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## Gamma-ray binaries detected by AGILE

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**Abstract** The AGILE satellite is observing the  $\gamma$ -ray sky since its launch on April 23, 2007. Several important discoveries have been made in Galactic and extragalactic astrophysics starting from its observations above 50 MeV. In this work, I reviewed the most important findings in the study of  $\gamma$ -ray emitting Galactic binary systems: the first detection above 100 MeV of Cygnus X-1, the discovery of  $\gamma$ -ray transient emission from Cygnus X-3, the first observation of a colliding wind binary in  $\gamma$  rays. The AGILE continuous monitoring of the  $\gamma$ -ray sky is a fundamental ingredient to investigate the non-thermal emission from these sources, the disk-jet coupling, the limit of relativistic particle acceleration in the jet, the origin of the high-energy  $\gamma$ -ray radiation.

**Keywords** Gamma rays · Binary Systems

### 1 Introduction

The AGILE (Astrorivelatore Gamma a Immagini LEggero) satellite [15] is monitoring the  $\gamma$ -ray sky since April 2007. It had operated in a “pointing” mode data-taking, characterized by fixed attitude observations, until November 2009, when the satellite entered in “spinning” mode, covering a large fraction of the sky with a controlled rotation of the pointing axis. In this current observing mode, typical 2-day integration-time sensitivity ( $3\sigma$ ) for sources in the Galactic plane and photon energy above 100 MeV is  $\sim 10^{-6}$  photons  $\text{cm}^{-2} \text{s}^{-1}$ . In this work, I took into account the data collected by the *GRID* (Gamma-Ray Imaging Detector [1,11]), the  $\gamma$ -ray silicon-tracker imager on board the AGILE satellite.

The AGILE observations have been crucial for better understanding the physical mechanisms regulating the most powerful Galactic and extragalactic particle-accelerator systems. Among them, a new class of Galactic  $\gamma$ -ray

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emitting astrophysical sources has been detected, showing strong transient emission above 50 MeV: the gamma-ray binaries. This class of high-energy emitting sources includes a large variety of heterogeneous binary systems [3]: microquasars, High Mass X-ray Binaries (HMXBs), colliding wind binaries, novae, millisecond pulsars.

In this paper I reviewed the most important AGILE findings in the field of  $\gamma$ -ray binaries, presenting the observations of the microquasars in the Cygnus region (Cygnus X-1, Cygnus X-3 and V404 Cygni), the colliding wind binary  $\eta$ -Carinae and the AGILE source AGL J2241+4454, possibly associated with MWC 656.

## 2 Microquasars in the Cygnus region

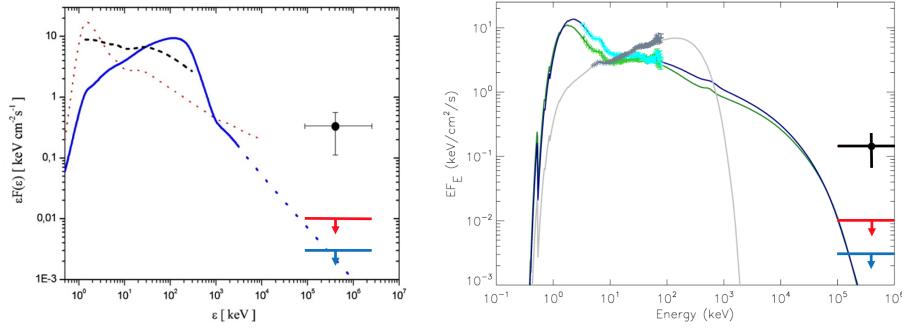
Observing towards the Cygnus region (Galactic coordinates  $l \sim 75^\circ\text{--}85^\circ$ ) means looking through the Local Arm (Orion Spur), the Perseus Arm and the Outer Arm along the same line-of-sight. Thus, there is a huge superposition of Galactic objects (mainly distributed in the high-density arms) located at the same angular coordinates, but at different distances along the line-of-sight. In the  $\gamma$ -ray band ( $E > 50$  MeV), AGILE and *Fermi*-LAT observed a strong diffuse emission underlying the radiation from several persistent (pulsars, SNRs, ...) and transient sources.

