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The *Crazy Diamond* 3C 454.3 and its siblings: confirmations and surprises

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Blazars show intense and variable γ-ray emission, and their properties have been investigated since the COS–B and CGRO era. Nevertheless, the AGILE and *Fermi* satellites are detecting recurrent flaring gamma-ray events from objects such as 3C 454.3 (the *"Crazy Diamond"*), 4C +21.35, 3C 273, and PKS 1510−089 which, for both their intensity and durations, are absolutely unique. This remarkable γ-ray activity is a powerful tool to investigate the central regions of those sources, especially when combined with optical and X-ray data. On the other hand, such an unprecedented level of activity challenges the current theoretical models. We present the γ-ray and multi-wavelength data collected so far, review the physical interpretations proposed for these extraordinary activity, and discuss the open points raised by these findings.

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1. Introduction

Multi-wavelength studies of γ-ray active galactic nuclei (AGNs) date back to the late '70s and the early '80s with the COS–B detection of 3C 273 [1, 2]. Nevertheless, the paucity of extragalactic γ-ray sources detected by SAS-2 and COS-B prevented systematic multi frequency studies. It was during the '90s, with the launch of CGRO, that EGRET allowed to establish blazars as a class of γ-ray emitters and to start multi wavelength studies of such sources. For a few sources, it was possible to study both the properties of the SEDs during different γ-ray states, and the search for correlated variability at different bands (e.g., 3C 279 [3, 4]).

The launches of the AGILE [5] and *Fermi* [6] satellites allowed the blazar community to observe a large fraction of the sky above 100 MeV, thanks to their wide ($\sim 3\,$sr) field of view (FoV), and to start a more effective multi-wavelength approach in their spectral energy distribution investigation.

2. The *flaring* sources

During the EGRET era, the most intense γ-ray flare was recorded on 1995 June 26 from PKS 1622$-$29 [7], with a peak flux (E$>$ 100 MeV) of the order of $(17 \pm 3) \times 10^{-6}$ photons cm^{-2} s^{-1} and a doubling time of about 3.8 hr, which made this event the first intra-day variability detection above 100 MeV. Neither PKS 1622$-$29, nor other sources showed a flux $> 10^{-5}$ photons cm^{-2} s^{-1} during the remainder of the EGRET observing period. By comparison, the most active γ-ray source in that period was 3C 279 [8], which was detected almost during each pointing, reaching a peak flux value of $(2.8 \pm 0.4) \times 10^{-6}$ photons cm^{-2} s^{-1}.

Immediately after the AGILE launch, two well-known γ-ray blazars were caught in flare in July 2007, 3C 279 [9], and 3C 454.3 [10]. While the γ-ray flux (E$>$ 100 MeV) of 3C 279 was of the same order of the peak flux reported by EGRET, the 3C 454.3 one was a factor of 3–4 higher than previously reported. Since then, 3C 454.3 played the same role for AGILE as 3C 279 had for EGRET, and for this reason we dubbed 3C 454.3 "*Crazy Diamond*". Roughly speaking, we can divide AGILE-detected flaring sources into three different categories (flux units in photons cm^{-2} s^{-1}): *Category–3, several tens* of sources whose γ-ray flux is of the order of $F_{\rm E>100\,MeV} \sim 2 \times 10^{-6}$; *Category–2, a dozen* of sources whose flux is of the order of $F_{\rm E>100\,MeV} \sim 5 \times 10^{-6}$; *Category–1, a handful* of sources whose flux is of the order of $F_{\rm E>100\,MeV} \sim 10 \times 10^{-6}$.

Among Category–3 sources, S5 0716+714 underwent a very bright γ-ray flare during September–October 2007 [11 – 13]. The estimate of the redshift of this intermediate BL Lac object, $z = (0.31 \pm 0.08)$ [14], allowed us to compare the total power transported in the jet ($P_{\rm jet}$) with the power that can be extracted from a rotating black-hole by means of the Blandford–Znajeck mechanism ($P_{\rm BZ}$) [15]. We obtained that, during the high γ-ray state of this object ($F_{\rm E>100\,MeV} = (2.0 \pm 0.4) \times 10^{-6}$ photons cm^{-2} s^{-1}), $P_{\rm jet} \simeq P_{\rm BZ} \simeq$ a few $\times\, 10^{45}$ erg s^{-1}.

