ELECTROMAGNETIC FOLLOW-UP OF GRAVITATIONAL WAVE TRANSIENTS: FIRST RESULTS AND PERSPECTIVES

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The recent detection of gravitational waves from the merger of binary black holes marked the birth of gravitational wave astronomy and opened a new chapter in the multi-messenger study of the Universe. Among gravitational wave sources, mergers of binary neutron stars and black holes are thought to be associated with electromagnetic transient phenomena, such as short Gamma Ray Bursts. Simultaneous observations with gravitational interferometers and ground-based or space telescopes will thus provide an unique opportunity to find the electromagnetic counterparts of these gravitational wave sources. In this paper I review the astrophysical sources expected to emit transient multi-messenger signals, discuss the results on the electromagnetic follow-up campaign performed during the first observing run of Advanced LIGO, and highlight the perspectives and challenges for future science runs.

1 Introduction

The detection of gravitational waves (GWs) by the two interferometers of the Advanced Laser Interferometer Gravitational-Wave Observatory (LIGO[1]) opened the era of GW astronomy. The two detected events, labeled GW150914 and GW151226, are both consistent with the coalescence of two black holes (BBH) at a distance of ∼400 Mpc (see Abbott et al. 2016a,b[2,3]).

Detailed analysis of the GW signals allowed to measure several of the source physical parameters. For example, the masses of the two BHs have been estimated to be (in the source frame) $36.2^{+5.2}_{-3.8}$ $M_\odot$ and $29.1^{+3.7}_{-4.4}$ $M_\odot$ for GW150914, $14.2^{+8.3}_{-3.7}$ $M_\odot$ and $7.5^{+2.3}_{-2.3}$ $M_\odot$ for GW151226 (Abbott et al. 2016c[4]). The measured BH masses in GW150914 are higher than any of the BH masses dynamically measured reliably from X-ray binaries (see, e.g., Özel et al. 2010[9]) and represent a clear evidence that relatively "heavy" BHs ($M > 25$ $M_\odot$) can form in nature. Such heavy BHs require massive progenitors and weak star winds. Given our current understanding of massive-star winds and their dependence on metallicity, the binary systems of heavy BHs form in an environment with a metallicity lower than about half of the solar value. The BBH formation in a dense star cluster or from an isolated binary are both consistent with GW150914 (see Abbott et al. 2016d [10]) and GW151226 (see Abbott et al. 2016c [4]).

To obtain a more complete knowledge of the environment of GW sources, as well as of the source nature, multi-messenger astronomy is needed. In fact, the detection of an EM counterpart would give a precise localization and potentially lead to the identification of the host galaxy of the source, thus also determining its redshift; furthermore, it would considerably increase the confidence in the astrophysical origin of the GW signal.

Joint EM and GW observations can be performed through the EM follow-up or the externally triggered GW searches. In the EM follow-up a GW event is detected by online data analysis pipelines and a GW alert is promptly issued to a network of EM observatories, that start observing the sky region consistent with the GW signal (see, e.g., Abadiet et al. 2012 [5], Evans et al. 2012 [6], Aasi et al. 2014a [7]). In the externally triggered GW searches a EM transient is detected, and then GW data are analyzed in detail to find a possible GW signal in temporal and spatial coincidence with the observed EM signal (see, e.g., Aasi et al. 2014b [8]).

The EM follow-up of GW transient events is challenging for several reasons. First of all, the sky localization of GW events can be very poor. In fact, GW sources are mainly localized via triangulation methods, based on the observed time delays, phase differences, and relative amplitude of the GW signal at different detectors. For this reason, the larger is the number of GW detectors in the network, the smaller is the GW error box in the sky localization; with only two detectors (i.e., the two Advanced LIGO interferometers), the GW sky localization areas are of the oder of 100-1000 square degrees. Another challenge is represented by the need of a low-latency program to detect GW candidates and send alerts to the astronomical community in nearly real-time, to allow astronomers to start EM observations as promptly as possible.

