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X-ray and gamma-ray astronomy - The AGILE view

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Abstract. More than 10 years after the demise of the last gamm-ray observatory, the EGRET experiment onboard the Compton Gamma Ray Observatory, Astronomy in the energy range above 50 MeV has become again accessible thanks to the launch of the AGILE and Fermi/GLAST missions in 2007 and 2008, respectively. The gamma-ray imagers onboard these two missions adopt improved technology with respect to EGRET, offering higher angular resolution and superior exposure (effective area times observing time). In this paper we present some highlights among the results achieved by the experiments onboard the AGILE mission, including the gamma-ray imager, a hard X-ray imager and a mini-calorimeter.

Key words. Instrumentation: detectors – Gamma-rays: observations

1. Introduction

Gamma-ray Astronomy in the energy range above 100 MeV (and below few tens of GeV) is a field of investigation explored with great difficulty and discontinuity in the past decades. SAS-2 and Cos-B made the pioneering job in the 70's, followed by the more systematic sky survey performed by the EGRET experiment onboard the Compton Gamma Ray Observatory from 1991 to, essentially, 1997. The following 10 years were dark ages for this field, until the launch of AGILE in 2007, followed by GLAST (Fermi) in 2008, offering a significantly more resolved and sensitive view of the gamma-ray emission from the celestial objects.

AGILE (Tavani et al. 2009a) is the first and to date only small mission of the Italian Space Agency. It is devoted to the observation of the sky in the gamma-ray energy range, between 30 MeV and 50 GeV. This task is accomplished by the main experiment of the mission, the Gamma Ray Imaging Detector (GRID, Barbiellini et al. 2002), composed by a Silicon Tracker (ST, Prest et al. 2003), a Caesium Iodide mini-calorimeter (MCAL, Labanti et al. 2009), surrounded by a plastic anti-coincidence system (ACS, Perotti et al. 2006). The AGILE payload is complemented by a hard X-ray imager, SuperAGILE (SA, Feroci et al. 2007), operating in the 18-60 keV energy range. The main instrumental performance of the GRID and SA experiments are summarized in Table 1. Also MCAL is used for independent observations in the energy range 300 keV - 50 MeV, with no imaging capability, mainly for impulsive events like gamma ray

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Table 1. Main characteristics of the AGILE instruments

	GRID	SuperAGILE
Energy Range	30 MeV - 50 GeV	18-60 keV
Angular Resolution	4.2°(100 MeV/E)	6 arcmin
Field of View	~2.5 sr	~1 sr
Sensitivity (5-σ)	30×10^{-8} ph cm^{-2} s^{-1} (10^6 s)	~15 mCrab (50 ks)
Absolute Time Accuracy	2 μs	5 μs
Point Source Location Accuracy	0.2 °	1.5 arcmin

bursts or terrestrial gamma-ray flashes (e.g., Marisaldi et al. 2009).

AGILE started its nominal scientific observations on August 2007, with it Science Verification Phase. Then, in December 2007 the AGILE Cycle 1 started, with a pre-defined pointing plan, mostly devoted to the observation of the Galactic plane. A fraction of the observed targets were put on public distribution through a competitive announcement of opportunity. A second cycle covers the data collected by AGILE over the period December 2008 - December 2009. Details about the AGILE data distribution are available at the ASI Science Data Center web site[1]

2. Highlights from AGILE

In this section we will provide a flavor of some of the scientific results achieved by AGILE in its first two years of operation on different subjects, from active galactic nuclei to colliding wind binaries. A more extensive discussion on each of the issues may be found in the referred papers.

2.1. The global view

During Cycle 1 and the first half of Cycle 2 the pointing strategy of AGILE privileged the Galactic plane, with particular emphasis on the Vela and Cygnus regions. The field of view of the GRID is very large (a diameter of ~120°) thus allowing a good exposure also to fields at higher galactic latitude. This was not the case of SuperAGILE, that covers a smaller solid angle, making its global exposure much less uniform, with several regions in the sky that were not exposed at all. In practice, most of the SuperAGILE exposure was spent on the Vela and Cygnus fields, with some minor peaks also on the Galactic center and anti-center.