Among Category–2 sources, PKS 1510$-$089 showed intense and repeated γ-ray flares. It was first detected by AGILE at the end of August 2007, at a flux level of $F_{\rm E>100\,MeV} = (2.8 \pm 0.7) \times 10^{-6}$ photons cm^{-2} s^{-1}[16]. A similar peak flux level was observed in March 2008 [17]. Nevertheless, the most intense emission detected by AGILE from PKS 1510$-$089 occurred during

March 2010, when the source underwent a series of three rapid and intense flares on March 9–16, 20–22, and 25–26 [18], reaching a peak flux on 2009 March 25–26 of $F_{\rm E>100\,MeV} = (7.0 \pm 1.3) \times 10^{-6}$ photons cm^{-2} s^{-1}. During the whole month, a multi-wavelength campaign confirmed the evidence of thermal signatures in the optical/UV spectrum of the source also during a high γ-ray state. Moreover, the flat optical/UV spectrum observed on 2009 March 25–26 suggests a shift of the synchrotron peak during the major γ-ray flare.

At least 4 sources can be enlisted into the Category–1 group, namely 3C 454.3, 4C +21.35, PKS 1830−21, and PKS 1622−297. We describe in details the former three below.

2.1 PKS 1830−21

This source is a well known gravitationally-lensed γ-ray blazar ($z = 2.507$) lying in the Galactic Bulge. The source average γ-ray flux reported in the Third EGRET Catalog and in the First *Fermi* Catalog was of the order of $F_{\rm E>100\,MeV} \sim 0.2 \times 10^{-6}$ photons cm^{-2} s^{-1} [19, 20]. On 2009 October 12–13, AGILE detected a γ-ray flare, $F_{\rm E>100\,MeV} = (1.6 \pm 0.5) \times 10^{-6}$ photons cm^{-2} s^{-1} [21]. One year apart, on 2010 October 14, *Fermi* detected rapid and extremely intense γ-ray flare,

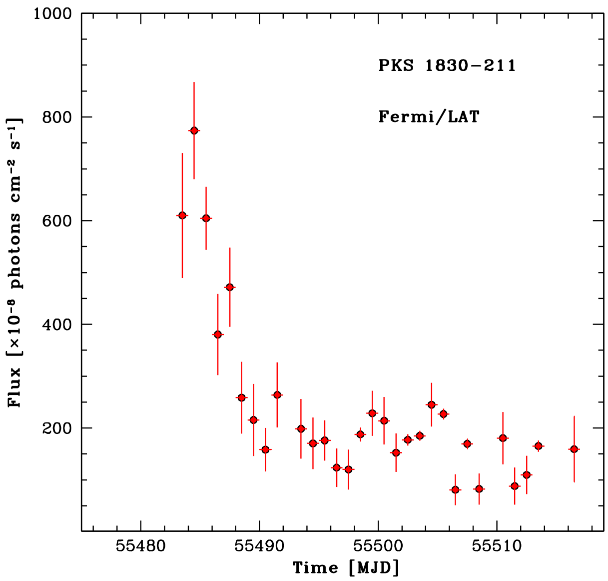

Figure 1: Light-curve (E> 100 MeV) describing the γ-ray flare of PKS 1830−21. The public *Fermi*/LAT monitored source list light curves were used, with a time-bin of 1–day.

whose 6-hour peak flux reached $F_{\rm E>100\,MeV} = (14 \pm 5) \times 10^{-6}$ photons cm^{-2} s^{-1} [22], and whose high state emission lasted for several days [23]. This remarkable γ-ray event triggered a multi-wavelength campaign, whose results will appear in [24]. Figure 1 shows the public[1] *Fermi*/LAT light curve of this event.

[1] `http://fermi.gsfc.nasa.gov/FTP/glast/data/lat/catalogs/asp/current/lightcurves/`

2.2 4C +21.35

4C +21.35 (PG 1222+216, $z = 0.432$) average γ-ray flux reported in the Third EGRET Catalog and in the First *Fermi* Catalog is below $F_{\rm E>100\,MeV} < 0.5 \times 10^{-6}$ photons cm^{-2} s^{-1} [19, 20]. This source became active in 2009, when AGILE detected a γ-ray flare with a flux $F_{\rm E>100\,MeV} > 2.5 \times 10^{-6}$ photons cm^{-2} s^{-1} [25]. On 2010 April 24, *Fermi* reported a very intense γ-ray flare with a 6–hours integration peak flux of $F_{\rm E>100\,MeV} = (16.2 \pm 2.6) \times 10^{-6}$ photons cm^{-2} s^{-1} [26]. During this extremely intense γ-ray flare, the MAGIC Telescope detected this source at a flux (E> 100 GeV) greater than 0.3 Crab [27]. On 2010 June 17–19 AGILE [28] and *Fermi* [29] detected another intense γ-ray flare, reaching on 2010 June 18 a 6–hours integration peak flux of $F_{\rm E>100\,MeV} = (16.4 \pm 1.9) \times 10^{-6}$ photons cm^{-2} s^{-1}. Figure 2 shows the public *Fermi*/LAT light curve of 4C +21.35, where the two intense γ-ray flares above 10^{-5} photons cm^{-2} s^{-1} are clearly visible. During this last episode, a multi-wavelenght campaign was conducted whose results will appear in [30].