During the “pointing” mode, AGILE repeatedly pointed at the Cygnus region for a total of  $\sim 275$  days, corresponding to a net exposure time of  $\sim 11$  Ms. The current “spinning” data-taking configuration allows a constant monitoring of such a crowded region of the sky. Several episodes of transient  $\gamma$ -ray emission from three microquasars of the Cygnus region (Cygnus X-1, Cygnus X-3 and V404 Cygni) were detected by the AGILE-GRID.

Microquasars [7] – the stellar-scale version of a quasar – are X-ray binaries powered by accretion of matter from a stellar companion onto a compact object (a black hole or a neutron star). In these systems a significant fraction of the accretion energy is channeled to launch relativistic jets, characterized by non-thermal emission.

### 2.1 Cygnus X-1

Cygnus X-1 is the archetypal black hole binary system of our Galaxy. It is located at a distance of 1.9 kpc, and is composed of a black hole of  $4.8\text{--}14.8 M_\odot$  and a O9.7 Iab supergiant star companion. The orbital period is 5.6 days. It is one of the brightest persistent sources in the X-ray sky. Typical X-ray spectral states of Cygnus X-1 have been classified as “low/hard” and “soft/high”. The system usually spends  $\sim 90\%$  of its time in the low/hard state, whose Spectral Energy Distribution (SED) is characterized by a prominent peak around 100 keV and a high-energy cutoff  $\sim 150$  keV. The soft/high spectrum is described by a strong black-body component ( $kT \sim 0.5$  keV) and a power-law tail with index  $\Gamma \sim 2 - 3$ .



**Fig. 1** *Left panel:* AGILE broad-band spectrum of Cygnus X-1 (black point) for the October 15-16 2009 flaring episode, with the corresponding typical X-ray SEDs for the soft/high (dotted red line), intermediate (dashed black line) and low/hard (blue solid line) states [12]. *Right panel:* AGILE broad-band spectrum of Cygnus X-1 (black point) for the June 30 – July 02 2010 flaring episode, with the corresponding X-ray spectra before and after the hard-to-soft spectral transition [13]. In both panels, red and blue points are AGILE 2-sigma upper limits related to long-time observations during soft and hard spectral states, respectively.

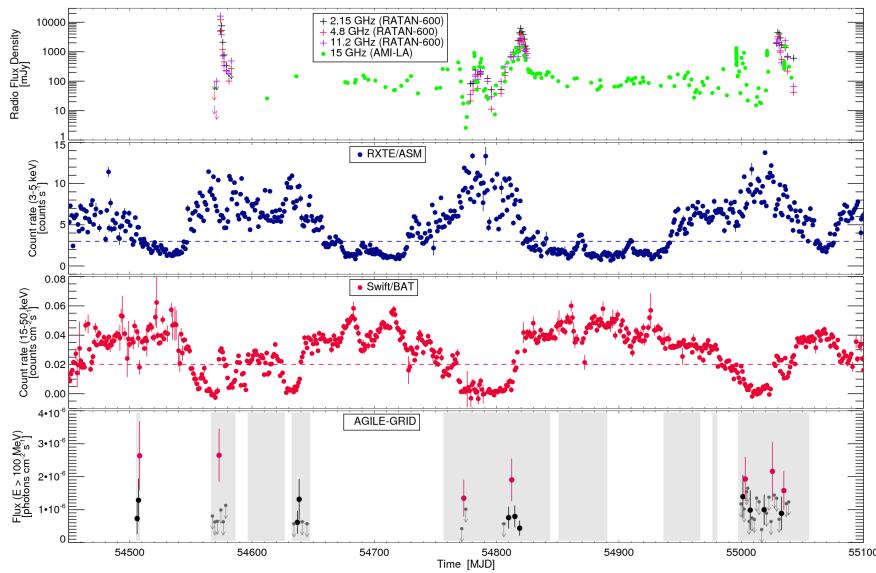
AGILE detected two strong  $\gamma$ -ray flares, the first one (October 15-16 2009) during a hard state [12], and the second one (June 30 – July 02 2010) during a hard-to-soft spectral transition [13]. The  $\gamma$ -ray flare detected by AGILE cannot be accounted for by the standard Comptonization models – related to the physics of the disk-corona – that perfectly fit the X-ray spectra of the system (see Fig. 1). A new component is required in order to account for the high-energy  $\gamma$ -ray flares, possibly related to the physics of the relativistic jets.

