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The LIGO-Virgo Collaboration electromagnetic follow-up program

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Summary. — The detection of the electromagnetic counterparts of gravitational wave sources enables to gain a wealth of complementary information, ultimately providing a more complete phenomenological picture of a number of astrophysical source classes. This paper reports on the past and current LIGO and Virgo Collaboration (LVC) electromagnetic follow-up program for transient sources of gravitational waves. The program improvements between different science runs are highlighted, as well as the expected scenarios for future science runs.

1. – Introduction

Ground-based interferometers as the Advanced Laser Interferometer Gravitational wave Observatory (LIGO) and Advanced Virgo [1, 2] are sensitive to high-frequencies gravitational waves (10 Hz–10 kHz). The frequency range can tell us which type of astrophysical source we could observe. At the frequencies detectable by the ground-based interferometers we expect to observe transient phenomena associated to catastrophic events, as compact object (neutron star, stellar-mass black hole) binary coalescence systems (CBCs) and core-collapsing massive stars, and to instability episodes from isolated neutron stars. CBC systems are the most promising sources since their energy output in gravitational waves (GW) is expected to be larger than for the other mentioned sources and the GW waveforms are well defined by the theory of general relativity, enabling the application of very efficient data analysis techniques in the signal search procedures.

CBC systems containing at least one neutron star (NS) are expected to emit electromagnetic (EM) radiation. Indeed, such systems are thought to be the progenitors of short gamma-ray bursts (GRBs) and their multi-wavelength afterglows [3]. Since short GRB are likely collimated, they will accompany only a fraction of GW-detected NS-NS or NS-BH coalescing systems. Other possible EM counterparts expected to emit isotropically are predicted from the tidally unbound material ejected during the coalescence.

The synthesis of r-process heavy elements inside the ejected matter and their radioactive decay are expected to eventually produce the "macronova" emission, an almost thermal emission predicted to peak in the optical/NIR bands at few days from the coalescence (*e.g.* [4,5]). Furthermore, the impact of the ejected material with the interstellar medium may also produce synchrotron radiation detectable as a late radio emission (*e.g.* [6]). Finally, isotropic X-ray (0.1–10 keV) emission is predicted if the remnant of merging NS-NS systems is a long-lived neutron star (*e.g.* [7, 8]). On the other hand, from CBC systems formed by the coalescence of two stellar-mass black holes no obvious EM counterpart is expected due to the likely lack of reprocessing matter. However, recent works have proposed some possible scenarios where some material may remain bound to the system and emit EM radiation (*e.g.* [9-11])

Finding the EM counterpart of a GW source provides a wealth of additional and in most cases complementary information, enabling to gain a more complete phenomenological picture of a number of classes of astrophysical sources. In the case of CBC systems, the detection of a temporally and spatially coincident short GRBs will confirm their progenitor nature and possibly distinguish between NS-NS and NS-BH. From the host galaxy identification, the interstellar matter (ISM) properties can be studied providing clues on the formation history of the GW source as well as an independent measure of distance from spectral line systems cosmological redshift z. Measuring z from optical spectra and the luminosity distance from GW for large sample of CBC systems, will possibly put interesting constraints on cosmological parameters.

GW sources are localized via triangulation methods by using a network of interferometers, thus the larger is the number of GW detectors in the network the smaller is the area of the localized sky region. With two detectors, as the network formed by the two LIGOs based at Hanford and Livingston, GW sources are typically localized in sky areas of about a few hundreds to a few thousands deg^2 [12]. Such poor localization represents one of the main challenges to the transient EM counterpart searches, together with the need of low-latency programs able to detect GW candidate signals and send alerts to the astronomical community.

2. – LVC past electromagnetic follow-up program

The first LIGO/Virgo Collaboration (LVC) low-latency follow-up program was applied during initial LIGO and Virgo science runs, from December 2009 to January 2010 and from September to October 2010 [13]. Automatic data analysis pipelines were built to continuously monitor the data flow and indentify GW source candidates in low-latency regime. During this run, the LVC EM follow-up program set the GW signal false alarm rate (FAR) threshold required to send an alert to partner astronomers in the range 1–0.25 day^{-1}. With this criterium, 8 GW event candidates were selected among bursts and CBCs signals during the observing run(^{1}) and communicated to partner astronomer teams who signed the LVC Memorandum of Understanding (MoU). The LVC program also centrally planned follow-up observations and different sky "tiles", covering the GW source candidates sky localization, were assigned to individual astronomical facilities. At that time, 10 telescopes among optical and radio ground-based facilities, plus the *Swift* high-energy satellite, were involved [13].

(^{1}) Off-line analysis later confirmed the non-astrophysical origin of these GW candidates.

3. – The LVC program during O1 and O2

The first Advanced LIGO and Advanced Virgo observational run (O1) started on September 2015 up to January 2016. The FAR threshold established to send an alert to partner astronomers for this run has been lowered with respect to the past one down to 0.5 per month per CBC and burst events. Another important difference with the past LVC follow-up program, consisted in a direct release of GW candidate event sky localizations to astronomer teams, rather than centrally planning assignments of sky tiles to each facility.

