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Galactic microquasar transients with *AGILE*

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Abstract. The *AGILE* satellite has been proven to be an excellent tool to study transient gamma-ray sources since it entered in a spinning operational mode in 2009. Thanks to its scanning capabilities it observes the whole sky every few hours. Several new interesting systems were discovered, such as AGL J2241+4454 in 2010, probably associated to the mysterious black-hole high-mass X-ray binary MWC 656. With a state of the art PSF and sensitivity in the 100 MeV – 1 GeV energy range, *AGILE* studied this system in order to identify new periods of gamma-ray activity that could be associated to the binary, and found a total of 10 flares spanning from 2008 until 2013.

AGILE studied also the Cygnus region, finding evidence of a new recent gamma-ray flare from the microquasar Cygnus X-3, with a flux of $\sim 2\times10^{-8}$ ph cm^{-2} s, during a state transition phase in the bright high-soft X-ray state. Also Cygnus X-1 was detected in the past by *AGILE*, although both systems are very different and show different behaviour.

INTRODUCTION

Microquasars

Microquasars are scaled versions of quasars, one of the most extreme systems in the universe. Usually they consist of a main sequence star, of either low or high mass, and an accreting compact object, either a neutron star (NS) or a black hole (BH). The accretion onto the compact object is done through an accretion disk which can reach very-high temperatures emitting up to X-rays. The accretion process also produces two bipolar jets of accelerated particles that will interact with the ambient medium producing the high-energy (HE) emission by means of different physical processes, like inverse Compton (IC), relativistic Bremsstrahlung or hadronic processes like the pp-interactions that in turn produce π^0-decay.

In X-rays, BH microquasars change considerably their state of emission along the time, spending long periods in a quiescent state or in a low-hard state for, in short time, start increasing their flux as they soften their X-ray spectrum. This high-soft state usualy precedes strong radio flares that are explained by a plasmoid from the jet being expelled away from the system emitting synchrotron radiation as it cools away. After the radio flare, microquasars return slowly to their quiescent state, where the jet is thought to disappear again or it is too faint to be observed in radio. These systems are usualy discovered when they go into outburst in X-rays and in radio, which are thought to be produced when instabilities in the accretion disk trigger the sudden infall of matter onto the compact object and the subsequent acceleration of particles in the jet. Also the behavior of the companion star may play a role in causing these long-term changes in the accretion rate. See [1] for a complete review.

The *AGILE* Telescope

AGILE is a gamma-ray astrophysics mission operating since 2007 April [2]. It carries two main co-aligned instruments observing at hard X-rays between 18 and 60 keV (Super-*AGILE* , [3]) and at HE gamma rays between 30 MeV and 30

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GeV (*AGILE*/GRID, [4, 5]). The instrumentation is completed by a calorimeter sensitive in the 0.4–100 MeV range [6] and an anticoincidence detector [7]. *AGILE* has a wide field of view of about 2.5 sr at HE gamma rays and good sensitivity above 100 MeV. The PSF at 100 MeV and 400 MeV is $3^{\circ}.5$ and $1^{\circ}.5$ (68% containment radius), respectively [8]. The sensitivity after one week of integration time in pointing mode is at the level of 20–30$\times 10^{-8}$ cm^{-2} s^{-1} above 100 MeV, depending on the off-axis angles and pointing directions [2].
For the first time in a gamma-ray mission we had the simultaneous coverage in hard X-rays with Super-*AGILE* and in gamma rays with the GRID, which allowed more complete studies of variable HE sources and enhanced our understanding of them. In this work we will present the latest results of *AGILE* observations of microquasars regarding some well known systems, like Cygnus X-1 and Cygnus X-3, and newly discovered systems like AGL J2241+4454.

