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MAGIC electromagnetic follow-up of gravitational wave alerts

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Abstract. The year 2015 witnessed the first direct observations of a transient gravitational-wave (GW) signal from binary black hole mergers by the Advanced Laser Interferometer Gravitational-wave Observatory (aLIGO) Collaboration with the Virgo Collaboration. The MAGIC two 17m diameter Cherenkov telescopes system joined since 2014 the vast collaboration of electromagnetic facilities for follow-up of gravitational wave alerts. During the 2015 LIGO-Virgo science run we set up the procedure for GW alerts follow-up and took data following the last GW alert. MAGIC results on the data analysis and prospects for the forthcoming run are presented.

Keywords. electromagnetic follow-up, gravitational wave alert, cherenkov telescope

1. Introduction

From September 2015 to January 2016 the first science run (O1) of the recently upgraded Advanced Laser Interferometer Gravitational-wave Observatory (Aasi *et al.*2015) and Advanced Virgo (Acernese *et al.*2015) experiments took place: the era of GW astronomy was opened with the first ever direct detections of gravitational waves (Abbot *et al.*2016a), (Abbot *et al.*2016b).

One of the most likely sources of gravitational waves detectable by the second generation of GW detectors is the coalescence of a compact binary, i.e. one containing neutron stars (NS) or stellar-mass black holes (BH) (Abadie *et al.*2012).

Electromagnetic signatures (EM) are expected, due to energetic matter outflows at different timescales and wavelengths. Together with the gravitational wave signal, the detection of an EM counterpart allows to build a complete picture of the physics of the event. While GWs are ideal probes for the innermost region of the newly formed black hole (Nakano *et al.*2016), the detection of EM radiation would allow to sharpen our understanding of the progenitor and post-merger environments.
An EM follow-up program has been set up between the LIGO and Virgo scientifc Collaboration (LVC) and a broad astronomy community with access to ground and space-based facilities. As one of these facilities, the Major Atmospheric Gamma-ray Imaging Cherenkov telescopes (MAGIC) system (Aleksić *et al.*2016a) participates in a shared bulletin board to announce, coordinate, and visualize the footprints and wavelength coverage of follow-up observations (GW-EM).

2. Motivations

Observing the EM counterparts will play a key role in localizing the GW source, in establishing the properties of the environment of the binary system, and in ascertaining the association to cosmic phenomena, such as gamma-ray bursts (GRBs). The EM and GW signals are essentially complementary in understanding the progenitor.
Even though BH mergers, such as the ones observed by LIGO, are not expected to have EM counterparts, it is still important to promptly react with follow-up observations. The Fermi GBM detector identified a weak gamma-ray transient 0.4 s after the GW signal with consistent sky localization (Connaughton *et al.*2016). Whether the association between GW150914 and the Fermi GBM candidate is real or not (Savchenko *et al.*2016), it opened a debate about the possibility that BH-BH mergers may also produce EM counterparts (Loeb 2016, Perna *et al.* 2016, Yamazaki *et al.* 2016, Zhang2016, see also Kamble & Kaplan 2013).
Of special interest are binaries that consist of at least one neutron star: NS-NS or NS-BH are ideal systems for a rich transient EM emission (Bartos *et al.* 2013, Berger 2014, Metzger & Berger 2012, Fernandez & Metzger 2015, Cowperthwaite & Berger 2016) as well as for other messengers, such as cosmic rays or neutrinos (Murase *et al.* 2013). The detection of an EM counterpart could confirm NS-NS merger as the progenitor of a short GRB (Veres & Meszaros 2014, Takami *et al.* 2014).

3. MAGIC observations

3.1. *The MAGIC telescopes system*

MAGIC is an array of two imaging atmospheric Cherenkov telescopes (IACTs) designed for the detection of gamma-rays in the energy band between few tens of GeV and few tens of TeV. It is located in the Canary island of La Palma (Spain) at 2250 m above the sea level. The two telescopes have a 17 m diameter reflective surface and fine pixelized cameras with a 3.5^o field of view (Aleksić *et al.*2016a). Currently the array has an energy threshold as low as 50 GeV for low zenith angle observations, and an integral sensitivity above 300 GeV of 0.6% of the Crab nebula flux in 50 hours of observation. The energy resolution is $15-17$ % at 1 TeV (Aleksić *et al.* 2016b).

3.2. *MAGIC follow-up of GW alerts*

The MAGIC response to external triggers relies on a dedicated GRB/transient alert monitor that manages the communication within the Gamma-ray Coordinates Network (GCN) and the MAGIC central control. Before and during the O1 run, the alert system has been adapted to receive/validate GW alerts.

During the first observing run O1 the Advanced LIGO observatory announced 3 GW triggers to the EM follow-up partners. The first two did not trigger MAGIC observations. The first one (GW150914), detected at the end of the Advanced LIGO engineering run immediately prior to O1, is the first ever direct detection of GW (Abbot *et al.*2016a): it was mostly outside the MAGIC field of view. The second one (GW151012), later on determined by the LIGO-Virgo offline analysis not to be a real GW event, could not be observed by MAGIC because of bad weather conditions.