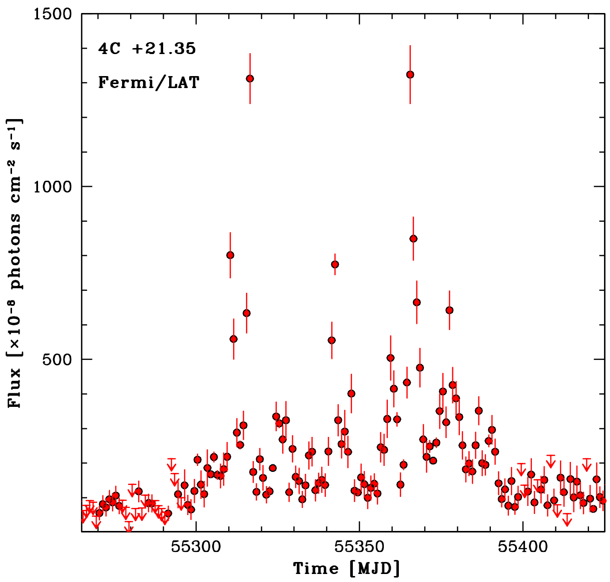

Figure 2: Light-curve (E> 100 MeV) describing the repeated γ-ray flares of 4C +21.35. The public *Fermi*/LAT monitored source list light curves were used, with a time-bin of 1–day.

Recently, [31] discussed the implication of a simultaneous detection both in the MeV–GeV and GeV–TeV energy bands. The fast γ-ray (E> 100 MeV) variability, of the order of 3–6 hours, would suggest a region of emission inside the broad-line region (BLR). On the contrary, the simultaneous lack of a spectral break at $\sim$a few tens of GeV would imply an emission region outside the BLR.

2.3 3C 454.3

3C 454.3 is, beyond any doubt, the most variable γ-ray blazar so far. In May 2005, it underwent an almost simultaneous flare from the radio to the X-ray energy bands (see [32] for a review of its properties on a 18-months time-scale). Since 2007, several γ-ray flares were recorded, both by AGILE and by *Fermi*. On 2008 July 10, *Fermi* detected the first γ-ray flare above 10^{-5} photons cm^{-2} s^{-1} from this source [33]. The detailed analysis of this event, reported in [34], showed a γ-ray flux of about 1.2×10^{-5} photons cm^{-2} s^{-1}, and the first evidence of a break in the γ-ray spectrum, at an energy of about 2–3 GeV. The second γ-ray "super-flare"