Besides the flaring-episode detections, the AGILE spectral upper limits from long-term observations gave important constraints to the standard Comptonization models both for the high/soft and low/hard states [13].

## 2.2 Cygnus X-3

Cygnus X-3 was discovered, as an X-ray source, in 1966 [5]. It is located at a distance of 7-10 kpc and it is composed of a Wolf-Rayet (WR) star ( $M > 7M_{\odot}$ ) with a strong helium wind and a compact object, whose nature is still uncertain. The orbital period, as inferred from infrared, X-ray and  $\gamma$ -ray observations, is 4.8 hours. Owing to its very tight orbit (orbital distance  $d \approx 3 \times 10^{11}$  cm), the compact object is totally enshrouded in the wind of the companion star.

High-energy  $\gamma$ -ray activity from Cygnus X-3 was firmly discovered in late 2009: the AGILE team found evidence of strong  $\gamma$ -ray transient emission above 100 MeV coincided with special X-ray/radio spectral states [16], and the *Fermi*-LAT collaboration announced the detection of  $\gamma$ -ray orbital modulation [4]. By analyzing the AGILE data, a repetitive pattern of multiwave-length emission was found (see Fig. 2.2): the  $\gamma$ -ray flares usually occur during



**Fig. 2** Multi-frequency light curve of Cygnus X-3 from 2007 December 12 to 2009 September 26 (MJD: 54450-55100). From top to bottom: radio flux density [RATAN-600 (2.15, 4.8, 11.2 GHz) and AMI-LA (15 GHz)], soft X-ray count rate [*RXTE*/ASM (3-5 keV)], hard X-ray count rate [*Swift*/BAT (15-50 keV)], and gamma-ray photon fluxes [AGILE-GRID (above 100 MeV)]. In the bottom panel, gray regions represent the AGILE pointing at the Cygnus region; magenta points are the main events of  $\gamma$ -ray activity with  $\sqrt{TS} \geq 3$ , black points are the  $\gamma$ -ray detections with  $2 \leq \sqrt{TS} < 3$ , and dark-gray arrows are the  $2\sigma$  upper limits related to  $\sqrt{TS} < 2$ . The dashed lines in the panels of the *RXTE*/ASM and *Swift*/BAT count rate represent the transition level of 3 counts  $s^{-1}$  and 0.02 counts  $cm^{-2} s^{-1}$  respectively [9].

soft X-ray spectral states, a few days before strong radio outbursts [9]. In particular, the  $\gamma$ -ray transient emission is revealed when the system is moving into or out of the quenched state of Cygnus X-3, a characteristic radio/X-ray spectral state that in general precedes major radio flares. Thus, from a phenomenological point of view, the quenched state represents a key condition for the  $\gamma$ -ray activity above 100 MeV. The flaring  $\gamma$ -ray emission requires a new component in the multiwavelength SED, possibly related to the physics of the relativistic jets: both a leptonic (inverse Compton – IC – processes between electrons/positrons in the jet and soft photons from the star and the accretion disk) and a hadronic ( $\gamma$  rays from the decay of  $\pi^0$  mesons produced in inelastic collisions between hadrons of the jet and nuclei of the WR wind) emission models can account for the  $\gamma$ -ray radiation detected by AGILE. Nevertheless, a leptonic scenario is favored: it can explain in a more natural way the observed  $\gamma$ -ray modulation (anisotropic IC scattering), requires a lower jet kinetic power ( $L_{kin}^e \leq 10^{37} \text{ erg s}^{-1}$ ,  $L_{kin}^p \approx 10^{38} \text{ erg s}^{-1}$ ), and suggests a spectral link with the X-ray hypersoft spectrum (the characteristic spectrum for the quenched state).