During O1, GW event candidate sky localizations were provided as sky probability maps (*skymaps*) in healpix projection [14] and formatted as Flexible Image Transport System (FITS) files. Event candidate triggers as well as their *skymaps* have been released with the Gamma ray Coordinates Network (GCN) protocol, consisting of machine-readable Notices plus short bulletins (Circulars) with human descriptions of the events(2). So far, LVC/GCN are currently restricted to MoU partners until the event has been published.

The interface between GW data analysis and EM follow-up observations of each candidate event is the Gravitational wave Candidate Data Base (GraceDB) webpage, where prompt low-latency analysis results as the detection pipeline, the FAR, the time and date of the event, etc., together with the *skymap* files, are provided to the astronomers. For each GraceDB event page, an "EM bulletin board" has also being created to coordinate EM follow-up observations. In the EM bulletin board, astronomers can insert planned or performed observations by providing sky coordinates of each pointing, instrument field of view and covered wavelength range. The inserted observations can then be visualized in real time in terms of sky coverage superimposed on the skymap with a dedicated GUI ("SkyViewer") based on the Aladin interactive sky atlas [15].

On September 14, 2015 the first GW event was detected as a clear signal with a false alarm rate (FAR) well below the established threshold. Estimated off-line analysis FAR resulted in less than one event per 203000 years, equivalent to a statistical significance of more than 5.3 σ [16]. An "informal" announcement (email text) on September 16th and then a proper GCN Circular (GCN 18330) on September the 20th, 2015, were sent out to 63 teams of astronomers who signed the LVC MoU as well as two *skymap* files. The latters were computed by two different data analysis pipelines (cWB and LIB) at different computational costs [17]. The most accurate skymap (LAL Inference) showed a 90% probability area of 630 $\deg^2$ [20]. Gamma-ray detectors provided the most complete sky coverage with a contained probability of 100%, while an 84% fraction was reached in X-rays (2–20 keV). Radio and optical survey telescopes monitored sky regions with 86% and 50% contained probability, respectively [17]. GW150914 event was identified with a coalescing BH-BH system.

On December 26, 2015 another GW event candidate was detected and further confirmed to be a real event, labelled as GW 151226, with more than 5.3 σ significance [18]. This event was announced to partner astronomers almost two days later with a GCN (GCN 18728). Contrary to the case of GW 150914, beside the date and time of the event candidate and its *skymap*, the first GCN also provided some information on the nature of the source, quoting a likely association with two merging black holes. The presence or absence of a neutron star in a CBC system is strictly linked with the probability to have

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(2) `https://gcn.gsfc.nasa.gov/lvc.html`

an EM counterpart (*e.g.*, [21]) and for this reason this crucial piece of information for the EM follow-up observational campaign was considered to be released promptly during the next scientific run.

The second run of aLIGO (O2) began on November 30, 2016 and is still ongoing. Several worldwide astronomical teams from several astronomical institutions, agencies and small groups of astronomers have signed the LVC MoU(3). Such large participation provides nearly hundreds of facilities among space- and ground-based telescopes, assuring the full EM spectrum coverage, from radio to very high-energy gamma rays. GW event candidate alerts are now provided within tens of minutes. Thanks to significant improvements in low latency data analysis softwares and source modelling, important additional information are now released in low latency. For CBC events, 3D *skymaps* are released, providing information also on the source distance [19]. In addition, an "EM-bright" flag is quoted, giving the probability that there is any NS tidal disrupted material to power an electromagnetic (EM) transient ([21, 22]).

As of March 23, 6 triggers have been identified by online analysis using a FAR threshold of one per month and shared with partner astronomers. Investigations of the data and offline analysis are so far still in progress (4).

4. – Expected scenarios

New constraints on the rate of BH-BH coalescing system population obtained from the O1 run results indicate a range of 9–240 $\mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$. These values imply that during O2, considering the volume of Universe that could be monitored and the expected duration of the run, there is about 90% of probability to see more than two BBHs and 50% probability to see more than 10 BBH. During O3, predictions are given for more than 10 BBHs at 90% probability, and 60% to see more than 40 BBH [23]. The non detection of NS-NS and NS-BH systems during O1 is still consistent with expectations, providing an upper limit of $R_{NS-NS} < 12600\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$ and $R_{NS-BH} < 3600\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$. Non-detection of BNS in O2 will provide constraints on the upper limits of this range [24].

5. – Summary

Electromagnetic counterparts of high-frequency GW transient signals are expected from gamma rays to radio. Their detection is fundamental to gain a complete phenomenological picture of a number of astrophysical source classes. EM follow-up observations are challenged by the poor localization of GW detectors and by the need of low-latency data analysis. Past LVC EM follow-up program has been significantly improved and it has been successfully tested in O1. Further improvements have been provided during the O2 run, by adding precious prompt information as the source distance and the EM expected brightness flag for CBC events.

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(3) `https://gw-astronomy.org/wiki/LV_EM/PublicParticipatingGroups`

(4) `http://ligo.org/news/index.php#O2Apr2017update`.

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