This review describes the transient sources expected to have a multi-messenger emission and summarize the results of the EM follow-up campaign associated to the first GW detections. The work is organized as follows. In section 2 we describe the GW transient sources and their expected EM and neutrino counterparts; in section 3 we explain how low-latency GW searches are performed; in section 4 we present the results obtained from multi-messenger searches during the first observing run of Advanced LIGO, while in section 5 we discuss the future observational scenario. Finally, in section 6 we present our conclusions.

2 Multi-messenger emission from transient sources

In the universe there are many transient sources expected to emit both GWs and radiation in different electromagnetic bands. In the following we will describe these sources and their expected multi-messenger emission.

2.1 GW transient sources

Besides BBHs, the most promising transient sources that emit GWs at the frequencies at which ground-based interferometers (such as Advanced LIGO) are sensitive (10 Hz - 10 kHz) are the coalescences of binary systems of compact objects (CBC) composed by two neutron stars (NS-NS) or a neutron star and a stellar mass black hole (NS-BH). These events are among the most energetic: for instance, the energy emitted in GWs from the inspiral of a NS-NS system is of the order of 10^{-2} $M_{\odot}$ c^2 (see Peters 1964 [11]). For CBC systems the GW waveform is accurately modeled by post-Newtonian approximation and numerical simulations, therefore the GW signals can be searched with the matched filter modeled search (see, e.g., Wainstein & Zubakov 1962 [12], Cannon et al. 2012 [13], Messick et al. 2017 [14], Adams et al. 2016 [15], Veitch et al. 2015 [16], Dal Canton et al. 2014 [17], Usman et al. 2016 [18], Nitz et al. 2017 [19]).

Another class of transient GW sources that may be observed by ground-based interferometers are the core-collapsing massive stars (see Ott 2009 [20] and Kotake et al. 2006 [21] for an overview).

These sources are expected to emit GWs if there is some asymmetry in the stellar envelope ejection phase. However, the large uncertainties affecting our knowledge on the collapsing phase of these objects makes highly uncertain the GW released energy (it is expected to be in the range 10^{-8} $M_\odot$ c^2 to 10^{-5} $M_\odot$ c^2) and, as a consequence, there is large uncertainty also in maximum distance at which these sources can be detected. Furthermore, the modeling of the GW signal is quite complicated, so the GW signals are searched with the so called "unmodeled searches", with minimal assumptions about the GW waveform.

The last class of transient GW sources is represented by rotating NSs with very intense magnetic fields, of the order of 10^{15} G (magnetars). Theoretical studies predict that when such stars undergo starquakes, asymmetric strains can temporally alterate the geometry of the star and GWs are expected to be emitted (see, e.g., Corsi & Owen 2011 [22]). Also in this case, the expected amount of GW energy emitted is highly uncertain (it might be in the range 10^{-16} - 10^{-6} $M_\odot$ c^2), and the GW waveform is uncertain as well, so the GW signals are searched with the unmodeled searches.

2.2 The EM and neutrino counterparts

The GW transient sources described in section 2.1 are expected to have also an associated EM emission. For instance, NS-NS and NS-BH mergers are thought to be the progenitors of short Gamma Ray Bursts (GRB): intense and highly variable flashes of γ-rays whose duration is < 2 s (the prompt emission), sometimes followed by a long lasting afterglow emission at lower energies (X-rays, optical, radio). Coalescing NS-NS systems are also theoretically predicted to isotropically eject a quantity of neutron rich matter; the radioactive decay of heavy nuclei synthesized in this ejecta through r-processes produces a thermal optical/NIR emission: the "kilonova". Finally, a radio blast wave emission can also be observed, due to the interaction of the merger ejecta with the interstellar medium. For a review see Metzger & Berger 2012 [23].

The core-collapse of massive stars are accompanied by supernova (SN) emission at optical and radio frequencies, generally observed starting from days to weeks after the collapse and lasting from weeks to years. The SN emission can be preceded by a bright flash of radiation created as the shock wave generated by the collapsing core reaches the surface of the star: this is the so called "shock break-out" (SBO) emission, that has been observed in X-rays and optical (see, e.g., Soderberg et al. 2008 [24] and Garnavich et al. 2016 [25]). Another EM emission expected from the core-collapse of massive stars is represented by long GRBs[a], that sometimes have been observed in association with SN emission (see, e.g., Modjaz et al. 2006 [26]).

