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Electromagnetic follow-up of gravitational wave sources and the case of GW150914

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Summary. — Simultaneous observations of an electromagnetic counterpart from gravitational wave (GW) sources is a powerful tool to gain a complete understanding of the astrophysical event, as well as to support GW data analysis. This proceeding summarizes the expected electromagnetic counterpart of GW sources detectable by the advanced LIGO and Virgo, the follow-up strategies to detect them with ground- and space-based observatories, together with an overview of the follow-up campaign of the first GW signal, GW150914, detected with the Advanced LIGO detectors by the LIGO/Virgo Collaboration team.

1. – Introduction

Gravitational astronomy has started on September 14, 2015 with the discovery of a binary black-hole system during its coalescing, merging and ringdown phase [1]. The detection was achieved with the two ground-based Advanced Laser Interferometer Gravitational wave Observatories hosted in the US (aLIGO, [2]). During spring 2017, the Advanced Virgo interferometer (AdV, [3]) based in Italy will start taking scientific data, and by 2019 both aLIGO and AdV are expected to reach their nominal sensitivity. At the beginning of the next decade two other interferometers (IndIGO in India [4] and KAGRA in Japan [5]) are expected to be completed and operative. All five detectors will work together as a single network and will realistically detect several GW sources per year in the high-frequency range, that is the one accessible to ground-based interferometers (10–1000 Hz).

At these frequencies, coalescencing binary systems of compact objects (*compact binary coalescence*, CBC) such a neutron star (NS) and a stellar-sized black hole (BH) are the most promising sources of gravitational radiation. Indeed, CBCs gravitational waveforms can be precisely predicted from General Relativity thus enabling to exploit the powerful matched filtering techniques in the challenging GW signal search processes. In addition, the CBC expected energy output in gravitational radiation is large with respect to other

GW source candidates. For example, the estimated GW energy from a coalescing NS binary system (BNS) is of the order of 10^{-2} $\mathrm{M}_{\odot}\mathrm{c}^2$ implying that these systems will be detected up to a distance range(^{1}) of 200 Mpc by aLIGO and 65–130 Mpc by AdV at their nominal sensitivity. From the estimated BNS merger rate density, that goes from $10^{-5}\,\mathrm{Mpc}^{-3}\,\mathrm{yr}^{-1}$ to $10^{-8}\,\mathrm{Mpc}^{-3}\,\mathrm{yr}^{-1}$ [6], their detection rate will be 0.2–200 per year [7].

CBC systems containing at least one NS are expected to have an electromagnetic (EM) counterpart, while the latter is not predicted for the case of two coalescing black holes (although some exceptions have been suggested under *ad hoc* circumstances [8-10]). Several indirect empirical evidence associate BNS and/or NS-BH systems to the progenitor of *short Gamma Ray Bursts* (sGRBs) and to their fading afterglows [11]. However, only a fraction of GW-detected BNS and NS-BH may be accompanied with a sGRBs because of the expected collimation of EM radiation from these objects. Estimates of jet opening angle θ_j for sGRBs are strongly model-dependent and require multiwavelength afterglow monitoring as well as a distance measure. For these reasons θ_j was measured so far only in a few cases ranging from $3°$ to $> 25°$ [12], thus indicating that only $\sim$1–10% (depending on the jet opening angle) of GW-detected BNS and NS-BH systems will be accompanied with a short GRB. Indeed, sGRB expanding jets are predicted to decelerate and spread laterally after about $\sim$ 1–10 days from the burst epoch [13]. Therefore, late afterglow emission can possibly enter into the observer line of sight and be detected as an *orphan afterglow* (*i.e.* not preceded by a gamma-ray burst detection). So far no *orphan afterglow* candidate has been found from past sky suveryes at optical wavelengths [14,15], radio [16] and X-rays [17]. Challenging elements in this search are the expected faintness of the emission, and the unknown burst onset time and position in the sky. GW triggers may address these issues providing the trigger epoch and rough sky localization.

