Prospects for joint GW and high-energy EM observations of BNS mergers

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Summary. — With the recent detection of two transient gravitational wave (GW) signals by the Advanced LIGO interferometers the era of GW astronomy has begun. The two events, labeled GW150914 and GW151226, are both consistent with the inspiral and the merger of a binary system of black holes (BBH). Besides the merger of BBH systems, one of the most promising candidates for the direct GW detection is the coalescence of binary neutron stars (BNS) and black holes (NSBH). These mergers are thought to be connected with short Gamma Ray Bursts (GRBs), but a definitive probe of this association is still missing. Combined observations of gravitational and electromagnetic (EM) signals from these events will provide a unique opportunity to unveil the progenitors of short GRBs and study the physics of compact objects. In particular, large field-of-view instruments such as *Fermi* will be crucial to observe the high-energy electromagnetic counterparts of transient gravitational wave signals and provide a robust identification based on a precise sky localization. We present the prospects for joint GW and high-energy EM observations of merging BNS systems with Advanced LIGO and Virgo and with *Fermi*.

1. – Introduction

The recent detection of gravitational waves (GWs) [1,2] 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. Beside BBHs, one of the most promising sources for future detection with Advanced LIGO and Advanced Virgo is the coalescence of binary systems formed by two neutron stars (BNS) or a neutron star and a black hole (NS-BH). The merger of BNS and NS-BH systems could be also accompanied by electromagnetic (EM) emission. In particular, there are several

evidences that short gamma-ray bursts (GRBs) originate from these mergers (see [3] and references therein), but a definitive probe of this association is still missing. The simultaneous detection of a short GRB and a GW signal will be a definitive proof of binary systems being the progenitors of these extremely energetic events. Furthermore, the detection of a coincident EM signal will increase the confidence of the GW detection of the merger, and provide complementary information (such as the precise sky localization or the redshift) on the event. Therefore, the EM follow-up of the merger of binary systems represents a key tool to better understand the physics underlying these extreme events and to unveil the nature of short GRB progenitors.

Among the various γ-ray instruments, the Large Area Telescope (LAT) on-board the *Fermi* satellite [4] is well suited for the EM follow-up of GW candidates for several reasons. First of all, its large field-of-view (FOV, $\sim 2.4\,\mathrm{sr}$) can cover with few tiled exposures the large error boxes associated with the GW sky localizations provided by the alerts. Moreover, it can localize accurately the sources (the on-axis, 68% containment radius at $10\,\mathrm{GeV}$ is $0.8\,\mathrm{deg}$), and disseminate these refined locations among other observatories for the follow-up of the GW events at other wavelengths.

Here we present the prospects for joint GW and high-energy EM observations of merging BNS systems with Advanced Virgo, Advanced LIGO and *Fermi*-LAT. The results here presented are based on [5].

2. – Simulating BNSs and their multimessenger detection

In order to estimate the rates of joint high-energy EM and GW detections of merging BNS systems and investigate the high-energy follow-up scenarios, we designed a specific Montecarlo simulation pipeline for the BNS multimessenger emission and detection by GW and gamma-ray instruments. For our study, we focused on the case of GW detection by Advanced Virgo and Advanced LIGO, and EM detection by *Fermi*-LAT. This simulation pipeline is composed of three main steps: i) creation of a plausible ensemble of merging BNSs (sect. **2**'1); ii) simulation of GW emission and detection by the interferometers (sect. **3**); iii) simulation of the associated short GRBs and detection with *Fermi*-LAT (sect. **4**). In order to estimate the detection rates, we simulated 1000 realizations, each one corresponding to an observing period of 1 year.

2'1. *The BNS systems*. – The first step to create a realistic ensemble of BNS merging systems detectable by Advanced Virgo and Advanced LIGO is the generation of a sample of synthetic galaxies. We assumed that Milky Way like galaxies dominate the Local Universe and we used a constant galaxy density of $0.0116\,\mathrm{Mpc}^{-3}$, that is the extrapolated density of Milky Way equivalent galaxies in space [6]. Simulated galaxies have an isotropic and homogeneous distribution in space. Our galaxy sample extends to a maximum distance of $500\,\mathrm{Mpc}$, consistent with the expected horizon for BNS mergers of Advanced Virgo and Advanced LIGO in their final configuration [7]. Each simulated galaxy was then populated with several merging BNS systems. We used the public synthetic database([1]) developed by [8]. They investigated the evolution of binary systems that leads to the formation of merging binary systems of compact objects (BNS, NS-BH and BBH) for a synthetic galaxy resembling the Milky Way. They used different population synthesis models, to account for the uncertainties associated with