Cygnus X-1

Cygnus X-1 is a microquasar consisting of an O9.7 Iab supergiant star [9] orbited by a $\sim 15 M_{\odot}$ BH every 5.6 days, being until 2014 the only known high-mass BH binary system in our Galaxy. Cyg X-1 spends most of its time in a sub-Eddington optically thick hard state whose spectral energy distribution is well described by a power law with photon index $\Gamma \sim 1.7$ and a broad emission peak at around 100 keV, undergoing episodes of major accretion when the luminosity increases up to a factor of three. During these episodes the source is in the soft state, which is well fitted by a power law with photon index $\Gamma \sim 2-3$. The interpretation of the different spectral states relies normally in the interplay of a relatively cool accretion disk and a hot optically thick corona that surrounds the compact object. In the hard state, Comptonization of the abundant black body photons from the accretion disk by a hot, quasi-thermal population of electrons in the corona explains well the detected emission [10].
The *AGILE* satellite pointed several times to the Cygnus region between 2007 and 2009 getting up to 315 days (~ 13 Ms) of exposure. These data were searched for persistent and transient gamma-ray emission. A transient event was detected in 2009 during a high state in X-rays [11]. During the spinning obervation mode of *AGILE* Cygnus X-1 was also detected in 2010 during a hard-to-soft state transition [12, 13]. These two detections reveal the capabilities of Cygnus X-1 to produce strong short-lived episodes of extreme particle acceleration.

Cygnus X-3

Cygnus X-3 is a microquasar composed by a Wolf-Rayet (WR) star and a compact object of unknown nature. It is also the brighest microquasar in the radio wavelengths. Since its discovery in 1966 as an X-ray source [14] it has fascinated the HE astrophysics comunity. The two components of the system orbit each other every 4.8h [15] in a very close orbit, in which the compact object is completely embedded within the strong wind of the WR star. In the radio domain, the system often produces strong radio flares which are preceded by strong changes in the X-ray emission. During these state changes also gamma-ray emission episodes can be observed. In [16] a strong anticorrelation between hard X-rays (seen by Super-*AGILE*) and soft X-rays (seen by *RXTE*) was observed for the first time simultaneously preceding a gamma-ray flare (seen by *AGILE*-GRID). Shortly after this episode, a strong radio flare was observed indicating the ejection of a plasmoid in the jet of this microquasar. Figure 1 shows the multiwavelength behavior of this microquasar during an active period in gamma rays [16].

The gamma-ray activity is usually forseen when the *Swift*/BAT count rate in the 15–50 keV falls below the 0.02 s^{-1} [17] and the soft X-ray emission starts to grow. This correlation, preceeding also strong radio flares, might open new areas to study the interplay between the accretion disk, the corona, and the formation of relativistic jets. As stated in [17], the gamma-ray detections of Cygnus X-3 provide with constraints to the emission models indicating that hybrid Comptonization mechanisms cannot explain the gamma-ray fluxes seen by *AGILE* and *Fermi*/LAT above 100 MeV, implying that the corona cannot be the site where the gamma-ray emission is produced. The nature of the emission is, however, still not clear since different models (leptonic model based on inverse Compton emission from a relativistic plasmoid injected into the jet, and a hadronic model based on π^0-decays) are compatible with the observed data.

In January 2016 *Fermi*/LAT [18] and *AGILE* [19] observed another gamma-ray event from this puzzeling microquasar in correspondence, as usual, with a decrease in the *Swift*/BAT 15–50 keV emission below the 0.02 s^{-1} which indicated a probable transition to the soft state.

