, the REM and MITSuME telescopes,
offering a broad band coverage that allowed a truly simultaneous sampling of the synchrotron and IC emissions (Donnarumma et al. 2009).

Figure 3 shows the SED during 2007 December 13, characterized by the broadest multi wavelength coverage. During this epoch the source was in a γ-ray state characterized by a flux for $E > 100$ MeV of the order of $\approx 200 \times 10^{-8}$ photons cm$^{-2}$ s$^{-1}$. We found that a model accounting for ECD and ECC components does not fully describe the SEDs in the three epochs. An additional contribution, possibly from the hot corona with $T = 10^6$ K surrounding the jet, is required to account simultaneously for the synchrotron and the inverse Compton emissions during those epochs.

Moreover, a detailed analysis of the correlation between the flux variations in the γ-ray and optical energy band yields a possible $\approx 1$ day delay of the γ-ray emission with respect to the optical one.

3.4. Eighteen Months of Monitoring

Starting from May 2008, AGILE conducted several multi wavelength observing campaigns on 3C 454.3. A detailed discussion of these results is presented in Vercellone et al. (2009b).

Figure 5 shows the 3C 454.3 light curves at different energies over the whole period July 2007 – January 2009. The different panels show, from bottom to
Simultaneous SED for 2007 December 13. We note the possible contribution of the EC on the hot corona component (dash-dot-dot line) to the model fit. Adapted from Donnarumma et al. (2009).

Figure 4.

We investigated the correlation between the \( \gamma \)-ray flux and the optical flux density in the \( R \) band by means of the DCF method, computing the DCF on four distinct periods: July 2007 (mid 2007), November–December 2007 (Fall 2007), May–August 2008 (mid 2008), and October 2007 - January 2009 (Fall 2008). The period “fall 2007” offers a good opportunity to test the correlation, since the \( \gamma \)-ray flux, and even more the optical flux, exhibited strong variability, and the period of common monitoring lasted for more than a month. The corresponding DCF shows a maximum DCF \( \sim 0.38 \) for a null time lag. However, the shape of the peak is asymmetric, and a centroid calculation yields a time lag of \(-0.42 \text{ days}\). This result is in agreement with what was found by Donnarumma et al. (2009) and by Bonning et al. (2009).

4. Conclusions

Since July 2007, 3C 454.3 has been playing the same role for AGILE as 3C 279 had for EGRET, and during the period July 2007 - January 2009 we acquired data not only in the \( \gamma \)-ray energy band, but across 14 decades in energy. This allowed us to construct simultaneous SEDs, sampling high, intermediate, and low \( \gamma \)-ray emission states, involving both ground and space based observatories.

We found that the role of the external Compton on the disk and the broad-line region radiation (and possibly also on hot corona photons) is crucial to
account for the hard γ-ray spectrum states. Moreover, thanks to the extremely dense optical coverage provided by the GASP-WEBT, we were able to study the
correlations between the \( \gamma \)-ray and optical fluxes. We found a \( \simeq 1 \) day possible lag of the high energy photons with respect to the optical ones.

The simultaneous presence of two \( \gamma \)-ray satellites, AGILE and Fermi, the extremely prompt response of wide-band satellites as Swift, and the long-term monitoring provided from the radio to the optical by the GASP-WEBT Consortium will assure the chance to investigate and study the physical properties of 3C 454.3 and of several more blazars both at high and low emission states.

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