### 2.3 V404 Cygni

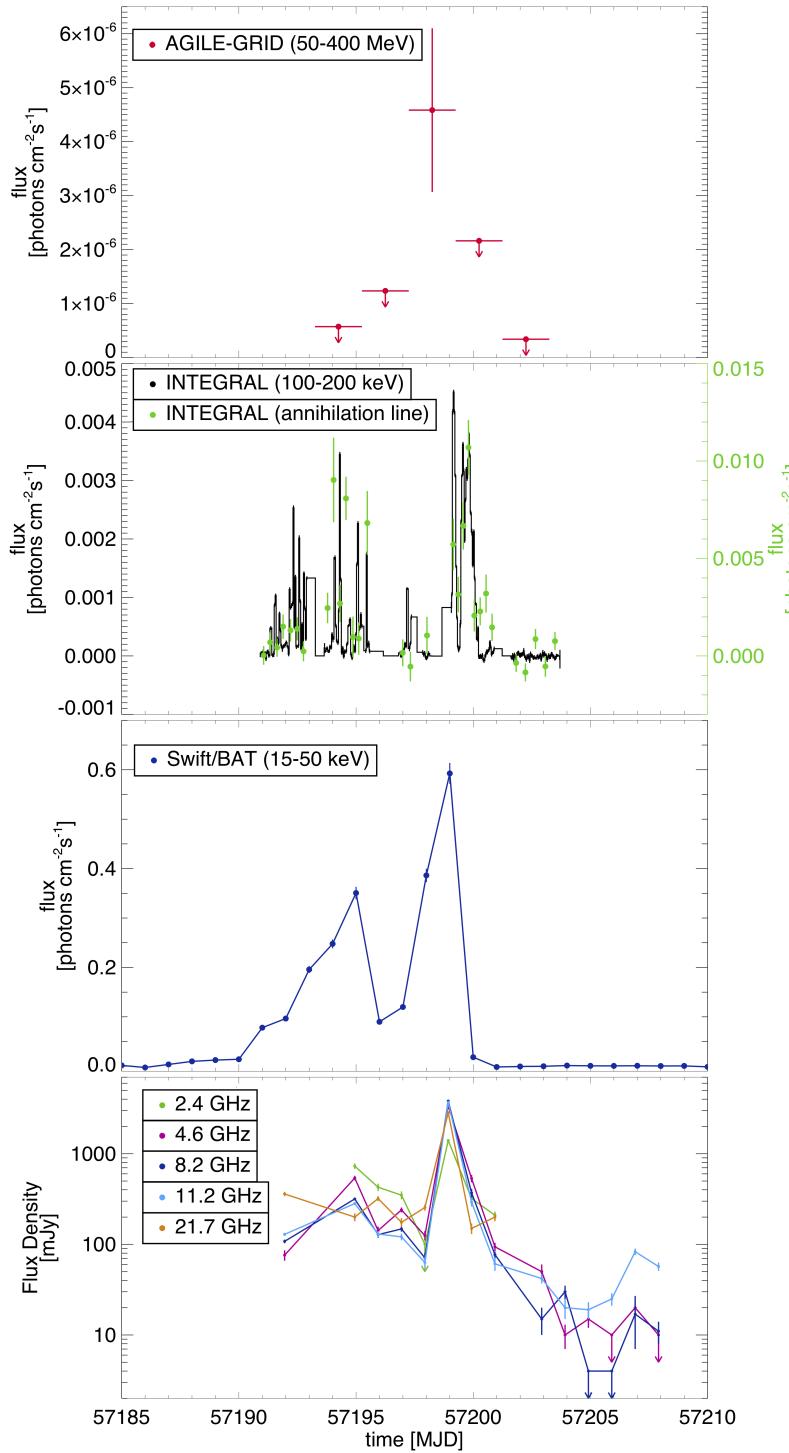
V404 Cygni is a Low Mass X-ray Binary (LMXB) located at a distance of  $(2.39 \pm 0.14)$  kpc. It is composed of a K3 III ( $0.7^{+0.3}_{-0.2} M_{\odot}$ ) and a  $9^{+0.2}_{-0.6} M_{\odot}$  black hole with an orbital period of  $6.4714 \pm 0.0001$  days. After a quiescence period of  $\sim 26$  years, the system entered in an active phase on June 15, 2015 that lasted  $\sim 2$  weeks and was observed across all wavelengths (from radio to  $\gamma$  rays). AGILE (50-400 MeV) and *Fermi*-LAT (60-400 MeV) detected a bright  $\gamma$ -ray flare on June 24-26, 2015 (see Fig. 3) [10], coincident with a bright outburst detected in radio (RATAN: 2.4-21.7 GHz), hard X-ray (*Swift*/BAT: 15-50 keV) and soft  $\gamma$  rays (INTEGRAL: continuum 100-200 keV and 511 keV annihilation line). The observations strongly support a microquasar scenario for V404 Cygni with a dominant leptonic component. In particular, the simultaneous  $e^+e^-$  annihilation line emission suggests a strong presence of antimatter (positrons) in the jet.