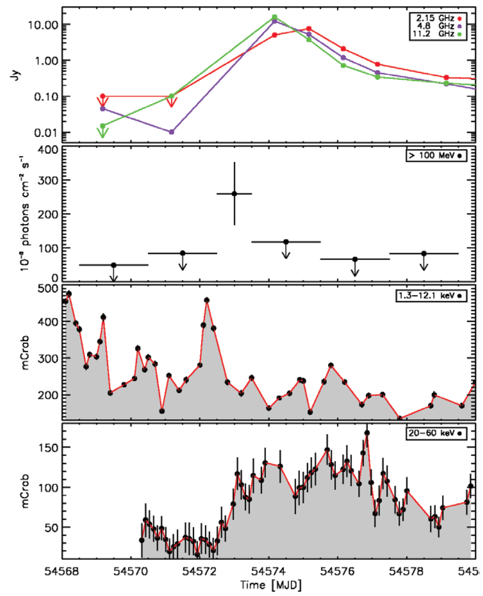

FIGURE 1. Multiwavelength light curve from Cygnus x-3 in the active period of 2008. Upper panel: radio RATAN at GHz frequencies. Central upper panel: *AGILE*-GRID data in the 100 MeV–50 GeV energy band. Central lower panel: *RXTE* data in soft X-rays between 1.3 and 12.1 keV. Lower panel: *SUPER-AGILE* data in the hard X-ray band between 20 and 60 keV. Figure from [16].

AGL J2241+4454

In July 2010 *AGILE* discovered a new transient gamma-ray source, namely AGL J2241+4454. Shortly after it was suggested to be the counterpart of MWC 656, a Be star showing a 60.37 variability period [20], indicative of the presence of a second body and hence, a possible binary system. In 2012 the binary nature of the system was confirmed by [21] and in 2014 the BH nature of the compact object was established by [22]. The X-ray conunterpart of the system was discovered by [23] using the *XMM-Newton* X-ray telescope. The X-ray emission of MWC 656 is very faint, indicating that the binary system was in a quiescent state, and thus, the spectral characterization of the system was dificult. A two component model was used to fit the data, interpreting a thermal component as the contribution of the hot wind of the Be star and a non-thermal powerlaw component as arising from the vicinity of the BH. The detection of the first Be/BH system in X-rays allowed also the study of the binary system in the context of the radio vs X-ray luminosity correlation at very low accretion rates, studied by [24, 25, 26].

In gamma rays we searched in the *AGILE* archive for more transient events coming from the same region of the sky and these results are published in [27]. In fact, we found another 9 gamma-ray events positionaly compatible with AGL J2241+4454 spreading from 2007 to 2013 (see Table 1). These detections are at the limit of the sensitivity of our instrument, but the stacking of all 10 events allowed us to perform a spectral analysis of the source, finding that the spectrum is well fitted with a powerlaw model with photon index $\Gamma = 2.3 \pm 0.2$ (see Figure 3). This stacked analysis allowed also for an improvement in the best fit position in the sky, with galactic coordinates $(l, b) = (100^{\circ}\!.37, -12^{\circ}\!.39) \pm 0^{\circ}\!.35$ (see Figure 2). The overall significance for the stacked analysis is $\sqrt{TS} = 8.9$. The post-trial analisis using the method described in [28] allowed us to be confident to say that the total 10 detections are not likely made by chance (overall chance probability of the detections $P = 6.8 \times 10^{-7}$).

The association of AGL J2241+4454 with MWC 656 is, however, still not clear: there is another possible counterpart, namely RX J2243.1+4441, a radio galaxy with a possible FR-II type classification (as interpreted from the radio observations by [30]) and thus less probable to be a gamma-ray emitter. However, given the binary nature of MWC 656, its X-ray emission compatible with the quiescent state in a high-mass X-ray binary and the transient gamma-ray emission observed by *AGILE*, we strongly consider MWC 656 the most probable counterpart of AGL J2241+4454.

TABLE 1. *AGILE* gamma-ray transient detections around the position of MWC 656. Table from [27].

