The MAGIC Multi-Messenger Transient Sources program

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Gamma-ray photons in the > 10 GeV energy band offer a powerful diagnostic tools for the emission processes and physical conditions of extreme transient events in a multi-messenger framework. Recently, a considerable number of observational facilities have entered in their operational phase or they will approach their designed sensitivity in the nearest future. First follow-up observations of transient events detected by such a large network of instruments have recently started allowing an unprecedented observational coverage spanning from neutrino to gravitational waves (GW). In the next years, the observations in both electromagnetic and non-electromagnetic channels will play a key role in our understanding of the astrophysics of transient events, yielding rich scientific rewards. In this contribution, I will present the motivations for high-energy observations of transient events and the current situation with respect to the Major Atmospheric Gamma-ray Imaging Cherenkov (MAGIC) telescopes.

1 Introduction

In the last years, an increasing number of experimental evidences has made clear the possibility of performing astrophysical observations by means of non-electromagnetic signals. The discoveries of high-energy astrophysical neutrinos [1] and gravitational waves [2] have recently opened the way to a multi-messenger approach in the study of cosmic objects. The era of GW astronomy was opened by the first direct detection of gravitational waves on 2015 September 14 [2]. Promising astrophysical sources of GW transient signals are usually related to extreme objects and environments that are also expected to emit photons and neutrinos. Observations in the GW/neutrino and electromagnetic (EM) channels represents the way to reach a more complete comprehension of the astrophysical sources, their emission engines and the physics of their progenitors and their environment. Furthermore, EM follow-up of neutrino and GW triggers is particularly important, as it could provide a more precise localization (arcsecond) of the GW/neutrino source allowing systematic multi-wavelength observations to acquire additional information about the event and its host galaxy. Within this framework, ground-based gamma facilities like the MAGIC telescopes have set up dedicated follow-up programs of GW/neutrino alerts in the very high energy band (VHE - E> 100 GeV). Observation in this band is particularly relevant as it could provide important information on GW/neutrino counterpart in an energy range not affected by selective absorption processes typical of other wavelenght.

2 The MAGIC Telescopes

The MAGIC system consists of two 17 m diameter Imaging Atmospheric Cherenkov Telescopes (IACTs) located at the Roque de los Muchachos observatory (28.8° N, 17.8° W, 2200 m a.s.l.),

Table 1: Current external triggers received by the MAGIC alert system

Source	Messenger	Received	Auto Repointing
GRB	x-rays/γ-rays	yes	yes
SGR/AXP	x-rays/γ-rays	yes	yes
AGN (FLARES)	γ-rays	yes	no
GW	GW	yes	planned
Neutrino	ν	yes	yes
FRB	radio	planned	planned

on the Canary Island of La Palma. The MAGIC system is currently carrying out stereoscopic observations with a sensitivity $< 0.7\%$ of the Crab Nebula flux for energies above ~ 220 GeV in 50 h of observation, and a trigger energy threshold of 50 GeV at zenith. The instrument response to external triggers is based on a dedicated alert system able to receive alerts coming from the GRB Coordinate Network (GCN [a]). As soon as an observable alert is received, a full automatic procedure stops on-going observations and start follow-up at alerts coordinates with a fast re-positioning. Thanks to their lightweight structures based on carbon fiber tubes, the MAGIC telescopes are able to point to the new coordinates using dedicated fast-slewing movements within few tens of seconds after the alert is received. This implies a remarkable re-pointing speed of around 7°/sec in GRB mode in both zenith and azimuth [b] [3]. Originally developed for GRB studies, nowadays the system has been modified to correctly receive and interpret alerts of different types in a multi-messenger approach like for neutrino and gravitational waves triggers. Furthermore, a parallel system based on a more recent VOEvent protocol [4] is under development to connect MAGIC to other facilities using virtual observatory (VO) standards.

The relatively large MAGIC field of view ($\sim 3.5°$) is well-suited for the current accuracy in localization typical of GW and neutrino alerts, although a more precise localization of the source position would be surely advantageous. For GW follow up, in particular, the joining of aVirgo during the forthcoming observing runs and of Kagra in the future, will greatly improve the localization capabilities of the interferometers.

