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The AGILE Mission: the first 2 years

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We summarize here the main highlights of the AGILE astrophysics mission. The satellite, launched in April 2007, is devoted to γ-ray observations in the 30 MeV – 30 GeV energy range, with simultaneous hard X-ray imaging in the 18–60 keV band, and optimal timing capabilities for the study of transient phenomena. The very large field of view (2.5 sr) of the gamma-ray imager coupled with the hard X-ray monitoring capability makes AGILE well suited to study Galactic and extragalactic sources, as well as GRBs and other fast transients. AGILE reaches its optimal performance near 100 MeV with good imaging and sensitivity. Gamma-ray and hard X-ray sources can be monitored 14 times a day, and an extensive database has been obtained for a variety of sources. We summarize here the breakthroughs and most important results obtained for several sources including microquasars and other Galactic compact objects (most notably, the discovery of gamma-ray emission above 100 MeV from Cygnus X-3), Supernova Remnants and pulsar wind nebulae, gamma-ray pulsars, a bright class of blazars (3C 454.3, TXS 0716+714, HB 1510-089, Mrk 421), short and long GRBs (including the remarkable short burst GRB 090510), and terrestrial gamma-ray flashes (TGFs).

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1. Introduction

AGILE (Astrorivelatore Gamma ad Immagini LEggero) [1] is a mission of the Italian Space Agency (ASI) with scientific and programmatic participation of the Italian Institutes of Astrophysics (INAF) and Nuclear Physics (INFN). The mission is devoted to γ-ray astrophysics in the 30 MeV – 30 GeV, and 18 – 60 keV energy ranges. AGILE was successfully launched on April 23, 2007 from the Sriharikota base in India in a $\sim$550 km equatorial orbit with very low inclination angle ($i = 2.5^o$) and a very low particle background.

The AGILE scientific instrument is very innovative and compact. The gamma-ray imager consists of a sophisticated Silicon Tracker (ST) [2, 3] sensitive in the energy range 30 MeV - 30 GeV. The ST analog readout, fast electronics and trigger logic lead to an optimal in-orbit performance. The angular resolution at 100 MeV is characterized by a 68% containment radius of $\sim 3.5^o$ for a large field of view (2.5 sr) and good sensitivity (average effective area near 400 MeV of $A_{eff} = 400\,\mathrm{cm}^2$). The gamma-ray imaging capability of the AGILE gamma-ray imager (GRID) is effective in resolving complicated regions of emission in our Galaxy, and is crucial for source monitoring. A co-axial detector based on a very light coded mask structure is sensitive in the hard X-ray range (18-60 keV) (called Super-AGILE) [4]. This detector adds a crucial feature to AGILE and allows the simultaneous study of cosmic sources in the hard X-ray and gamma-ray energy ranges. Super-AGILE is ideal for GRB detection and Galactic source monitoring, but also extragalactic sources can be effectively detected. A non-imaging CsI(Tl) detector is positioned at the bottom of the instrument, and is sensitive in the 0.3-100 MeV range (Mini-Calorimeter, MCAL) [5]. This detector supports the gamma-ray data acquisition, and in addition provides an independent way to study transient events. In particular, the MCAL millisecond and sub-millisecond trigger capability is implemented on board with success for the study of very fast GRBs and TGFs. The instrument is completed by a segmented anticoincidence system (ACS) that surrounds all active parts of the detectors [6]. The innovative AGILE instrument was the first to be launched of a new generation of high-energy space missions based on solid-state Silicon technology. Today, AGILE together with the *Fermi* NASA mission (formerly GLAST, launched on June 11, 2008) demonstrate the effectiveness and reliability of Silicon detectors applied to space missions. AGILE and *Fermi* are configured and optimized differently, and provide a complementary view of the gamma-ray universe. AGILE is optimized from 100 MeV to a few GeV. The *Fermi*-LAT instrument is currently most effectively operating in the energy range 1-100 GeV.

The AGILE data are transmitted to the ground for each pass over Malindi (Kenya) (at the moment of this writing, November, 2009, the satellite orbits reached about 13.000). The data are then transferred through a fast link to the Mission Operations Center in Fucino (Italy), and then to the ASI Science Data Center in Frascati, near Rome . A companion paper [7] describes the scientific ground segment and the AGILE Guest Observer Program.