Other promising counterparts of BNS and NS-BH merging systems are *kilonovae*, transients powered by the radioactive decay of heavy nuclei synthesized in the merger ejecta [18, 19]. Contrary to short GRBs, kilonova emission is expected to be almost isotropic thus all GW-detected BNS and NS-BH should be accompanied by such EM counterpart. However, the existence of kilonova is still speculative, with only few, not fully conclusive evidence observed so far [20-22]. Beside CBC systems, other possible sources of high-frequency gravitational radiation are core-collapsing massive stars or phenomena connected with isolated NSs. However, the GW energy output and thus the detection rates predicted for these sources are highly model-dependent and still widely uncertain. Possible EM counterparts of these sources are the prompt and afterglow emission of long GRBs [23], supernovae of type II or Ib/c [24], X-ray phenomena as Anomalous X-ray Pulsars or Soft Gamma Repeaters and their Giant Flares [25-28].

Observing the electromagnetic counterparts of GW sources provides a wealth of additional and complementary information such as: i) Refined sky localization, down to arcminute/arcsecond levels. Beside the possibility to use the refined sky position as useful prior in the GW source parameter estimation process, precise localization may lead to the discovery of any host galaxy, providing important additional information on the nature and evolution history of the radiating source. ii) Gain a more deep understanding of the source nature and physical processes generating the observed emission. For example, a simultaneous detection of a GW signal from a CBC and a short GRB not only will

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(^{1}) Averaged distance at which a BNS would be detected with a signal-to-noise ratio (SNR) of 8 in each detector. The average is computed over all possible binary system orientations (*e.g.*, edge-on/edge-off) and localizations in the sky.

definitively confirm the nature of the progenitors of these EM events but it may also put fundamental constraints on the jet opening angles from the measure of the orbital plane inclination that can be obtained from GW data anaysis [29]. iii) Increase the confidence on astrophysical origin of low signal-to-noise ratio GW detections. iv) Obtain independent source distance estimates. Cosmological redshift from EM spectral line systems and luminosity distance estimates from GW data analysis for a large number of sources will likely provide in the next future useful constraints to cosmological parameters [30].

2. – Observational strategies for joint GW and EM detection

A network of two GW detectors can provide only a rough source localization in the sky [7]. For example, with the two aLIGO, sky localizations are of the order of 100–1000 $\deg^2$ [31]. These values will be reduced to a few $\sim 10 \deg^2$ with the addition of AdV and to a few square degrees with a 5-detector network, as planned with the further addition of IndIGO and KAGRA in the next years [32]. The large localized sky regions, that can also have irregular and fragmented shapes, are encoded as sky probability distributions (*skymaps*), where a sky projection is conveniently divided into equal-area pixels(²) with assigned probability. At present there are two dedicated GW data analysis softwares that can provide low-latency *skymaps* (within minutes from trigger [33]) and other two that provide refined ones within days up to weeks [34, 35]. These softwares use a sequence of algorithms with increasing accuracy and computational cost and some of them are tailored for a CBC-like or a burst-like waveform. *Skymaps* are then formatted into FITS(³) files and distributed to the astronomical community via GCN(⁴) circulars and notices, a successful machine readable system that has already been in use for many years for GRB detection, that enables astronomers to rapidly react in order to search for the electromagnetic counterpart.

Different observational strategies are performed depending on whether the astrophysical source has first been discovered via an EM or GW signal. In the case of a GW signal with no obvious simultaneous EM counterpart detected independently (*e.g.* a GRB detected by a space mission), a massive EM follow-up campaign is activated as soon as the GW alert is communicated to the astronomical community in order to monitor the large sky regions provided by the low-latency *skymaps*. Latencies reached during the first scientific run of aLIGO (O1) were of the order of days but improvements down to less than half an hour are planned for the next runs. The EM follow-up strategy is tailored on the characteristics of the GW signal (*i.e.* a CBC or a burst-like event), available almost immediately from low-latency data analysis. For CBC with at least one NS, predicted EM counterparts are *afterglows* or *orphan afterglows*, expected to be detected in the soft X-ray and optical within hours/days from the trigger and at radio wavelengths within weeks up to months, and *kilonovae*, predicted to peak at optical wavelengths during the first few days and then in the IR after several days. Possible X-ray counterpart at earlier epochs (< 1 day) may also be detected. For CBC with two black holes, no EM counterpart is expected although possible exceptions are predicted, and follow-up campaigns in this case lack of clear theoretical predictions. Alternatively, a GW burst-like signal can be detected as for example from a core collapsing star or possibly from a magnetar