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([1]) `www.syntheticuniverse.org`

several evolutionary processes such as., *i.e.*, stellar winds and consider two metallicities: $Z = Z_\odot$ and $Z = 0.1 Z_\odot$, where $Z_\odot$ is the solar metallicity. In this work we considered a stellar population composed by a 50%-50% combination of systems with $Z = Z_\odot$ and $Z = 0.1 Z_\odot$, according to the bimodal distribution of the star formation in the last Gyr observed by the Sloan Digital Sky Survey [9]. We chose as our reference model the so called "standard model B", that uses the best estimates of the key parameters describing the physics of double compact objects [8]. To take into account the uncertainties related to the physics of the systems, we also considered the "V12, A and B" models (for systems with $Z = Z_\odot$) and the "V2 A and V1 B" models (for systems with $Z = 0.1 Z_\odot$). For each model and metallicity, if the systems merge within the age of the simulated host galaxy (assumed to be 10 Gyr), they are included in our sample. We then randomly extracted from the sample several BNS systems in accordance with the merger rates reported in [8] and we populated the synthetic galaxies with them.

3. – The GW detections

We assigned to each BNS merging system the same sky position (right ascension, declination and distance) of the host galaxy, and a random inclination of the orbital plane with respect to the line of sight. For simplicity, we assumed that the systems are non-spinning.

For each merging BNS sytem, we simulated the expected GW inspiral signals, using the "TaylorT4" waveforms (see, *e.g.*, [10]). After the GW signals have been simulated, we convolved them with the GW detector responses. We used the sensitivity curves of Advanced LIGO and Advanced Virgo reported in [7], describing five possible observing scenarios representing the evolving configuration and capability of Advanced LIGO and Advanced Virgo. In particular, we focused on the expected final "design" configuration, that will be achieved in 2019 and 2021 by Advanced LIGO and Advanced Virgo respectively.

The data obtained in this way were then analyzed with the matched filtering technique [11]. With this technique the data from all detectors are Wiener filtered with an array of theoretically modeled template waveforms (a "template bank"), constructed with different choices of the intrinsic parameters (*e.g.* the masses) of the binary systems. The output is an estimate of the signal to noise ratio (SNR) with respect to that template in that detector. If the signal results in a SNR above a given threshold in at least two detectors, with the same binary parameters and within approximately one light-travel time between detectors, it is considered as a GW candidate.

For simplicity, we constructed template banks specifically designed to detect our simulated signals, *e.g.* with the same intrinsic parameters used for the simulated signals; the waveform we used is the "TaylorF2" (see [10]). We imposed a network (two or three detectors) SNR (root sum square of the individuals SNR) threshold $\rho_c = 12$, that corresponds to a false alarm rate (FAR) below 10^{-2} yr^{-1} [7]. We considered the case in which the GW detectors have an independent 80% duty cycle (see for example [7]).

4. – The simulated GRBs and their EM detection with *Fermi*

We assumed that all the BNS mergers are associated with a short GRB having an afterglow emission at high energies ($E > 100$ MeV). We also assumed that the GRB jet is beamed perpendicular to the plane of the binary's orbit (*i.e.*, that the angle of the observer with respect to the jet is equal to the inclination angle of the BNS system θ)

TABLE I. – *Expected rates of EM and joint EM and GW detections for the 2019+ (design) configuration, considering a 80% duty cycle of the interferometers and a latency of* 0 s*; two values of* E_γ *have been considered (see sect.* **4***). The reported estimates refer to the Standard model B, while the range of rates have been estimated considering the range of BNS merger rates reported by* [8] *(see sect.* **2**˙1*).*

Integration time (s)	E_γ (ergs)	EM (yr^{-1})	EM and GW (yr^{-1})
10	3.5×10^{52}	0.5 (0.02–6.6)	0.06 (0002–0.9)
	1×10^{49}	0.08 (0.002–1.1)	0.05 ($< 10^{-3}$–0.6)
10^2	3.5×10^{52}	0.5 (0.02–6.6)	0.06 (0002–0.9)
	1×10^{49}	0.09 (0.002–1.2	0.05 ($< 10^{-3}$–0.6)
10^3	3.5×10^{52}	0.5 (0.02–6.6)	0.06 (0002–0.9)
	1×10^{49}	0.1 (0.002–1.2)	0.05 ($< 10^{-3}$–0.6)