2. Scientific Highlights

Fig. 1 shows the 2-year gamma-ray sky intensity map above 100 MeV obtained by the AGILE-GRID. Fig. 2 shows the hard X-ray sources detected by Super-AGILE. The AGILE pointing strategy during the period 2007-October 2009 focused on 2-3 week pointings centered in the Galactic

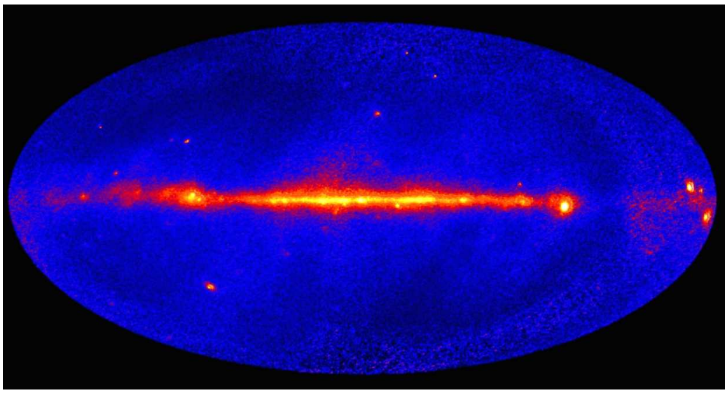

Figure 1: Gamma-ray intensity map of the entire sky in Galactic coordinates for photon energies above 100 MeV obtained by AGILE during the first 2 years of operations (mid-2007/mid-2009).

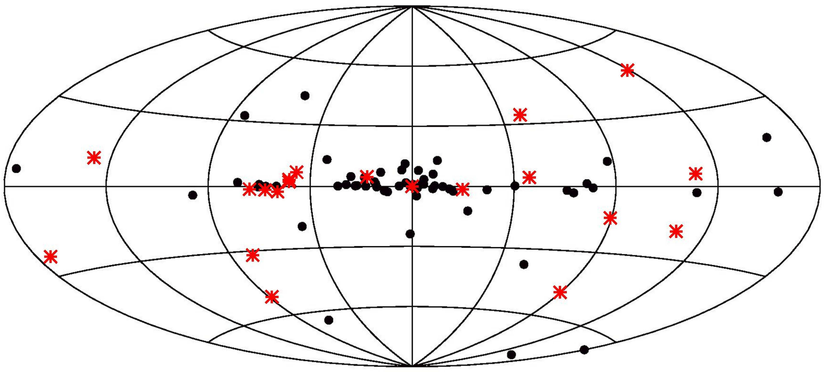

Figure 2: Map (in Galactic coordinates) of the hard X-ray sources (black dots) and GRBs (red stars) detected by Super-AGILE in the energy range 18-60 keV during the first 2 years of operations.

plane. The large GRID FOV allowed also a good coverage of the extra-galactic sky, and several blazars were monitored and detected. AGILE substantially contributed to a variety of scientific topics. A First catalog of high-confidence gamma-ray sources was obtained based on the first year of data [8], and a detailed analysis is in preparation [9]. Furthermore, a second catalog of AGILE gamma-ray sources is in preparation [10]. Many hard X-ray sources extensively monitored by Super-AGILE are reported in ref. [11]. We briefly summarize here the main scientific results of the AGILE mission during the first 2 years.

* Galactic compact sources and transients. Given its characteristics (hard-X/gamma-ray combination of detectors, optimal sensitivity at 100 MeV, quasi-continuous monitoring of sources) the study of Galactic gamma-ray sources is a crucial goal of the mission. The unprecedented angular resolution near 100 MeV and the daily exposure in the energy range 100 MeV - a few GeV lead to large number of results. The AGILE Galactic diffuse emission model [12] has been tested on the new gamma-ray data of the mission. Even though the complexity of several regions of the Galactic plane complicates the analysis (e.g., Galactic Center, Cygnus region, Norma region), the overall results are satisfactory [13]. In several cases, single molecular cloud complexes can be individually resolved for the first time. Individ-

ual gamma-ray sources (prominent molecular cloud complexes, pulsars, pulsar wind nebulae (PWNe), SNRs, exotic binaries (e.g., LS I +61 303 and LS 5039) were studied with important results that are being finalized in forthcoming publications. We concentrate here on a few highlights.

