Gravitational Wave Astrophysics: Early Results from Gravitational
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AGILE Observations of GW Events

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Abstract. AGILE is a space mission of the Italian Space Agency dedicated to γ-ray astrophysics, launched in 2007. AGILE performed dedicated real-time searches for possible γ-ray counterparts of gravitational wave (GW) events detected by the LIGO-Virgo scientific Collaboration (LVC) during the O2 observation run. We present a review of AGILE observations of GW events, starting with the first, GW150914, which was a test case for future searches. We focus here on the main characteristics of the observations of the most important GW events detected in 2017, i.e. GW170104 and GW170817. In particular, for the former event we published γ-ray upper limits (ULs) in the $50\,\mathrm{MeV} - 10\,\mathrm{GeV}$ energy band together with a detailed analysis of a candidate precursor event in the Mini-Calorimeter data. As for GW170817, we published a set of constraining γ-ray ULs obtained for integrations preceding and following the event time. These results allow us to establish important constraints on the γ-ray emission from a possible magnetar-like remnant in the first ~ 1000 s following T_0. AGILE is a major player in the search of electromagnetic counterparts of GW events, and its enhanced detection capabilities in hard X-ray/MeV/GeV ranges will play a crucial role in the future O3 observing run.

Keywords. gravitational waves, gamma rays: general

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1. Introduction

The first historical discovery of a gravitational wave (hereafter, GW) detected by the LIGO detector from the source GW150914 (Abbott *et al.* 2016), opened the era of GW detection from astronomical sources. Furthermore, the most recent discovery of the first electromagnetic (e.m.) counterpart of the source GW170817/GRB170817A, obtained with the contribution of the Virgo detector, definitely started the era of multi-messenger astronomy with GWs. AGILE is a space mission of the Italian Space Agency dedicated to γ-ray and X-ray astrophysics, in a near equatorial orbit since 2007. It consists of an imaging gamma-ray Silicon Tracker (sensitive in the energy range 30 MeV − 30 GeV), a coded mask hard X–ray imager Super-AGILE (SA; 20 − 60 keV), a Mini-Calorimeter (MCAL; 0.4 − 100 MeV) and an anticoincidence (AC) system (see Tavani *et al.* 2009). The combination of Tracker, MCAL and AC working as a gamma-ray imager constitutes the AGILE-GRID. The instrument is capable of detecting γ-ray transients and GRB-like phenomena for timescales ranging from sub-milliseconds to tens-hundreds of seconds.

Table 1. AGILE observations of LVC GW events.

GW ID	GCN #	Perc.[1]	Δ t [T - T_0]	Comments
150914	—	0	+330	LR missed by 300 s; earliest ever *gamma*-ray data on GW event; Tavani *et al.* 2016
151226	—	30	0	
170104	20375, 20395	36	0	partially exposed by GRID, fully exp. by MCAL; Verrecchia *et al.* 2017a
170608	21224, 21228	40	0	partially exposed by GRID, exposed by MCAL
170814	21477, 21482	0	+500	exposed after 500 s (1st with Virgo data); —
170817	21525, 21526 21562, 21785	0	+930	exposed after 930 s; prompt OT not exposed; limits to magnetar-like emission; Verrecchia *et al.*2017c

Notes:
[1] Percentage of the prompt AGILE-GRID exposure of the 90% c.l. LVC LR.