In Fig. 1 (top panel) we show the map in galactic coordinates of the gamma ray sources of the first AGILE catalogue (Pittori et al. 2009). The map include about 50 sources that were significantly detected over the full integration time available after the AGILE Cycle 1, with an average flux between 20 and 800 $\times10^{-8}$ ph cm^{-2} s^{-1}. This list is then mostly related to persistent sources. A time resolved analysis reveals additional sources, that are not included here, and will be reported in a future "variability" catalog. ~45% of the gamma-ray sources in the plot have been associated to candidate or confirmed gamma-ray pulsars, ~30% were identified as Blazars, the rest being galactic binary systems and SNRs, except for a residual 17% of unidentified sources.

The bottom panel of 1 shows the map of the X-ray sources detected by SuperAGILE (from Feroci et al. 2009). In this case the list is very preliminary as it is not the result of a systematic and uniform analysis of the data archive. The typical exposure for each source is 40 ks. The average flux of the sources varies from ~15 mCrab to ~ 1.5 Crab. As expected, the sources detected by SA are generally not the same as those detected by the GRID, with the exception of a couple of AGNs and the Crab Pulsar. The ~60 SA sources are typically X-ray binaries (90% of the total, 2/3 low mass

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[1] `http://agile.asdc.asi.it`

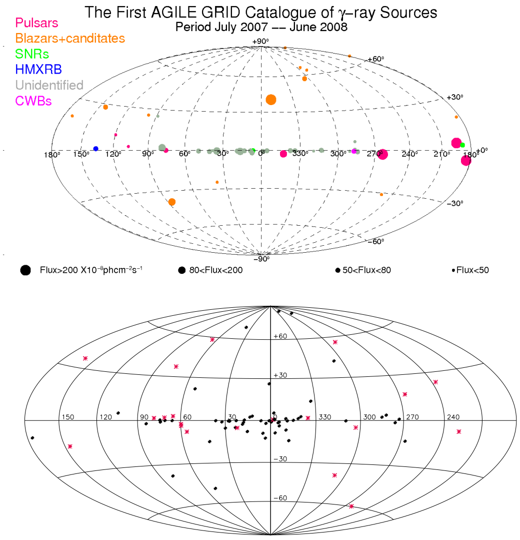

Fig. 1. *Top:* Map in galactic coordinates of the persistent gamma ray sources detected by the AGILE/GRID over the Cycle 1 (from Pittori et al. 2009). *Bottom:* The map of sources detected by SuperAGILE (from Feroci et al. 2009).

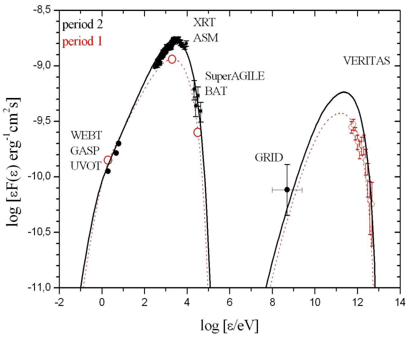

Fig. 2. Multifrequency observations of a hard-X/gammma-ray flare of the blazar source Mkn 421 (from Donnarumma et al. 2009). The plot shows the spectral energy distribution at two epochs, modelled in the framework of the synchrotron self-Compton emission scenario.

and 1/3 high mass). The stars in the plot are the positions of localized gamma ray bursts. The map also includes sources that were detected through their bursting emission, like X-ray bursters or magnetars. The sources are concentrated in those regions with the higher exposure (Vela and Cygnus) or the higher density of bright sources (the Galactic Center).