On 2015 December 26 at 03:38:53.648 UT the Advanced Laser Interferometer Gravitational wave Observatory detected a high significance candidate GW event designated GW151226 (Abbot *et al.*2016b); one day later provided spatial location information in the form of probability sky maps via a private GCN circular (GCN18728). The candidate was identified by an expanded low-latency pipeline configuration that is sensitive to

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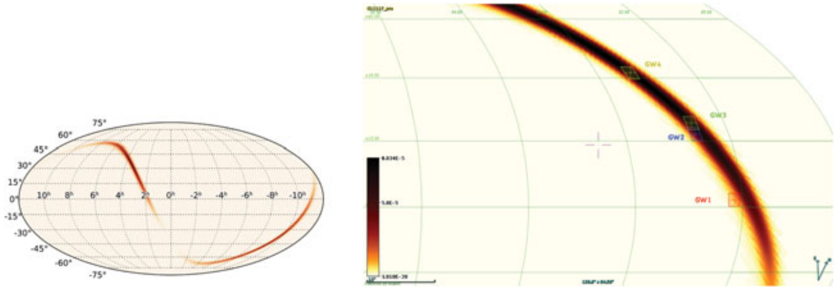

Figure 1. Left: The LIGO localization probability skymap of GW151226. Right: Zoom on the region with the four MAGIC pointing positions of GW151226.

Table 1. The four pointing positions followed up by MAGIC. Observations on target 3 and 4 have been performed under moderate-to-strong moon illuminations. This made necessary a dedicated analysis to account for the higher level of the night sky background. (a) V. Lipunov *et al.*, GCN Circular 18804 (2016). (b) E. Brocato *et al.*, GCN Circular 18734 (2016).

#	Target	RA	Dec (J2000)	Duration	Zenith angle
1	*PGC*1200980(*MASTER OT*)(*a*)	02 h 09m 05.800 s	+1° 38′ 03.00”	48 min	[27°, 30°]
2	*strip from GW map*	02 h 38m 38.930 s	+16° 36′ 59.27”	59 min	[13°, 24°]
3	*Field VST* (b)	02 h 38m 02.210 s	+19° 13′ 12.00”	30 min	[22°, 30°]
4	*Field VST* (b)	03 h 18m 23.712 s	+31° 13′ 12.00”	30 min	[19°, 27°]

stellar-mass NSNS, NSBH, and BBH mergers. Its false alarm rate (FAR), as determined by the online analysis, passed the stated alert threshold of $\sim$ 1/month, later refined to a FAR lower then one per hundred years (Abbot *et al.* 2016). The event probability sky map (Singer & Price 2016) was concentrated in two long, thin arcs on opposite directions in the sky (Fig. 1, left). The 50% credible region spans about 430 deg^2 and the 90% region about 1400 deg^2.

Four sky pointing positions (Fig. 1, right) for MAGIC observations were manually selected in the region showing maximum probability according to the visibility, observations of EM-partners, and overlap with existing catalogs. Observations started on 2015 December 28 at around 21 UT, covering the four $\sim$ 2.5 x 2.5 deg^2 target regions reported in Table 1. The observations were performed in the so-called wobble mode, where the pointing position is offset by 0.4^o from the camera center.

4. Results

The data analysis was performed using the standard MAGIC Analysis and Reconstruction Software package (MARS) adapted to stereoscopic observations (Aleksić *et al.* 2016b). From neither of the 4 pointed regions we detected significant emission above the instrument energy threshold. Furthermore, no VHE gamma-ray counterpart emission was detected within the MAGIC Field of View (FoV). Integral upper limits (ULs, 95% CL) above the energy threshold in the observed FoV are being estimated. The standard MARS routine calculates the flux UL from the pointing position (nominal position) of the telescopes. However the case of interest requires a different approach to determine meaningful flux ULs, since the source position in the MAGIC FoV is not known. This is a consequence of the fact that there is not a precise localization of the event and only a probability skymap is provided to search for an EM emission.

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5. Discussion and outlook

The MAGIC telescopes system, with its $\sim$ 50 GeV energy threshold, is filling the gap between the space and ground-based gamma-ray instruments. Thanks to its fast re-positioning capabilities, it is well suited for fast transient follow-up observations, like Gamma Ray Bursts. MAGIC performed a follow-up observation of the third GW alarm released to the EM partners by the aLIGO team during the O1 science run. No very high energy gamma-ray counterpart was found. Integral upper limits for four selected regions of the GW probability map will be estimated.
The MAGIC field of view is $\sim 3.5^o$. For follow-up observations of GW alerts, a more precise localization of the source position would be advantageous. The joining of Advanced Virgo for the forthcoming science run O2, expected to take place in Spring 2017, and of Kagra (Somiya *et al.* in the future, will greatly improve the localization capabilities of the interferometers (Aasi *et al.* 2016). Information provided by other high-energy space based wide-field instruments, such as Fermi-GBM & LAT, would also improve the follow-up capabilities; a more strict collaboration between the EM follow-up community is then desirable.

Future EM follow-ups of GW sources will shed light on the presence or absence of firm EM counterparts and astrophysical processes that may trigger EM emission from these systems. MAGIC is ready to contribute to the quest.

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