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(²) The LSC team has adopted the Hierarchical Equal Area isoLatitude PIXelization.
(³) Flexible Image Transport System.
(⁴) Gamma-ray burst Coordinates Network.

flare. In the former case, possible EM counterpart can be *type II, Ib, Ic SNe*, expected in optical/UV/X-rays bands at hours from the trigger (shock-breakout) and in optical/NIR and radio bands peaking weeks from the trigger (optical/NIR and radio), and/or an *orphan afterglow* from a long GRB. Magnetar flares can originate *Soft Gamma Repeaters* that can be detected in the X-rays. Independently of the nature of the detected GW sources, to cover the wide sky localization of the GW signal, large field-of-view (FOV) telescopes will start observations first, in order to detect and precisely localize interesting transients. Eventually, more sensitive telescopes with much narrower FOV and larger diameters, provide deep phometric and spectroscopic observations for their characterization and classification. Archival searches are performed on data acquired by those facilities that were covering the GW localized credible sky regions during the epoch of the GW trigger, in order to look for nearly simultaneous EM counterpart (as for example a sub-threshold GRB).

In the case of an EM signal from a source expected to emit GWs with no obvious gravitational wave counterpart detected independently, GW signal searches are performed "offline" on archived data acquired near the epoch of the EM event by the GW inteferometers operating at that time. The search will be driven by the properties of the EM sources as for example its nature and/or its precise sky localization. This situation may happen for example during the discovery of a distant cc-SN in optical, or a distant GRB or a SGR in gamma and X-rays.

3. – GW150914

The long-standing search of a direct evidence of GWs has finally being accomplished on September 14th, 2015, at 09:50:45 UT, when the online aLIGO low-latency search pipelines detected an event with false alarm rate (FAR) well below the threshold value established to assess a GW source detection ($<$ 1 every 100 yrs), namely FAR $= 4.4 \times 10^{-5}\,\mathrm{yr}^{-1}$, and signal-to-noise ratio of 24 [1]. The waveform perfectely matched the expectation from the merging of two $\sim$30 $\mathrm{M}_\odot$ black holes at a distance of $z \sim 0.09$ with an energy output of $3\mathrm{M}_\odot \mathrm{c}^2$ [1]. An extensive multiwavelength observational campaign covered all the $\sim 750\,\mathrm{deg}^2$ credible sky area indicated by the promptly available skymaps [32]. Several dozens of optical transients were identified but no one was recognized as a possible counterpart of the BH-BH system that generated GW150914. A temporally coincident ($+0.4$ s after the GW trigger) weak gamma-ray signal at energies $> 50\,\mathrm{keV}$ and lasting 1 s was found in the archival data of the Gamma-ray Burst Monitor on board *Fermi* satellite, with false alarm probability of 0.0022 [36]. However, this measure was not confirmed by other high energy satellites that were observing the same sky region at that time [37, 38].

4. – Expected rates and future perspectives

Realistic rates of detection by 2019, when both the aLIGO network and AdV are expected to reach their nominal sensitivity, are of about 40 BNS systems and 10 BH-NS systems per year with uncertainties of the order of 100 [6]. Localizations of GW sources will remain of the order of 10–100 deg^2 until the network will increase to five GW detectors providing $< 10\,\mathrm{deg}^2$ sky regions. These numbers enable to confidently expect the possibility to have within the next decade a statistically significant sample of sources that can be analyzed using simultaneously both their gravitational and EM radiation.

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