The current list of transient sources implemented in the alert system is summarized in Tab. 1

3 The Gravitational waves follow-up program

The mergers of two black holes (BH-BH), two neutron stars (NS-NS), or a black hole and a neutron star (BH-NS) are the most likely sources of GW to be detected due to the large amount of energy released in the process. The expected gravitational waveform and energy release ($\sim 10^{-2}$ $M_\odot$) have been predicted by several authors (see, e.g., [5,6]), and BH-NS coalescence has also been discussed as a possible central engine of short gamma-ray bursts (SGRB) [7]. It is indeed possible that, during the merger, the NS will be tidally disrupted, resulting in the formation of an accretion disk around the BH. In a short timescale, gravitational energy could be released in the form of an electromagnetic/neutrino flow, with the formation of a relativistic jet. Thus, the detection of an EM counterpart could confirm BH-NS mergers as the progenitors of SGRB. Furthermore, also follow up of BH-BH mergers is significantly important. In the case of GW 150914, the Fermi GBM detector identified a weak gamma-ray transient 0.4 s after the GW signal with consistent sky localization [8]. This association, although controversial, opened a debate about the possibility that BH-BH mergers may also produce EM counterparts [9,10].

[a] http://gcn.gsfc.nasa.gov/

[b] The normal pointing speed for MAGIC is around 3°/s.

3.1 MAGIC observations during O1 run

In the last years, in view of the first science runs, an EM follow-up program has been set up between the aLIGO and Virgo scientific collaborations and a broad astronomy community with access to ground- and space-based facilities. As one of these facilities, MAGIC participates in a shared bulletin board to announce, coordinate, and visualize the footprints and wavelength coverage of follow-up observations. Differently from GRB alerts, GW notices do not report precise event coordinates but, besides time and significance of the alert in terms of False Alert Rate (FAR), a probability sky map (Fig. 1) is delivered.

During the first observing run (O1), the aLIGO collaboration announced three GW triggers to the EM follow-up partners. The first two did not trigger MAGIC observations. The first one (GW 150914), detected at the end of the aLIGO engineering run immediately prior to O1, turned out to be the first ever direct detection of GW; for this event the higher probability region of sky within which it was localized, was mostly outside the MAGIC field of view. The second one (LVT 151012), later on determined by the LIGO-Virgo offline analysis not to be a GW event, could not be observed because of bad weather conditions. Then, on 2015 December 26 at 03:38:53.648 UT aLIGO detected a high significance candidate GW event, later designated GW 151226 [11], and one day later provided spatial localization information in the form of probability sky maps via private GCN circular.

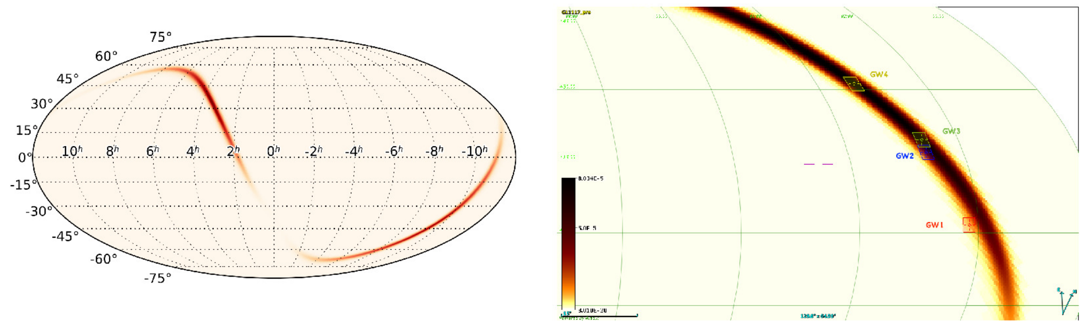

Figure 1 – *Left:* The LIGO localization probability skymap of GW 151226. It is important to remark that the 50% confidence level credible region spans over 430 deg^2. *Right:* Zoom on the region with the four MAGIC pointing positions of GW 151226.

MAGIC observations were performed in four sky pointing positions (Fig. 1 right) selected in the region showing maximum probability according to the visibility, observations of EM-partners and overlap with existing catalogs. The target regions are reported in Tab. 2. Observations started on 2015 December 28 at around 21 UT, covering a $\sim$ 2.5 x 2.5 deg^2 region around the pointed positions. The follow-up was performed in the so-called wobble mode, where the pointing position is offset by $\pm 0.4°$ from the camera center, with four and two symmetric positions for the first two and the last two targets respectively.