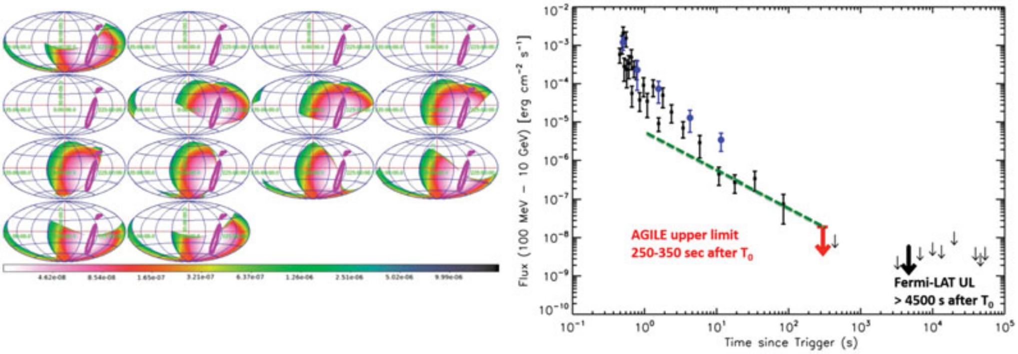

Figure 1. The sequence of UL maps for passes over the GW150914 LR preceeding and following T_0, with the best exposure of the LVC LR occurred at +330 s (left panel). The AGILE-GRID $2\,\sigma$ UL in the 50 MeV – 10 GeV compared with the GRB 090510 AGILE-GRID and Fermi/LAT light curves rescaled at the GW redshift 0.1 (right panel).

Moreover, with the standard maximum likelihood analysis, AGILE routinely detects gamma-ray transients varying from time scale of $\sim$ hours to weeks.

The AGILE Team signed a Memorandum of Understanding with the LIGO-Virgo Collaboration (LVC) on November 2016. We review the AGILE observations and the dedicated activities for the GW γ-ray counterpart search.

2. Overview

AGILE observations of the main LVC GW events detected since 2015 are summarized in Table 1. We report in the table the time difference $\Delta\,t$ between the AGILE observations and the GW trigger time (T_0). At time $T = T_0 + \Delta\,t$ the AGILE-GRID Field of View overlapped the LVC 90% c.l. localization region (LR), covering a fraction reported in the table. We show that in three events we had a partial coverage of the LR at event T_0.

Taking into account the AGILE spinning operative mode, we considered the sequence of exposure maps for 100 s integrations preceeding and following the first GW event GW150914 (see Fig. 1). All integrations are independent and consecutive, and if combined to an integration time of about 7 minutes, we obtained a coverage of 80% of the sky.

The first GW event, whose analysis was executed after the event public announcement (about five months after the discovery), was then used to plan the on-ground dedicated automatic pipelines. We report below the main results obtained for this event:

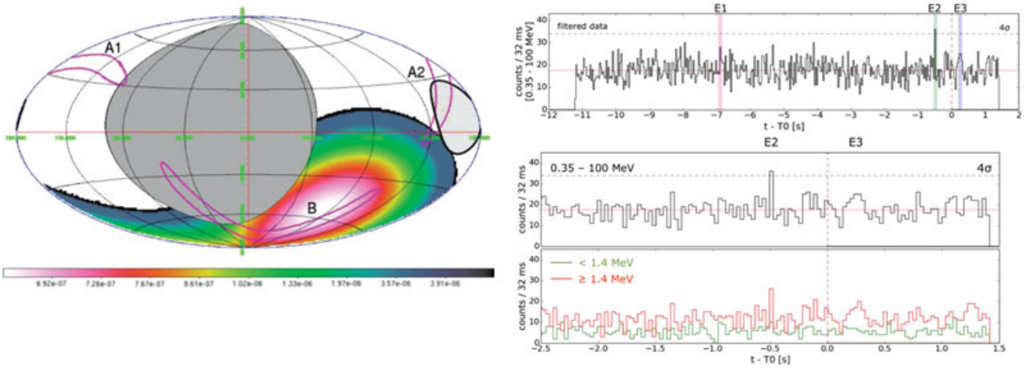

Figure 2. The GRID 3 σ UL map (in 50 MeV – 10 GeV) on 4 s integration around GW170104 T_0 showing a partial spatial coverage of the event LR (left panel). MCAL 12.6 s photon-by-photon data, including T_0 (right top panel), showing three flagged times of which E2 is a candidate precursor event. A smaller time interval around E2 in two energy bands is also shown (right bottom panel).