2.2. Active Galactic Nuclei

In the energy range above 100 MeV the Blazars are known to be among the brightest objects in the sky. This was verified also by AGILE, that detected several of these objects in high state. The blazar 3C 454.3 was certainly a prime actor in 2007-2008, being one of the brightest object in the sky (up to fluxes of 500×10^{-8} ph cm^{-2} s^{-1} and more) and extremely variable, down to the timescale of less than a day (Vercellone et al. 2008; Donnarumma et al. 2010; Vercellone et al. 2010).

Other sources, although dimmer, provided very interesting results as well (e.g., Pucella et al. 2008; Chen et al. 2008; Pacciani et al. 2009, and others). A noticeable case is that of the high-frequency peaked blazar Mkn 421 that was discovered in a flaring state by SuperAGILE in hard X-rays, and subsequently detected by the GRID at a flux level of $\sim40\times10^{-8}$ ph cm^{-2} s^{-1}. A target of opportunity observation with Swift/XRT detected the blazar at its brightest soft X-ray flux ever. The TeV observatories MAGIC and VERITAS, and the GASP-WEBT network of optical telescopes also detected the source in the same days. Using the 12-decade wide spectral coverage, a spectral energy distribution was built separately for the two flares (Fig. 2) and it was modelled in the framework of the synchrotron self-Compton model, in terms of an episode of rapid acceleration of the leptons in the jet (Donnarumma et al. 2009).

2.3. Galactic sources

AGILE spent a large fraction of its observing time pointing at the Galactic plane. This is the region in principle most rich of sources, but in practice also the most difficult to analyze and understand, due to the large contribution of the diffuse emission and the large density of the potential sources, when compared to the angular resolution of the experiments.

2.3.1. Gamma-ray pulsars

Before the launch of AGILE the population of pulsars with known emission above 100 MeV consisted of only 6 objects (e.g., Thompson 2004). During the first year of scientific operations AGILE detected and measured four of the known gamma pulsars, namely Vela, Crab, Geminga and B1706-44 (Pellizzoni et al. 2009a). In Fig. 3, left panel, we show an AGILE image including the 3 brightest pulsars, Vela, Crab and Geminga, in one single shot. Considering that the angular distance between the Vela and the Crab pulsars is about 80°, this image is well representative of the AGILE/GRID capability of monitoring simultaneously large regions of the sky.

Thanks to its timing accuracy and its large effective area times solid angle factor, AGILE was able to collect in only 9 months a number of photons from the known pulsars comparable and in some cases larger than that detected by EGRET. The gamma-ray photons were folded using accurate radio ephemeris deriving from a simultaneous monitoring program, except for Geminga for which the X-ray ephemeris from XMM-Newton observations were used. Fine structures in the light curves were studied, like the "third peak" in the Vela pulse shape. During the AGILE monitoring the radio observers detected a small ($\Delta\nu/\nu \sim 10^{-9}$) glitch in the period evolution of the Vela pulsar. The epoch of the glitch in radio could be determined only with an uncertainty of ~6 days. In this same period the AGILE/GRID detected a $> 5\sigma$ counts excess of gamma-ray photons in a few-minute time bin. Fig. 3, panel on the right, shows the unfolded light curve of the Vela Pulsar, as measured by the GRID above 50 MeV, with the peak possibly associated with the glitch. If larger glitches will be observed in the future, their possible detection in gamma-rays would provide important clues towards the physics behind this phenomenon, well known but yet poorly understood.

The radio monitoring (at the Jodrell Bank, Nançay and Parkes telescopes) simultaneous to the AGILE observations was extended to a sample of ~35 pulsars with high rotational losses and/or short distance, making them good candidates as gamma-ray emitters. Indeed, 7 new pulsars were discovered in this campaign of the AGILE team (Pellizzoni et al. 2009b), and one additional object (PSR J2021+3651) was discovered in gamma-rays by a guest observer (Halpern et al. 2008), thanks to its radio monitoring at the Green Bank Telescope. Among the 7 new pulsars discovered by Pellizzoni et al. (2009b), three have the most secure detections (J2229+6114, J1513-5908 and J1824-2452) while other four (J1016-5857, J1357-6429, J2043+2740 and J1524-5625) have a smaller detection significance. Among the new sources, two have remarkable properties. PSR J1824-2452 is a ms pulsar in the globular cluster M28 and it showed pulsations only in a 5-day interval of its observation, although at high significance and with an excellent agreement with the radio period. The other noticeable object is PSR J2043+2740, with an estimated age in excess of one million years.