Soft Gamma Repeaters (SGRs) and Anomalous X-ray Pulsars (AXP) are sources which sporadically emit short bursts of gamma-rays and X-rays at irregular intervals (see Mereghetti 2008 [27] for a review). Both objects are largely believed to be associated to magnetars experiencing starquakes and consequent crust disruption. GW emission associated to starquakes can also be accompanied by a radio/X-ray pulsar glitch: a sudden increase in the rotational frequency of a highly magnetized, rotating NS (pulsar) followed by exponential decays, which bring back the pulsar to the initial value (see e.g. Espinoza et al. 2011 [28]).

The above described EM sources, in particular GRBs and SNe, are expected to produce relativistic outflows in which particles (protons and nuclei) can be accelerated and produce high-energy neutrinos by interacting with the surrounding medium and radiation. For instance, MeV neutrinos have bee detected from SN 1987A in the Large Magellanic Cloud (at a distance of D$\sim$50 kpc) by the Kamiokande-II (Hirata et al. 1987 [29]) and the Irvine-Michigan- Brookhaven (Bionta et al. 1987 [30]) neutrino detectors, a few hours before its optical counterpart was discovered.

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[a] Long GRBs are characterized by a longer duration (> 2 s) of the prompt emission and a softer spectrum with respect to short GRBs.

3 Low-latency GW data analysis

As mentioned in the Introduction, one of the challenges of successfully obtaining prompt EM observations is to identify the GW candidates quickly: the data from the interferometers must be transferred and analyzed in near-real time. The LIGO Scientific Collaboration and the Virgo Collaboration (the LVC collaboration) developed a low-latency follow-up program, that is schematized in figure 1.

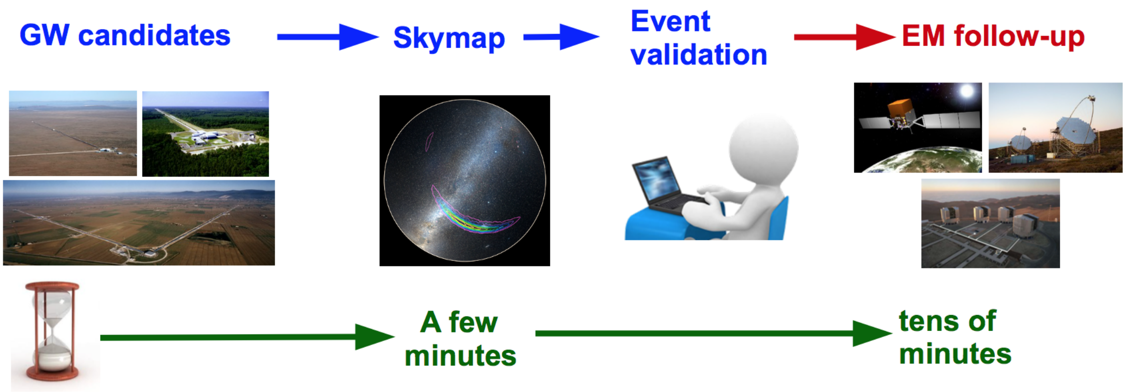

Figure 1 – Schematization of the low-latency follow-up program.

Several automatic low-latency GW data analysis pipelines have been built to continuously monitor the GW data, to search for transient GW signals that are coincident in the two detectors within the 10 ms light travel time separating them (see, e.g., Klimenko et al. 2016 [31], Lynch et al. 2015 [32], Cannon et al. 2012 [13], Messick et al. 2016 [14], Adams et al. 2015 [15], Usman et al. 2016 [18]). These pipelines report GW candidates within a few minutes of data acquisition, and estimate the potential sky position of the source. Once the candidates are identified, there is a manual "event validation": a team of experts evaluate the detector performances at the time of the trigger and the quality of the data. If the event candidate passes all the checks, a GW alert is sent to the astronomers, and the EM follow-up of the GW event can start.