t_{start} $[UT]$	t_{end} $[UT]$	Flux $[\times10^{-6}$ cm^{-2} s$^{-1}]$	$\sqrt{TS}$
2007-11-23 UT00:00:00	2007-11-24 UT00:00:00	1.5 ± 0.5	4.5
2008-06-28 UT00:00:00	2008-06-30 UT00:00:00	0.6 ± 0.3	3.2
2009-01-04 UT00:00:00	2009-01-07 UT00:00:00	0.5 ± 0.2	3.1
2010-06-13 UT00:00:00	2010-06-14 UT00:00:00	1.4 ± 1.1	3.2
2010-06-30 UT00:00:00	2010-07-02 UT00:00:00	1.3 ± 0.6	3.1
2010-07-25 UT00:00:00	2010-07-27 UT00:00:00	1.4 ± 0.6	5.3
2011-04-09 UT00:00:00	2011-04-11 UT00:00:00	2.2 ± 1.1	3.1
2011-10-08 UT00:00:00	2011-10-10 UT00:00:00	2.5 ± 1.1	3.4
2013-03-07 UT00:00:00	2013-03-08 UT09:00:00	2.6 ± 1.4	3.1
2013-07-10 UT00:00:00	2013-07-12 UT00:00:00	3.2 ± 1.6	3.5

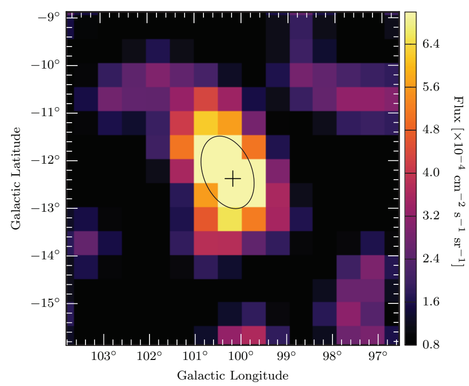

FIGURE 2. *AGILE* 2-day integration intensity map corresponding to data published in [29] at date 2010–07–25 (MJD 55402). Black ellipse represents the 95% c.l. containment of gamma-ray flux and black cross marks the nominal position of the Be star MWC 656. Color-map represents 3-pixels kernel gaussian smoothed number of counts, with a pixel size of 0.°5. Figure from [27].

A study of the distribution of the gamma-ray events seen by *AGILE* shows that there is no repetitive pattern over time and also that there is no preferred orbital phase in which the emission might be concentrated. This is not surprising, however, since the orbital excentricity is very low (0.10±0.04, [22]) and hence there is not much diference in the relative position of both the Be star and the BH along the orbit.

Conclussions

AGILE is a superb instrument to study transient emission in galactic and extragalactic sources. Thanks to its state of the art PSF and sensitivity, specially at low energies between 100 and 400 MeV, it allows us to monitor several variable galactic sources in the gamma-ray domain. Its wide field of view also allows for a simultaneous observation of distant parts of the sky. Thanks to these capabilities, *AGILE* detected repeatedly some of the most prominent and puzzeling sourdes in the Galactic sky, like Cygnus X-1 and Cygnus X-3. Both systems show a non regular pattern of emission. The understanding of the acceleration and emission processes going on in these binaries require of the continous observation and data collection by space missions like *AGILE*. Also the discovery of new intriguing sources is done by *AGILE*, as the case of AGL J2241+4454, which detection triggered the study and discovery of the first Be/BH binary system in our Galaxy. We studied the 10 detected transient episodes of AGL J2241+4454 in order to understand if it might be the counterpart of MWC 656. Given the observational evidence, although it is still not clear, we think that the most probable gamma-ray counterpart of MWC 656is AGL J2241+4454.

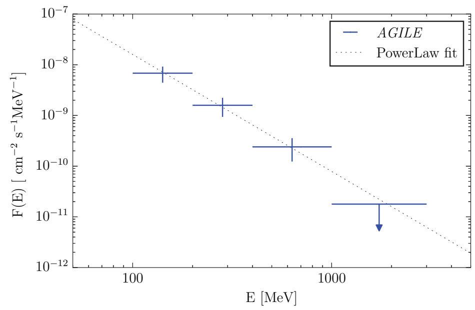

FIGURE 3. Photon spectrum between 100 MeV and 3 GeV of MWC 656 as detected by *AGILE*/GRID by integrating all flaring episodes in pointing and spinning mode. Dotted line represents the best powerlaw fit, with a photon index $\Gamma = 2.3 \pm 0.2$. Figure from [27]

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