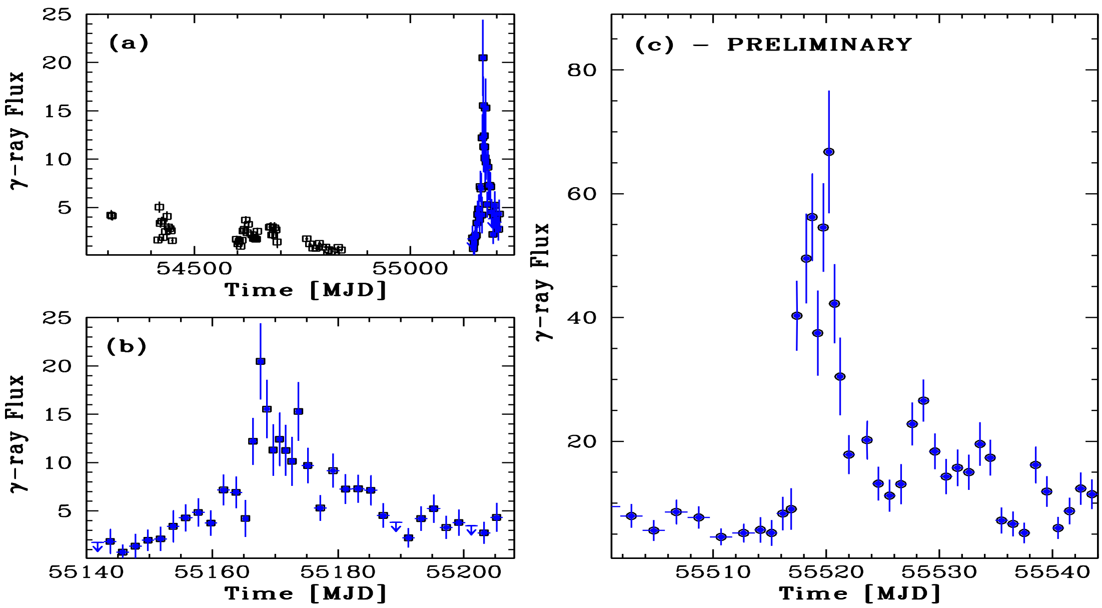

Figure 3: *Panel (a):* light-curve (E> 100 MeV) of the 2009 December 2–3 γ-ray super-flare. Data from [32] (grey squares) and from [35] (blue squares). *Panel (b):* zoom on the super-flare episode. *Panel (c):* light-curve of the 2010 November 20 super-flare [36]. γ-ray fluxes are in units of 10^{-6} photons cm^{-2} s^{-1}.

was detected on 2009 December 2–3 both by AGILE and by *Fermi*. Figure 3 (panel a and b) shows both the historical (grey squares) and the flaring (blue squares) γ-ray light curves. The source reached a γ-ray flux of $F_{\mathrm{E}>100\,\mathrm{MeV}} \sim (20 \pm 4) \times 10^{-6}$ photons cm^{-2} s^{-1}, remaining above 10^{-5} photons cm^{-2} s^{-1} for more than a week [35]. The results of a multi-wavelength campaign that began immediately after this super-flare are discussed by [37], who invoked, during the super-flare, the presence of a second model component super-imposed to the canonical one-zone emission model. A third super-flare was detected on 2010 April 3 [38], reaching a γ-ray flux of $F_{\mathrm{E}>100\,\mathrm{MeV}} \sim (16 \pm 1) \times 10^{-6}$ photons cm^{-2} s^{-1} on a 1-day time-bin. Recently, on 2010 November 20, this source reached a flux approximately 6 times more intense than the Vela pulsar, above $F_{\mathrm{E}>100\,\mathrm{MeV}} \sim 60 \times 10^{-6}$ photons cm^{-2} s^{-1} on a 1-day time-bin [39 – 42]. Figure 3 (panel c) shows the preliminary γ-ray light-curve during this extraordinary super-flare. A multi-wavelength campaign was immediately triggered, whose results will appear in [36].

3. Discussion: what we know and what we miss

The γ-ray flares and, above all, the intense and extremely fast super-flares are partially shedding light on the physical properties of these sources. Nevertheless, there are some important key characteristics which are still being debated.

The "special ones". Up to now, only a few sources have displayed extremely intense γ-ray flares ($F_{\mathrm{E}>100\,\mathrm{MeV}} > (5-10)\times 10^{-6}$ photons cm^{-2} s^{-1}), and most of them have shown repeated flaring events. On the other hand, a remarkable number of sources showed flares above $\sim 2\times 10^{-6}$ photons cm^{-2}s^{-1}. While for the latter objects a possible explanation is given in terms of jet with a higher Doppler-boosting factors [43], the behavior of the former objects is still difficult to explain.

The γ-ray emitting region. The variability studies of γ-ray super-flares are extremely important in order to constraint the size of the γ-ray region. A flux doubling time of the order of 3 hr, as derived by [44] for three flat-spectrum radio quasars (3C 279, 3C 454.3, and 4C +21.35), would suggest a very compact size of the γ-ray emitting region, $\ll 1$ pc, and thus well inside the BLR. However, the recent findings of TeV emission in PKS 1510−089 [45] and 4C +21.35 [31] challenge the current simple one-zone emission model and could require a different jet morphology.

The long-term trends. Both AGILE and *Fermi* allow us to obtain a simultaneous long-term monitoring of several flaring blazars, and to study their variability properties. 3C 454.3 average flux during the EGRET era was of the order of $\sim 0.5\times 10^{-6}$ photons cm^{-2} s^{-1}, with flares lasting no longer than a week. Since August 2009, it has been always detected, and its "ground level" increased of about one order of magnitude, up to a few times 10^{-6} photons cm^{-2} s^{-1}. Currently, its flux level is of the order of 3×10^{-6} photons cm^{-2} s^{-1}, with no clear sign of decline. Such a change could be interpreted as the changing of the orientation of a curved inhomogeneous jet, as suggested in [46].

Acknowledgments

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