A first important result concerns the extensive monitoring of Galactic micro-quasars. The large AGILE exposure in the Cygnus region allowed a thorough study of especially Cygnus X-1 and Cygnus X-3. These erratic binary systems have been the main objective of high-energy investigations for many years with contradictory results. A crucial discovery of gamma-ray emission above 100 MeV from Cygnus X-3 was achieved by AGILE by collecting a large number of observations of the Cygnus region [14]. Several prominent Cyg X-3 gamma-ray flares were detected in a reproducible pattern, all *preceding* major radio jet emissions.

In addition to known sources, the processing of AGILE gamma-ray data devoted particular attention to the detection of new gamma-ray sources in the Galactic plane. During the first 2 years AGILE detected many transient candidates in the Galaxy, for phenomena typically occuring during a timescale of a 1-2 days. These transients are not associated with hard X-ray detectable sources, and their origin is a mystery at the moment. A special class of binaries or Wolf-Rayet systems can contribute to this population, as shown by the case of the gamma-ray detection of the Eta-Carinae system [15, 16].

* Pulsars. AGILE has been the first post-EGRET gamma-ray mission and about ten PSRs have been detected above 100 MeV [17, 18] including PSR J2021+3651 [19], PSR B1509-58 and the powerful millisecond pulsar B1821-24 in the globular cluster M28. AGILE's very good imaging capability in the energy range 0.1-1 GeV allows to study in detail a variety of pulsar wind nebulae (PWNe). The nebula associated with the Vela pulsar (Vela X) is among the most prominent (and close to the Earth) and energetic PWNe. AGILE remarkably detects gamma-ray emission concentrated in the inner nebula of Vela X in coincidence with the soft X-ray and TeV emission [20]. This result (obtained after subtraction of the Vela PSR pulsed gamma-ray signal) is a demonstration of the optimal AGILE-GRID imaging capability near 100 MeV, and of the complementarity between AGILE and *Fermi*-LAT.

* Supernova Remnants (SNRs). A detailed account of the very important AGILE investigations on SNRs is beyond the scope of this paper. Understanding the origin of cosmic rays is at stake, and AGILE high spatial resolution observations focused on the 0.1-1 GeV range can reveal the long-awaited hadronic (pion) spectral signatures. We can briefly mention here only a few results obtained by the AGILE-GRID deep imaging and spectral analysis for three important SNRs. The relatively old remnant IC 443 has been initially focused for its remarkable characteristics (relatively closeness to Earth ($\sim$2 kpc, molecular clouds in interaction with the SNR, TeV detection at the center of the SNR [21, 22]). AGILE remarkably detects the most intense component of the gamma-ray emission in spatial coincidence with the North-eastern part of the SNR shell interacting with a dense medium and a shocked molecular cloud [23]. The morphology of the gamma-ray emission in the 0.1-1 GeV range is non-trivial and follows the SNR shape. The non-coincidence of the 0.1-1 GeV and TeV sources has great

theoretical implications, and provides a first direct evidence for hadronic cosmic-ray acceleration in a SNR [23]. A second system with a remarkable combination of a nearby SNR with close and farther away molecular clouds is provided by the SNR W 28. AGILE detects a pattern of 0.1-1 GeV emission that is concentrated on the main SNR shocked shell as well as on the nearby molecular clouds [24]. The combination of AGILE gamma-ray and TeV HESS data [25] can be used to set crucial morphological and spectral constraints on the nature of the accelerated particles. A hadronic model emerges as a self-consistent model of particle acceleration and emission in W 28 [24]. Last but not least, the AGILE data on the young SNR RX 1713.7-3946 reveal a surprising pattern [26]. Again, the 0.1-1 GeV emission is concentrated on nearby molecular clouds in interaction with the SNR shell, and this emission is not associated with the very prominent TeV emission [27]. In this case, leptonic and hadronic models of emission are more difficult to disentangle, and the AGILE data appear to support a hadronic contribution only for regions associated with dense molecular clouds [26].