## 3 Eta Carinae

$\eta$ -Carinae is a Colliding Wind Binary (CWB) system located at a distance of 2.3 kpc, and is composed of a  $\sim 100 M_{\odot}$  luminous blue variable star and a O companion star. The orbit has a period of 5.53 years and is highly eccentric ( $e > 0.9$ ). It represents the first CWB ever observed in  $\gamma$  rays [17]: AGILE monitored the periastron passage (2007 July - 2008 October) and detected  $\gamma$ -ray activity from the source (average flux  $F_{\gamma} = (37 \pm 5) \times 10^{-8}$  photons  $\text{cm}^{-2} \text{s}^{-1}$ ), with a time evolution consistent with the X-ray light curve. According to the theoretical models, the  $\gamma$ -ray emission is produced by relativistic particles accelerated by shocks produced by the interaction of the dense and high velocity gaseous winds of the stars ( $\dot{M}_1 \simeq 2 \times 10^{-4} M_{\odot} \text{ yr}^{-1}$ ,  $\dot{M}_2 \simeq 2 \times 10^{-5} M_{\odot} \text{ yr}^{-1}$ ,  $v_1 \simeq 600 \text{ km/s}$ ,  $v_2 \simeq 3000 \text{ km/s}$ ).

## 4 AGL J2241+4454

AGILE detected transient  $\gamma$ -ray activity from a previously unidentified source, AGL J2241+4454, in July 2010 [6]. This detection triggered an important discovery: the first Be binary system hosting a black hole, MWC 656, was discovered by analyzing optical data from the source [2]. After the first serendipitous detection, we carried out a blind search in the AGILE data, looking for other transient  $\gamma$ -ray signals from AGL J2241+4454. We found 10 2-day flaring events from the source between 2007 and 2013 (both in pointing and spinning data-taking periods). In order to test the possible association with the binary system, we folded the data with the 60.37 day orbital period, but no periodicity was observed [8]. Thus, the association with MWC 656 remains uncertain.



**Fig. 3** Multiwavelength light-curve throughout the June 2015 outburst of V404 Cygni. From top to bottom: AGILE-GRID 50–400 MeV, 48 hours integration; INTEGRAL/SPI continuum (100–200 keV, black histogram) and annihilation line (green points); *Swift/BAT* 15–50 keV, 1-day bin; RATAN-600 radio flux density (2.4, 4.6, 8.2, 11.2 and 21.7 GHz) [10].

## 5 Conclusions and future perspectives

The AGILE observations shed new light in the understanding of  $\gamma$ -ray binaries, giving important constraints to the theoretical models that describes the physics of this heterogeneous class of astrophysical sources. AGILE's continuous monitoring of the  $\gamma$ -ray sky represent a fundamental ingredient to study the transient activity from these systems in a multiwavelegth and multimesenger context.

Future missions as e-ASTROGAM [14] would be crucial in the study of this important class of sources, analyzing with unprecedented sensitivity a new window of the non-thermal spectrum. In particular, observations in the 10-100 MeV band would be compelling in order to better understand the physics of disk-jet coupling, to disentangle between leptonic and hadronic emission model, and to explore new physics in these intriguing Galactic sources (see Fig. 4).