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). Due to the large uncertainties in the localization of GW alert, a dedicated analysis method has been developed to provide upper limits (ULs) evaluation within the full MAGIC field of view. The UL skymap will be the subject of a forthcoming dedicated publication.

4 The neutrino follow-up program

The possibility of identifying extraterrestrial neutrino point sources largely depends on the physics of the accelerators and the possible emission processes at work. Hadronic $p\gamma$ or pp in-

Table 2: 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.

Target	RA (J2000)	Dec (J2000)	Duration	Zenith
PGC 1200980 (MASTER [12])	02 h 09 m 05.800 s	$+1^\circ\ 38'\ 03.00''$	48 min	$[27^\circ, 30^\circ]$
strip from GW map	02 h 38 m 38.930 s	$+16^\circ\ 36'\ 59.27''$	59 min	$[13^\circ, 24^\circ]$
Field VST [13]	02 h 38 m 02.210 s	$+19^\circ\ 13'\ 12.00''$	30 min	$[22^\circ, 30^\circ]$
Field VST [13]	03 h 18 m 23.712 s	$+31^\circ\ 13'\ 12.00''$	30 min	$[19^\circ, 27^\circ]$

teractions can lead to the production of detectable neutrinos through Δ resonance production. Many works pointed out the possibility of having such a processes in variable objects as BL Lacs or FSRQs, Galactic systems like binary system including a white dwarf (WD) or transient objects like GRBs [14]. The energy of the produced neutrinos could be up to $\sim 10^{15}$ eV making them detectable by experiments like IceCube [c]. The recent results by IceCube [1] have opened, for the first time, an extragalactic astrophysics source model via neutrinos observations. On the other hand, no clear correlation with known astrophysical sources has been yet identified leaving the questions about possible sources of these neutrinos unanswered. Within this framework, the contemporaneous observations of an EM counterpart in the high-energy gamma-ray band is crucial by increasing the possibility to unambiguously identify the possible associated astrophysical sources.

4.1 MAGIC program on neutrino

IceCube is a 1 km^3 neutrino telescope located at South Pole. The detector operates continuously with only very minimal downtime, and has a full sky field of view, with energy threshold depending on declination. The real-time alert system separates the neutrino candidate selection at the South Pole from the analysis, and transmits the event information as a stream of single high energy events to North via rapid satellite communication channels.

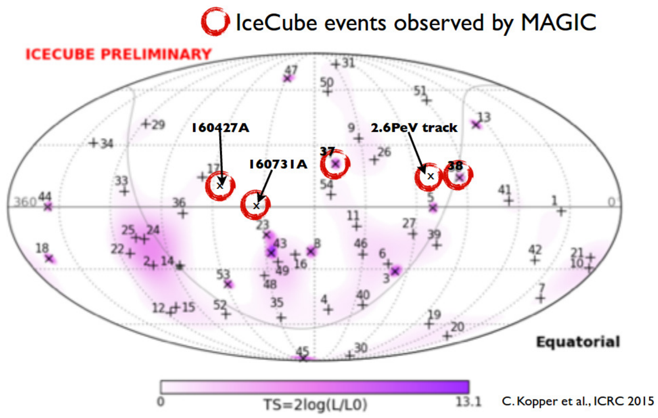

Figure 2 – The IceCube events observed by MAGIC [17].

The two Icecube alerts streams for High Energy Starting Events (HESE) and Extremly High Energy (EHE - see for details [15]) are delivered via GCN Notice generated by the Astrophysical Multimessenger Observatories Network (AMON [16]). The MAGIC alert system is able to receive

[c] http://icecube.wisc.edu/

these alerts in real time. In 2016 MAGIC carried out follow-up observations of 5 selected HESE track-like events from the Northern hemisphere: the archival events HESE-37, HESE-38, HET [18], and the real time alerts HESE-160427A [19] and HESE/EHE-160731A. The details of MAGIC observations are summarized in Tab. 3

Table 3: Summary of the follow up performed by MAGIC at IceCube neutrino positions. Columns represent respectively: the source name, coordinates, localization accuracy and the deposited energy in IceCube. Last two columns are the zenith range and the observation time of the MAGIC observations. In the case of the two real-time alerts HESE-160427A and HESE/EHE-160731A, the time delay between the events onset and the starting time of observation is also reported.