TABLE II. – *Same as in table I, for a latency of* 600 s*.*

Integration time (s)	E_γ (ergs)	EM (yr^{-1})	EM and GW (yr^{-1})
10	3.5×10^{52}	0.01 ($< 10^{-3}$–0.2)	0.007 ($< 10^{-3}$–0.1)
	1×10^{49}	$< 10^{-3}$($< 10^{-3}$–$< 10^{-3}$)	$< 10^{-3}$($< 10^{-3}$–$< 10^{-3}$)
10^2	3.5×10^{52}	0.3 (0.01–4.1)	0.06 (0.002–0.9)
	1×10^{49}	$< 10^{-3}$($< 10^{-3}$–$< 10^{-3}$)	$< 10^{-3}$($< 10^{-3}$–$< 10^{-3}$)
10^3	3.5×10^{52}	0.5 (0.02–6.6)	0.06 (0.002–0.9)
	1×10^{49}	$< 10^{-3}$($< 10^{-3}$–$< 10^{-3}$)	$< 10^{-3}$($< 10^{-3}$–$< 10^{-3}$)

and that the jet opening angle is $\theta_j = 10°$; we then focused only on the on-axis GRBs ($\theta < \theta_j$, see [5] for details).

We constructed the light curve and spectrum of the simulated sources using GRB 090510 as a template. This choice is motivated by the fact that GRB 090510 is, to date, the only short GRB to show emission up to GeV energies and, in particular, to show an extended emission (~ 200 s) at high energies (~ 4 GeV) [12]: this is a fundamental characteristic, since the overall time required to send GW alerts (a few minutes) will not allow to follow-up the short GRBs themselves, but only their weaker afterglow emission.

We corrected the light curve of GRB 090510 to take into account the distance of the simulated sources with respect to GRB 090510 and we re-scaled it considering the following range of isotropic energy: 10^{49} ergs $\leq E_\gamma \leq 3.5 \times 10^{52}$ ergs. We then investigated the detectability of this emission with *Fermi*-LAT. To do this, we estimated the total time t_f each GRB should be observed so that its fluence reaches the high-energy LAT sensitivity. We used the sensitivity estimated with the "Pass 7" reprocessed instrument response function(^{2}), focusing on the value corresponding to a GRB localization at 1-σ of 1 deg.

(^{2}) http://www.slac.stanford.edu/exp/glast/groups/canda/archive/p7rep_v15/lat_Performance.htm

5. – Results

In tables I and II the rates of GRB high-energy afterglows detectable by *Fermi*-LAT are shown, as well as the rates of events detectable both in EM and GW, for different values of the integration time $t_{\rm f}$, for a GW-alert latency of 0 s and 10 minutes respectively. It can be seen that, for a latency of 0 s, there will be some chance to detect both the highest energetic GRBs ($E_\gamma = 3.5 \times 10^{53}$ ergs) and the less energetic sources ($E_\gamma = 1 \times 10^{49}$ ergs), with EM detection rates in the ranges (0.02–6.6) yr^{-1} and (0.002–1.2) yr^{-1} respectively. For the highest energetic GRBs there will be also some chance for a joint GW and EM detection, with an expected rate in the range $(0.002 - \sim 1) \text{ yr}^{-1}$. It can also be noted that these rates are almost independent on the integration time: all the simulated sources are located at lower distances with respect to GRB 090510, so their flux is intense enough to be detected with a short observing time. When a 600 s latency is considered it can be seen that, for the highest energetic GRBs, an integration time of 10^3 s is needed to reach the same EM detection rate obtained for a 0 s latency. However, when the less energetic GRBs are considered, the rate of EM and joint EM and GW detections are both < 1.

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REFERENCES

[1] Abbott B. P. *et al.*, *Phys. Rev. Lett.*, **116** (2016) 061102.
[2] Abbott B. P. *et al.*, *Phys. Rev. Lett.*, **116** (2016) 241103.
[3] Berger E., *Annu. Rev. Astron. Astrophys.*, **52** (2014) 43.
[4] Atwood W. B. *et al.*, *Astrophys. J.*, **697** (2009) 1071.
[5] Patricelli B. *et al.*, *JCAP*, **11** (2016) 056.
[6] Kopparapu R. K. *et al.*, *Astrophys. J.*, **675** (2008) 1459.
[7] Abbott B. P. *et al.*, *Living Rev. Relativ.*, **19** (2016) 1.
[8] Dominik M. *et al.*, *Astrophys. J.*, **759** (2012) 52.
[9] Panter B. *et al.*, *Mon. Not. R. Astron. Soc.*, **391** (2008) 1117.
[10] Buonanno A. *et al.*, *Phys. Rev. D*, **80** (2009) 084043.
[11] Wainstein L. A. *et al.*, *Extraction of Signals from Noise* (Prentice-Hall, Englewood Cliffs) 1962.
[12] Ackermann M. *et al.*, *Astrophys. J.*, **716** (2010) 1178.