2.3.2. Colliding wind binaries

Among the candidate gamma-ray sources not yet identified after the EGRET era, the colliding wind binaries play an important role. A masterpiece in this class is Eta Carinae, a spectacular binary system composed of two highly massive stars, whose winds collide and give rise to highly variable emission at wavelengths from radio to X-rays. The binary system has a high eccentricity ($e \sim 0.9$) and an orbital period of ~5.5 years. AGILE observed the source at different epochs, between July 2007 and January 2009 (Tavani et al. 2009b). In Fig. 4, left panel, we show the intensity map (>100 MeV) of the relevant sky region, with the gamma-ray source at a position consistent with the Eta Carinae. The map is obtained by integrating the period from July 2007 to October 2008. The detected source has a significance of $\sim 8\sigma$ and an average flux of $(37 \pm 5) \times 10^{-8}$ ph cm^{-2} s^{-1}. The gamma-ray flux is detected as highly variable over the observing period, as it is shown by the AGILE points

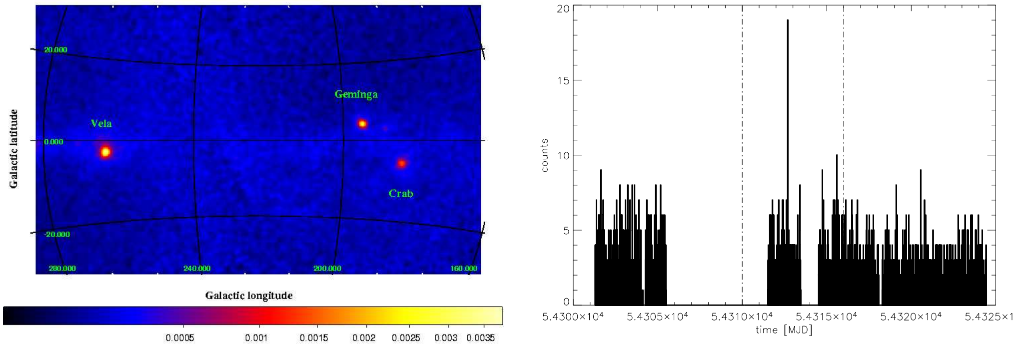

Fig. 3. *Left:* An AGILE map of the sky region showing simultaneously the Vela, Crab and Geminga pulsars, despite their large angular distance. *Right:* Unfolded light curve of >50 MeV photons from the Vela pulsar at the epoch (August 2007) of the period glitch observed in the radio. The vertical lines delimit the time of the glitch. A short counts excess ($> 5\sigma$) was detected by AGILE on the timescale of a few minutes. (from Pellizzoni et al. 2009a)

overlaid to the RXTE/PCA soft X-ray light curve in the right panel of the same figure. In the context of variability it is worth to mention a 2-day flare detected by AGILE/GRID on October 2007, when the source flux was measured as $(270\pm65)\times10^{-8}$ ph cm^{-2} s^{-1} at a statistical significance in excess of 5σ. We also note that AGILE monitored the days immediately following the periastron passage occurred on 11th January 2009. The observation was carried out on January 12-19 and did not provide a significant detection of the source in gamma-rays, as shown in the light curve. Given the relatively large positional uncertainty (~0.5°) of the AGILE source, the association with Eta Carinae cannot be considered as secure. However, circumstantial evidence suggest the association between the two sources is real, and the AGILE measurement would be the first detection of gamma-ray photons from this type of systems.