Target	RA(J2000) [h]	Dec(J2000) [deg]	Loc. Accuracy	Deposited E [TeV]	Zenith [deg]	T_{obs} [h]
HESE-37	11.15	20.70	$< 1°(50\%)$	$30.8^{+3.3}_{-3.5}$	$[8°, 32°]$	6.6
HESE-38	6.22	13.98	$< 1°(50\%)$	200±16	$[15°, 32°]$	5.9
HET	7.36	11.48	0.27°(50%)	2600±300	$[21°, 32°]$	4.3
160427A	16.04	9.34	0.6°(90%)	≈ 140	$[18°, 26°]$	2.0 (T_0+42 h)
160731A	214.54	-0.33	0.75°(90%)	not given	$[45°, 65°]$	1.3 (T_0+16 h)

In neither of the performed follow up observations a significant gamma-ray emission above the energy threshold has been detected [17,20]. Fig. 3 reports the sky-maps for the HESE-37 and HESE-38 region surveys obtained by MAGIC. As for GW, an ULs skymap has been produced for these observations characterized by large uncertainties in the pointing positions. ULs (95% C.L.) have been estimated for above the energy threshold of 120 GeV assuming a power-law spectrum with index -2.3. The obtained ULs span between $1-10\%$ and $2-10\%$ of the Crab Nebula flux above the same threshold for HESE-37 and HESE-38, respectively [17,20].

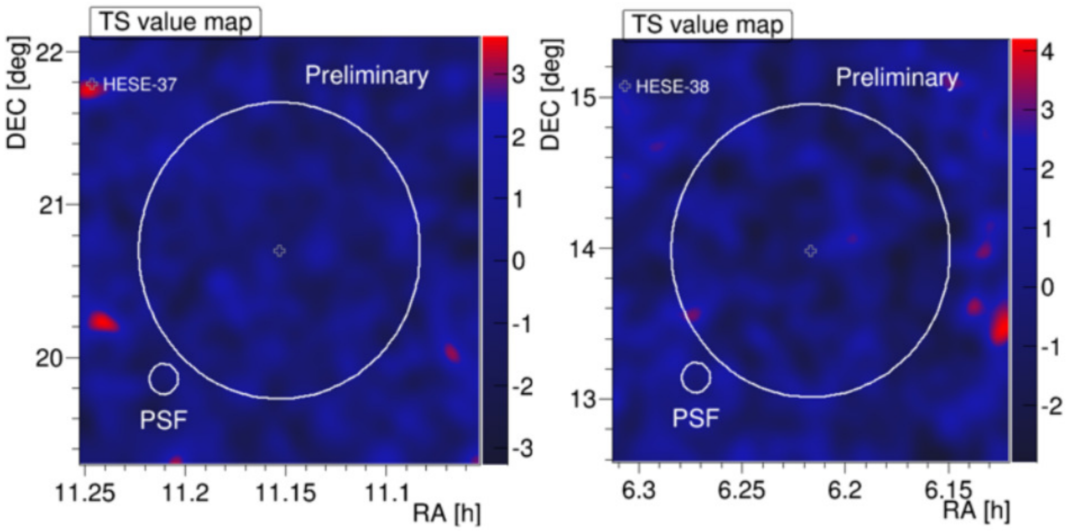

Figure 3 – Pre-trial significance sky maps for HESE-37 and HESE-38. Larger circles are the angular resolution of each neutrino event while the smaller circles represent the MAGIC point spread function (PSF).

5 Conclusion

The dawn of multimessenger astronomy recently started to require a significant effort for coordinate a global network of different facilities both ground- and space-based. This interdisciplinary effort is crucial to interpret observations, constrain physical models and improve our comprehension of cosmic accelerators. Observations using the weakly interactive GW and neutrinos are particularly relevant as they can probe regions opaque to photons although their detection is still challenging. At the same time, coordinate follow up in the EM channels and in particular in the VHE band, have the key role to unambiguously identify the GW/neutrino sources shedding light on their progenitors and environment.

The MAGIC telescopes system, with its ~ 50 GeV energy threshold at the zenith and its fast re-pointing capabilities is good performer in fast follow-up observations, e.g. for GRB and galactic transients. Recently, the MAGIC alert system has been modified in order to accept GW and neutrino alerts in a multi-messenger framework. In the last year, MAGIC started to perform follow-up observations searching for VHE counterparts of both GW and neutrino triggers. Nowadays, no VHE gamma-ray counterpart was found. Integral upper limits above the energy threshold for these positions, as well as for the the whole FoV, have been evaluated and they will be the target of a dedicated forthcoming publications.

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