GW150914: the event occurred at $T_0 =$ 09:50:45 UTC, 2015 September, 14. AGILE analysis started after event publication on 2016 February 11, with the execution of an archival search. We missed the coverage of the prompt event just for few tens of seconds. We obtained a good coverage of the 90% c.l. LR with the GRID at +330 s (time with respect to T_0) with an integration of 100 s (Tavani *et al.* 2016). We determined a 2 σ γ-ray upper limit (UL) of 1.9×10^{-8} erg cm^{-2} s^{-1} in the 50 MeV – 10 GeV energy band. This UL is compared in Fig. 1 with the GRID and Fermi/LAT light curves of the short GRB 090510 rescaled at z = 0.1. This UL was the earliest available measurement in the γ-ray band for a GW event. An extrapolation of the GRID sensitivity at T_0 green dotted curve in Fig. 1) shows that AGILE might be able to detect prompt γ-ray emission similar to that of GRB 090510. In any case the AGILE early data near +300 s are very significant.

2.1. *Learned lesson: AGILE preparation for O2 in 2016*

In preparation for the LIGO O2 run, a reconfiguration of the AGILE instrument was carried out in August 2016. The activity included an improved MCAL burst detection with a lower threshold to allow triggering from the "sub-threshold" events (assumed to be similar to the GRB 090510 precursor event). Moreover, an AGILE-GW LVC notice/Circular reaction pipeline was developed to improve the performance of MCAL and GRID data processing at the publication of an LVC notice or circular, and to alert members of the AGILE-GW flare advocate group active round-the-clock.

3. Recent results: AGILE observations during O2 run

We report below the results of the observations of the main GW events detected during O2.

GW170104: the event occurred at $T_0 =$ 10:11:58.59 UTC, 2017 January 4. AGILE analysis started soon after the LVC circular publication (Abbott *et al.* 2017a) and two GCN on MCAL and GRID data analysis were published (Tavani *et al.* 2017a, Tavani *et al.* 2017b) reporting that at T_0 the 90% LR was partially covered by AGILE (Fig. 2). A dedicated paper was later published, reporting the main analyses of AGILE detectors data (Verrecchia *et al.* 2017a). In particular, MCAL photon-by-photon data were

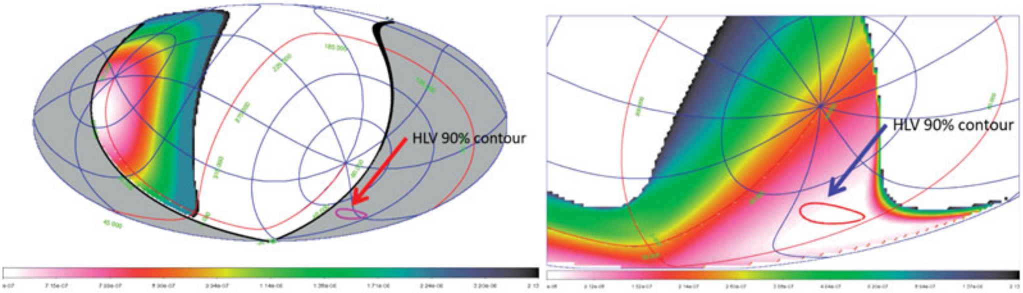

Figure 3. The GRID 3 σ UL map (in 50 MeV – 10 GeV) on 4 s integration around the GW170814 T_0 showing Earth occultation of the event LR (left panel). The 100 s best exposure of the LR at +550 s after T_0, with a complete coverage (right panel).

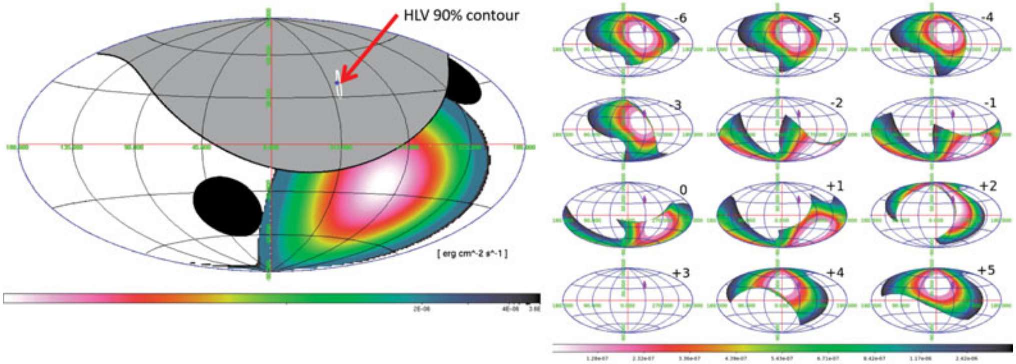

Figure 4. The GRID 2 σ UL map (in 30 MeV – 10 GeV) on 4 s integration around GW170817 T_0, showing the LR occulted by the Earth (left panel). The 150 s exposure UL map scan preceding and following T_0 (right panel) evaluated at the optical transient position.