2.3.3. Long-term monitoring of GX 301-2

The long-term monitoring of the sky by SuperAGILE offers a continuous flux monitoring for bright sources, for long stretches of time. This was the case for the high mass X-ray binary GX 301-2, displaying an orbital period of 41.5 days and a spin period of ~700s. In Fig. 5 (left panel) we show the hard X-ray light curve of the source over the orbital period. The SuperAGILE data allowed to study the timing parameters of the system over 6 orbital cycles, such as: the long-term evolution of the flux and of the spin period, the orbital-phase dependence of the pulse shape and of the pulsed fraction. The SuperAGILE data provided new information about the system behaviour along its very eccentric orbit.

3. Conclusions

In this paper we provided an overview of the scientific results achieved by the AGILE mission over its first ~1.5 years of scientific observations.

A number of target sources detected by AGILE/GRID and AGILE/SuperAGILE could not be discussed here, like several AGN sources, supernova remnants, gamma-ray pulsars, X-ray binaries (among these we mention the very noticeable first detection of Cyg X-3 Tavani et al. 2009c in gamma-rays), the gamma-ray transients on the Galactic plane, and gamma-ray bursts. We refer the reader to the individual papers to see the subjects reported in this paper, as well as several other results, more deeply and extensively discussed.

The AGILE payload is performing nominally after more than 2 years, with no sign

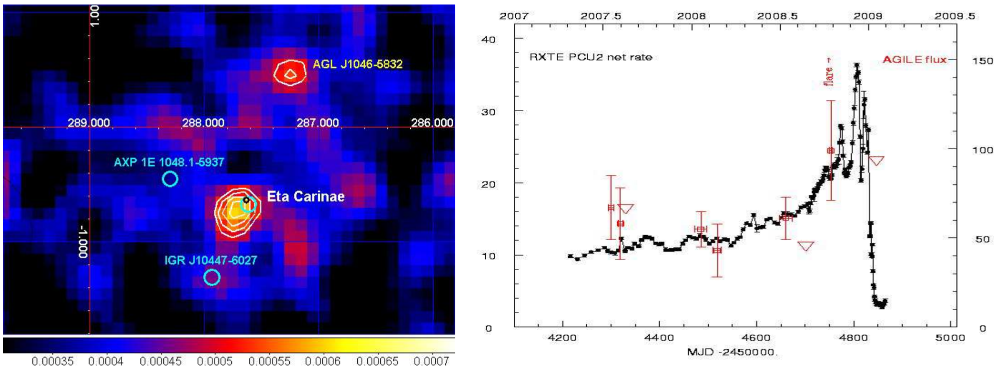

Fig. 4. The AGILE view of Eta Carinae (from Tavani et al. 2009b). The left panel shows the gamma-ray sky map showing the gamma-ray source coincident with Eta Carinae. On the right, the AGILE data (scale on the right, in units of 10^{-8} ph cm^{-2} s^{-1}) are overlaid to the soft X-ray light curve obtained with RossiXTE/PCA.

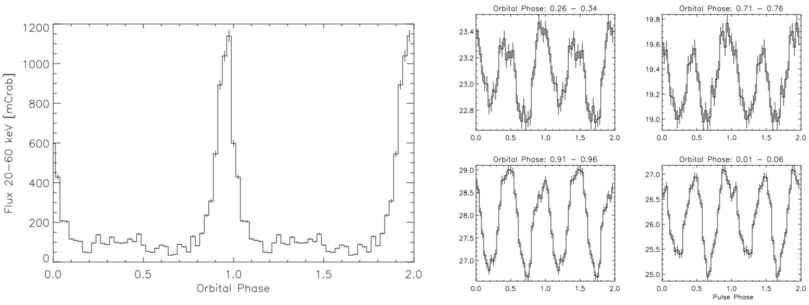

Fig. 5. The orbital light curve of the GX 301-2 and the pulse shape in four different orbital phases (from Evangelista et al. 2009)

of losses or degradation. The Italian Space Agency has then decided to extend the mission until at least 2011.

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