Event candidate triggers as well as their skymaps are shared with astronomers through the Gamma ray Coordinates Network (GCN) protocol, consisting of machine-readable Notices plus short bulletins (Circulars) with human descriptions of the events[b]. These GCNs are currently restricted, until the GW event has been published, to astronomers who signed a Memorandum of Understanding (MoU)[c] with the LVC collaboration.

4 The EM follow-up campaign during O1 and O2

The first Advanced LIGO observational run (O1) took place from September 2015 up to January 2016. During O1, three GW alerts have been shared with the astronomers who signed a MoU. Although binary BH mergers are not expected to emit detectable EM emission nor neutrinos, the GW detections were followed by an impressive multi-messenger campaign, involving tens of instruments (satellites and ground-based telescopes) covering the whole electromagnetic spectrum, from radio to very high energy γ-rays (see Abbott et al. 2016e [33]).

On September 14, 2015, there was the first GW detection (Abbott et al. 2016 [2]): GW150914, with a statistical significance of more than 5.3 σ and a False Alarm Rate (FAR) $< 6\times10^{-7}$ yr^{-1}. An initial announcement (via email) on September 16, and a GCN Circular (GCN 18330) on September 20, were sent to the 63 teams of astronomers who signed the MoU, together with two skymaps obtained by two different data analysis pipelines: Coherent Wave Burst (cWB,

[b] https://gcn.gsfc.nasa.gov/lvc.html
[c] https://gw-astronomy.org/wiki/LVEM/PublicParticipatingGroups

Klimenko et al. 2016 [31]) and Omicron+LALInference Burst (oLIB, Lynch et al. 2015 [32]). The most accurate skymap by LALInference (Veitch et al. 2015 [16]) showed a 90% probability area of 630 deg^2 (Abbott et al. 2016f [34]). Despite this very huge GW error box, there was a good sky coverage at all wavelengths, with a contained probability of 100% in gamma-rays, 85 % in X-rays, 86 % in radio and $\sim$ 50 % in optical (see Abbott et al. 2016e [33]). Several optical candidate counterparts have been found, but all of them have been identified to be normal population type Ia and type II SN, with a few dwarf novae and active galactic nuclei (AGNs) that are all very likely unrelated to GW150914 (see, e.g., Smartt et al. 2016a [35], Kasliwal et al. 2016 [36], Copperwheat et al. 2016 [37]). A weak transient signal was found in *Fermi* GBM data 0.4 s after the time of GW150914 (Connaughton et al. 2016 [38]), but no corresponding signal was found in the INTEGRAL SPI-ACS instrument (Savchenko et al. 2016 [39]) or AGILE (Tavani et al. 2016 [40]). The IceCube and ANTARES collaborations performed a high-energy-neutrino follow-up of the GW event, but they found no neutrino candidates in both temporal and spatial coincidence with GW150914 (Adrián Martínez et al. 2016 [41]).

On October 22, 2015 a second GW candidate was observed and a GW alert was released to the astronomical community (GCN 18442). However, off-line GW data analysis found it not to be an event of interest and a retraction was submitted with a new GCN about one month later (GCN 18626).

On December 26, 2015, a third GW candidate was detected. Off-line refined analysis of the GW data confirmed this event, labeled GW151226, to be a real event, with a significance of more than 5.3 σ and a FAR $< 6\times10^{-7}$ yr^{-1} (Abbott et al. 2016 [3]). The GW alert was sent to partner astronomers nearly two days after the GW event occurred with a GCN (GCN 18728), together with a skymap. As for GW150914, many optical candidate counterparts have been found, but all of them have been identified to be normal population type Ia and type II SN, dwarf novae and AGNs, all unrelated to GW151226 (see, e.g., Copperwheat et al. 2016 [37], Smartt et al. 2016b [42], Cowperthwaite et al. 2016 [43]). The IceCube and ANTARES collaborations performed a high-energy-neutrino follow-up of the GW event, but they found no neutrino candidates in both temporal and spatial coincidence with GW151226 (Adrián Martínez et al. 2017 [44]).