acquired over a time window of 12.6 s including T_0 due to an onboard trigger. However, after a refined filtering of data, the original trigger was found to be spurious, while a candidate event was detected on the 32 ms time binning in full energy band at -0.5 s. This possible "precursor" event has a pre-trial significance of 4.4 σ. After considering its "false-alarm" rate ($\mathrm{FAR}_{E2} = 1 \times 10^{-4}$ Hz), the post-trial significance resulted to be between 2.4 and 2.7 σ.

Additional learned lesson: the analysis of MCAL data of the first event, led to the development of a new automatic detection MCAL pipeline, using various binning time scales from 8 to 128 ms. This procedure has integrated the functionality of the past GRB and TGF pipelines, together with the new one dedicated to "sub-threshold" events.

GW170814: the event occurred at T_0 = 10:30:43 UTC, 2017 August 14, the first event with a crucial contribution to the localization by the Virgo detector. AGILE analysis started immediately after the LVC circular notification, and two GCN on MCAL and GRID data analysis were published a few hours later (Abbott *et al.* 2017b, Longo *et al.* 2017a, Longo *et al.* 2017b).

The event LR, much smaller than previous ones because of Virgo detector data, was occulted by the Earth at the T_0 (see Fig. 3). The earliest complete coverage of the event

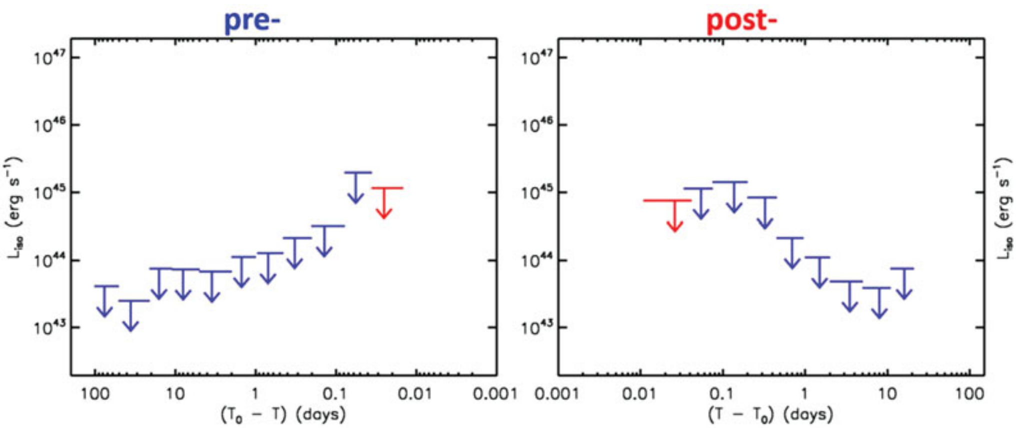

Figure 5. The GRID $2\,\sigma$ luminosity limits (in 30 MeV – 10 GeV) with integrations ranging from 150 s to 50 days preceding and following (right panel) GW170817 T_0. The UL values on 150 s exposures nearest in time to T_0, preceding and following it, are shown in red.