* The bright population of gamma-ray blazars. AGILE has been the first gamma-ray instrument capable of simultaneously monitoring a large fraction of the sky (2.5 sr), and many expectations regarding the AGN gamma-ray flaring activity anticipated the satellite launch. Immediately after the first months of operations, the EGRET-based predictions on the number of intense gamma-ray flares from blazars were confirmed. However, the surprise, and it is still an open issue, was to recognize that all of the AGILE bright gamma-ray blazars have been already detected by EGRET and COS-B decades ago. In other words, no entirely new bright gamma-ray blazar showed up during the first year, contrary to reasonable expectations on the blazar population (e.g., ref. [28]). This trend is confirmed also by the brightest blazar detections by *Fermi*, and it can be addressed as the "blazar gamma-ray activity problem". After 2 years, AGILE detected a few blazars with a gamma-ray flux larger than $F = 100 \times 10^{-8}$ ph cm^{-2} s^{-1} above 100 MeV. For all of these blazars exensive multifrequency campaigns were organized by the AGILE Team in a remarkable joint effort together with radio, optical, X-ray and TeV astrophysicists. The most prominent blazar of all, showing up already from the very first weeks of the AGILE scientific life, is 3C 454.3 dubbed by the AGILE Team as the "Crazy Diamond" [29, 30, 31, 32]. This Flat Spectrum Radio Quasar (FSRQ) turned out to be the most prolific blazar in the gamma-ray energy range during the last 2-3 years, showing multiple flaring activity and a variety of very interesting spectral and intensity behaviors. (At the moment of this writing, early December 2009, 3C 454.3 is the brightest gamma-ray source of the sky, surpassing in intensity even the Vela pulsar ! Other very prominent FSRQs repeatedly flaring in the last years are HB 1510-089 [33, 34, 35] as well as 3C 279 and 3C 273 [36]. AGILE detected one of the brightest gamma-ray flares from a BL Lac source, TXS 0716+714 [37], a detection that has deep theoretical implications for testing the fundamental mechanism of energy production (e.g., Blandford-Znajek) near a rapidly rotating black hole such as a BL Lac [38]. Also a very important detection of the famous HBL Mrk 421 was obtained by AGILE during a TeV flaring state [39]. Many physics issues are involved in these detections, including the evidence for new and unanticipated spectral components in the gamma-ray range and the possible existence of a photon

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UV "cloud" comoving or near the jet (e.g., ref. [31]).

* Gamma-Ray Bursts. AGILE detected several important gamma-ray bursts (GRBs), even though the "big one" is still being eagerly awaited (see also [40]). The Super-AGILE X-ray imager detects several GRBs in its energy band (18-60 keV) at a rate of about 1 per month [41], while MCAL detects about 1 GRB per week in the energy range 0.7-1.4 MeV on several time scales [42]. At GRID energies only 3 confirmed GRBs with a high energy component $E > 50$ MeV were detected [43]. Among them, AGILE detected the remarkably short GRB 090510 [44] for which the Fermi collaboration claims to have obtained limits on the speed of light [45]. However, caution is needed when interpreting GRB gamma-ray emission that can have different origins. The AGILE data on GRB 090510 show a clear distinction between the first prompt phase (lasting about 250 ms) and the subsequent gamma-ray "delayed emission" (lasting several tens of seconds). The spectra of these two phases are quite different and belong to different processes (it is not clear the mechanism for the prompt phase, and synchrotron emission is the most likely mechanism for the delayed phase). Gamma-rays above 100 MeV were detected for the first time from a short GRB, a fact with deep theoretical implications.

* Terrestrial Gamma-Ray Flashes. The AGILE MCAL is ideally equipped for the detection of very fast transients (millisecond trigger logic, equatorial orbit, large energy range). It turns out that after 2 years of operations the AGILE MCAL detected hundreds of Terrestrial Gamma-Ray Flashes (TGFs) originating from a special class of thinderstorms in the tropical region [46]. The TGF physics is very rich and full of surprises: particle are impulsively accelerated by very large potential drops, and AGILE is contributing in a substantial way to elucidate many important points. The AGILE record energy detected from a TGF (in the range 40-50 MeV) establishes that the potentials involved are of order of hundreds of millions of Volts. This discovery and the AGILE capability of issuing fast TGF-alerts will have a big impact on atmospheric research and aircraft safety [47].

3. The new AGILE life

Starting in early November, 2009 AGILE changed its scientific operation mode. The non-operatibility of the satellite reaction wheel led to a new configuration for scientific observations in a "spinning mode". AGILE is now spinning around its solar panel axis with an angular speed of about 1 degree/second, and is collecting data over a large fraction of the sky (only the Sun and anti-Sun directions are excluded from the solar panel constraints). All on-board instruments detectors are working nominally, and we expect AGILE to produce a wealth of data in this new configuration. A very large fraction ($\sim$ 80%) of the entire sky is now monitored. The data integration during December 3-4, 2009 shows the most remarkable gamma-ray flare from a blazar surpassing even the Vela PSR and becoming the brightest gamma-ray source of the sky, the Crazy Diamond indeed !