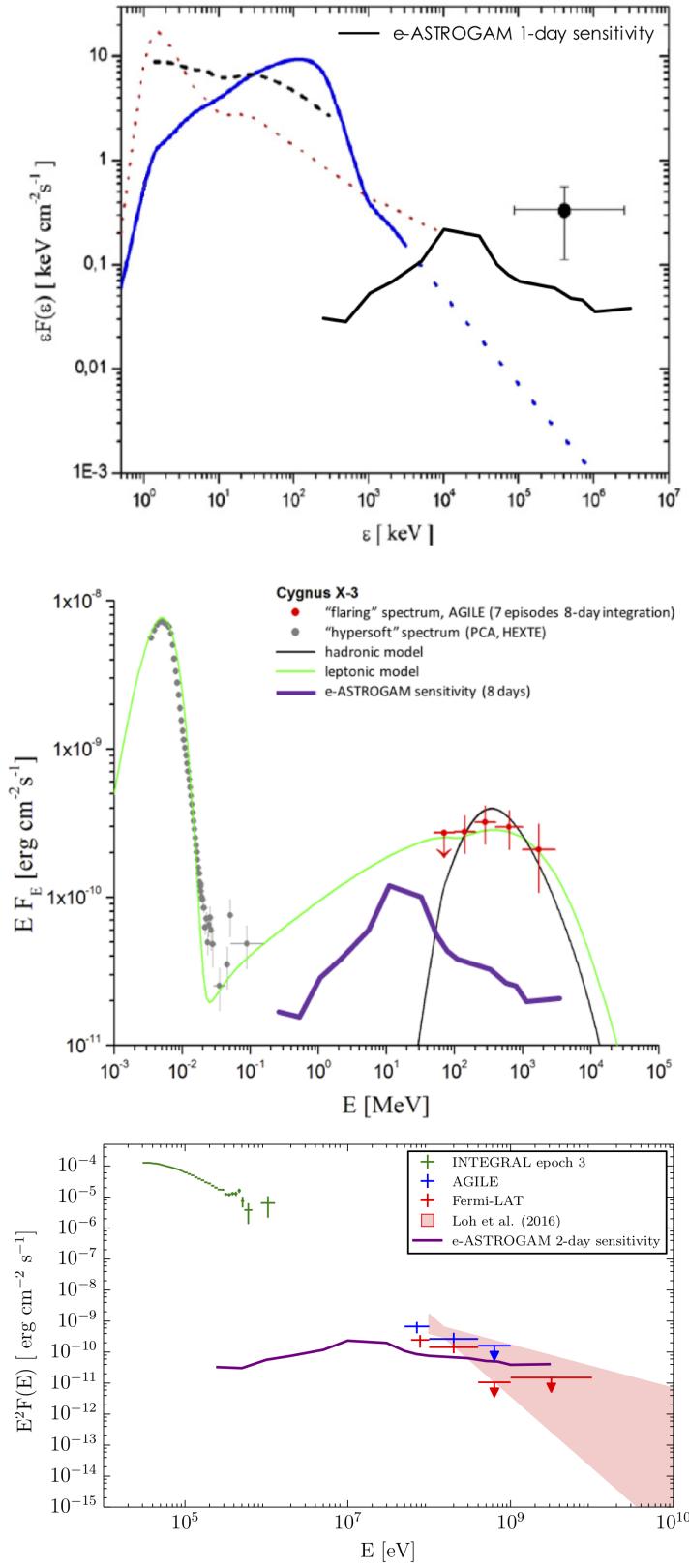
The Cherenkov Telescope Array (CTA)<sup>1</sup> will be fundamental in exploring the limit of extreme particle acceleration that is responsible of the high-energy  $\gamma$ -ray radiation from these binary systems.

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<sup>1</sup> <https://www.cta-observatory.org>



**Fig. 4** *Upper panel:* Cygnus X-1 flaring spectrum (October 15-16 2009 [12]) with the corresponding e-ASTROGRAM sensitivity. *Central panel:* Cygnus X-3 flaring spectrum [9], leptonic (green) and hadronic (black) emission models, with the corresponding e-ASTROGRAM sensitivity. *Bottom panel:* V404 Cygni flaring spectrum [10] with the corresponding e-ASTROGRAM sensitivity.

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