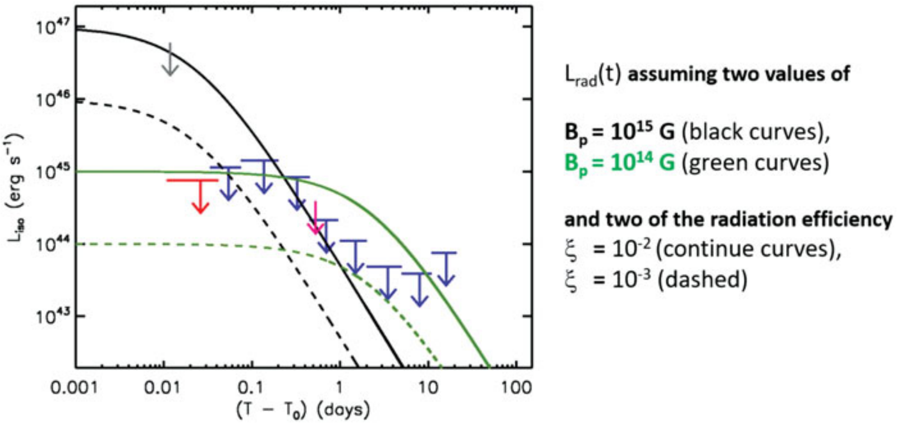

Figure 6. The isotropic luminosity limits (in erg s^{-1}) derived from flux ULs following GW170817 T_0 for the OT distance of 40 Mpc. The AGILE-GRID ULs in 30 MeV – 10 GeV (red and blue arrows), and the SA and MCAL ones (magenta and gray) in the 20 – 60 keV and 400 keV – 100 MeV energy bands, respectively. We also show the high-energy luminosity curve relative to the magnetar-like remnant model described in the text.

LR was been obtained with a 100 s exposure centered at +550 s, producing a $3\,\sigma$ γ-ray UL of 3.4×10^{-8} erg cm^{-2} s^{-1} in the 50 MeV – 10 GeV energy band.

GW170817: the event occurred at $T_0 =$ 12:41:06 UTC, 2017 August 17, together with the detection of GRB 170817A by Fermi/GBM (Abbott *et al.* 2017c, Abbott *et al.* 2017d).

AGILE analysis started soon after the LVC circular submission, and two GCN on MCAL and GRID data analysis were then published. Later on, two more GCNs on GRID data analysis exposing the position of the optical transient (OT) were published (Pilia *et al.* 2017, Piano *et al.* 2017, Bulgarelli *et al.* 2017, Verrecchia *et al.* 2017b). The event LR was occulted by the Earth at T_0 (see Fig. 4), and the earliest exposure was obtained +930 s after T_0. Furthermore, several time windows before and after T_0 were explored to search for possible precursor and/or delayed emissions. GRID data analysis was executed on three time scales with two different methods (Verrecchia *et al.*

2017c), with increasing integration times from 150 s to 50 days. We did not detect a significant emission (although two low significant detections were reported in Verrecchia *et al.* 2017c). This exposure scan allowed to obtain an interesting set of $2\,\sigma$ flux ULs in the 30 MeV − 10 GeV (see Fig. 5). The SA hard X–ray imager had useful data starting at +0.53 d after T_0. The γ-ray flux ULs converted to luminosity limits, assuming the OT distance of 40 Mpc, were applied to a magnetar model (Fig.6), (i.e., a rapidly rotating NS remnant with an high poloidal magnetic field B_p). We assume the γ-ray emission to be proportional to the magnetar spin-down luminosity with conversion to radiation efficiency ξ. AGILE γ-ray ULs are particularly constraining in the first thousand of s after T_0 for $B_p = 10^{15}$G and $\xi = 10^{-2}$.

4. Summary

AGILE interestingly observed all the GW events detected by the LIGO detectors as well as the recent ones detected also by Virgo in the O2 run. Considering the two confirmed 2015 events and all the confirmed O2 ones, we had partial coverage at T_0 for 50% of the events. The results for GW170817/GRB 170817A and those obtained on MCAL data for GW170104, have shown the importance of enhanced on ground activities, such as an automatic MCAL detection pipeline to issue alerts to LVC. Also important will be the continuous onboard TM acquisition of the hard X–ray SA data, which could *detect and localize* X–ray counterparts similar to GRB 170817A.

AGILE is expected to play a crucial role in O3 in the search for e.m. counterparts of GW events. Its unique detection and imaging capabilities in the hard X-ray/MeV/GeV ranges are special assets for future searches. A dedicated effort is ongoing to improve on-board and on-ground detection, processing and automatic alerting procedures. AGILE is well equipped for unveiling the exciting phenomena of this New Astronomy.

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