The second scientific run of Advanced LIGO (O2) started on November 30, 2016 and is currently in progress. Up to now, 92 teams of astronomers have signed a MoU with LVC (this number includes ANTARES and IceCube for the neutrino follow-up). Among these groups, 84 have observational capabilities for O2 and receive alerts. As of April 23, 2017 6 triggers have been identified by the online analysis, using a loose FAR threshold of one per month, and shared with astronomers who have signed MoUs with LIGO and Virgo for electromagnetic follow-up. A thorough investigation of the data and offline analysis are in progress; results will be shared when available[d].

5 Future perspectives: observing and localizing GWs in the next LIGO and Virgo scientific runs

Advanced Virgo [45] is expected to joint Advanced LIGO in the data taking before the end of O2. In the next years, both Advanced LIGO and Advanced Virgo will be upgraded, and will progressively increase their sensitivity up to a factor of ten with respect to the initial LIGO and Virgo: this will also increase the volume of the explorable universe, enhancing the probability to detect GW sources.

From the observations of BBH mergers during O1, it has been possible to infer the stellar-mass BBH merger rate in the local Universe, that is in the range 9-240 Gpc^{-3} yr^{-1}. Given this merger rate, it has been possible to estimate the expected number of detections during O2 and the third scientific run (O3), considering the space-time volume that will be surveyed. In particular, during O2 the probability to observe more than two (ten) BBHs is higher than $\sim$

[d] http://ligo.org/news/index.php#O2Apr2017update

80% (∼15%); during O3, the probability to observe more than ten (forty) BBHs is higher than $\sim$ 90% ($\sim$ 20%; see Abbott et al. 2016c [4]).

The non detection of NS-NS and NS-BH systems during O1 allowed to put upper limits on their merger rate: $R_{\rm NS-NS} < 12600$ Gpc^{-3} yr^{-1} and $R_{\rm NS-BH} < 4600$ Gpc^{-3} yr^{-1}; these rates are consistent with the expectations from many theoretical models. The no detection of these systems during O2 and O3, with higher sensitivities and longer operation time, would imply stronger upper limits on these merger rates (see Abbott et al. 2016g [46]), possibly ruling out several theoretical models (e.g., Vangioni et al. 2016 [47]).

The sky localization of GW events is expected to significantly improve when three (or more) interferometers will be operative as a network. For instance, the presence of a third GW detector such as Virgo would have improved the sky localization of GW150914 to a few tens of square degrees both for the unmodeled and CBC searches (see Abbott et al. 2016e [33]). During O3, the percentage of NS-NS mergers expected to be localized within 5 deg^2 for the network composed by the two LIGO interferometers and Advanced Virgo is > 1-2 % (Abbott et al. 2016h [49]). Within the next six years, other GW detectors are expected to join Advanced LIGO and Advanced Virgo: KAGRA in Japan [48] and another LIGO detector in India[e]: this will further improve the sky localization of the GW events. For instance, with a network composed by the three LIGO interferometers and Advanced Virgo, the percentage of NS-NS mergers expected to be localized within 5 deg^2 is > 20% (Abbott et al. 2016h [49]). This will enhance the probability to find the EM counterparts, further expanding the frontiers of GW astronomy and the multi-messenger investigation of cosmic sources.

6 Conclusions

In this paper we have discussed the GW transient sources and their expected EM counterparts; furthermore, we have summarized the main results of the EM follow-up campaign performed during the first science run of Advanced LIGO. This campaign clearly demonstrated the capability of ground-based telescopes and satellites to provide a very good sky and energy coverage, as well as an optimal coordination among many astronomical facilities (ground-based telescopes and satellites). Advanced Virgo is expected to start operations soon and, within the next few years, also KAGRA and LIGO-India will become operative. With a 4 GW detector network, the sky localization of GW events is expected to significantly improve: this will enhance the probability to find the EM counterparts. The detection of an EM signal associated to a GW event is an important milestone for the future: GWs and photons provide complementary information about the sources and their environment, and a joint GW and EM detection will allow to better understand the physics underlying the most extreme objects in the Universe.

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