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4. References

References

[1] Tavani, M., Barbiellini, G., Argan, A. et al., 2009, A&A, 502, 1015

[2] Barbiellini, G., Bordignon, G., Fedel, G., et al., 2001, AIP Conf. Proc. 587, 754

[3] Prest, M., Barbiellini, G., Bordignon, G., et al., 2003, NIM A, 501, 280

[4] Feroci, M., Costa, E., Soffitta, P., et al., 2007, NIM A 581, 728

[5] Labanti, C., Marisaldi, M., Fuschino, F., et al., 2006, SPIE, Volume 6266, 62663Q.

[6] Perotti, F., Fiorini, M., Incorvaia, S., Mattaini, E., and Sant'Ambrogio, E., 2006, NIM A 556, 228

[7] Pittori, C., et al., 2009, these Proceedings.

[8] Pittori, C., et al., 2009, A&A 506, 1563

[9] Verrecchia, F., et al., 2009, in preparation.

[10] Bulgarelli, A., et al., 2009, in preparation.

[11] Feroci, M., et al., 2009, A&A, in press.

[12] Giuliani, A., Chen, A.W., Mereghetti, S., Pellizzoni, A., Tavani, M., Vercellone, S., 2004, Mem. SAIt Suppl., 5, 135

[13] Giuliani, A., et al. 2009, in preparation.

[14] Tavani, M., et al., 2009, Nature, 462, 620; doi:10.1038/nature08578 (arXiv:0910.5344)

[15] Tavani, M., et al., 2009, ApJ 698, L142 (arXiv:0904.2736)

[16] Sabatini, S. et al., 2009, these Proceedings.

[17] Pellizzoni, A., Pilia, M., Possenti, A. et al., 2009, ApJ 691, 1618 (arXiv:0810.1516)

[18] Pellizzoni, A., Pilia, M., Possenti, A. et al., 2009, ApJ 695, L115 (arXiv:0903.0087)

[19] Halpern, J. P., et al. 2008, ApJ 688, L33

[20] Pellizzoni, A., et al., 2009, Science Express, 31 Dec. 2009, .

[21] Albert, J., et al. (MAGIC Collab.) , 2008, ApJ, 674, 1037

[22] Acciari, V.A., et al. (VERITAS Collab.), 2009, ApJL, in press (arXiv:0905:3291v1)

[23] Tavani, M., et al., 2010, ApJLetters, in press.

[24] Giuliani, A., et al., 2010, A&A, submitted.

[25] Aharonian, F., et al. (HESS Collab.), 2008, A&A, 481, 401

[26] Tavani, M., et al., 2010, ApJLetters, to be submitted.

[27] Aharonian, F., et al. (HESS Collab.), 2007, ApJ, 661, 236

[28] Vercellone, S., Soldi, S., Chen, A. W., Tavani, M., 2004, MNRAS 353, 890

[29] Vercellone, S., et al., 2008, ApJ 676, 2008, L13

[30] Vercellone, S., et al., 2009, ApJ 690, 1018

[31] Vercellone, S., et al., 2010, ApJ, in press.

[32] Donnarumma, I., et al., 2010, ApJ, in press (arXiv0910.4883)

[33] Pucella, G., et al., 2008, A&A 491, L21 (arXiv:0712.0500)

[34] D'Ammando, F., et al., 2009, A&A, in press (arXiv:0909.3484)

[35] D'Ammando, F., et al., 2009, ApJ, in press (arXiv:0909.4883)

[36] Pacciani, L., et al., these Proceedings.

[37] Chen, A., et al., 2008, A&A 489, L37

[38] Vittorini, V., et al., 2009, ApJ, in press

[39] Donnarumma, I., et al., 2009, ApJ 691, L13 (arXiv:0812.1500)

[40] Del Monte, E., et al., these Proceedings.

[41] Del Monte, E., et al., 2008, A&A 478, L5 (arXiv:0712.0500)

[42] Marisaldi, M., et al., 2008, A&A 490, 1151

[43] Giuliani, A., et al., 2008, A&A 491, L25

[44] Giuliani, A., et al., 2009, ApJ, in press (arXiv0908.1908)

[45] Abdo, A.A., 2009, Nature 462, 331

[46] Marisaldi, M., et al., 2009, accepted for publication in JGR, available online from *http://www.asdc.asi.it/news/Marisaldi2009_AGILETGF.pdf*

[47] Tavani, M., et al., 2010, in preparation.