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Studies on the high-energy follow-up of gravitational wave transient events

Massimiliano Razzano

Department of Physics, University of Pisa, and INFN-Pisa, Largo B. Pontecorvo, 3, 56127, Pisa, Italy

E-mail: `massimiliano.razzano@pi.infn.it`

Barbara Patricelli

Department of Physics, University of Pisa, and INFN-Pisa

Giancarlo Cella

Department of Physics, University of Pisa, and INFN-Pisa

Francesco Fidecaro

Department of Physics, University of Pisa, and INFN-Pisa

Elena Pian

Scuona Normale Superiore, Pisa, and Istituto Nazionale di Astrofisica

Antonio Stamerra

Scuona Normale Superiore, Pisa, and Istituto Nazionale di Astrofisica

Marica Branchesi

University of Urbino

Abstract. Second-generation gravitational wave interferometers, such as Advanced LIGO and Advanced Virgo, will soon reach sensitivities sufficient to first detect gravitational waves and open a new era in the multi-messenger investigations of the cosmos. The most violent and energetic astrophysical phenomena, including the mergers of compact objects or the core collapse of massive stars, are promising sources of gravitational waves, and are thought to be connected with transient phenomena such as Gamma Ray Bursts and supernovae. Combined observations of gravitational and electromagnetic signals from these events will thus provide a unique opportunity to unveil their progenitors and study the physics of compact objects. In particular, gamma-ray ground-based and space observatories such as Fermi or the Air Cherenkov Telescopes 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 will report on our studies of possible joint observation strategies carried on by gravitational interferometers and gamma-ray telescopes, with particular attention to the high-energy follow-up of Gamma Ray Bursts.

1. Introduction

The second-generation gravitational wave (GW) interferometers Advanced LIGO (aLIGO) and Advanced Virgo (AdV) are currently undergoing major upgrades that will progressively increase their sensitivity and the volume of the explorable universe. The final sensitivity of these detectors is expected to be a factor of ten greater than the one of the initial LIGO and Virgo detectors [1, 2]: with this significative improvement, aLIGO and AdV are expected to detect the first GW signals, paving the way to the GW astronomy and the multi-messenger investigations of the Universe.
aLIGO has already started their observation, with a first observing campaign ("O1") from mid-September, 2015 to mid-January, 2016. In 2016, the construction of AdV will be finished and a first, 6-months, joint aLIGO-AdV run ("O2") will take place, followed by longer runs in the next years [14]. One of the most promising candidates for the direct GW detection with aLIGO and AdV is the coalescence of binary systems of compact objects: binary neutron stars (NS-NS) and/or black holes (NS-BH, BH-BH). In fact, during the late stages of the inspiral phase, these systems are thought to be very strong emitters of GWs in the aLIGO and AdV frequency range ($\sim$ 10 Hz - 10 kHz). The coalescences of NS-NS and NS-BH systems could also have observable electromagnetic (EM) counterparts (see e.g. [3]). In particular, there are observational results suggesting that these mergers are generating short Gamma Ray Burts (sGRBs), among the most energetic phenomena in the Universe (see [4] for a review). sGRBs are bright, and highly-variable flashes of γ rays lasting less than 2 seconds (the "prompt" emission), sometimes accompanied by a long lasting weaker multiwavelength emission (the so-called "afterglow" emission). They are believed to be powered by ultra-relativistic jets produced by rapid accretion onto the central compact object formed in the NS-NS or NS-BH system coalescence. Within this context, a coincident detection of a short GRB and a GW signal would be of great importance for several reason. First, it would prove the connetion between these phenomena and the mergers of compact objects. Furthermore, detecting an electromagnetic counterpart of a GW event would greatly increase the confidence of the GW detection itself. Finally, a joint, multimessenger, detection, would provide complementary information about the source: for instance, the GW detections would allow to estimate some physical parameters of the binary system such as the mass, the inclination and possibly the distance of the event, while the EM observations permit a precise sky localization and the identification of the host galaxy. Therefore, joint EM and GW observations 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.
There are two possible scenarios for joint GW and EM detections: I) a GW event is detected and an alert is sent to EM telescopes, that start looking for an EM counterpart (EM follow-up), or II) an EM transient, e.g. a sGRB, is discovered and GW data are analized for possible events (external trigger). In both scenarios, the field of view (FOV) is an important parameter: in fact, the larger is the FOV, the higher is the probability to catch a transient source in the act. This is one of the main reasons for the large FOVs of instruments onboard $Swift$ or $Fermi$ missions. In particular, the EM follow-up poses various challenges from the observational point of view. The localization provided by the network of gravitational interferometers is in the order of tens to hundreds of square degrees [5]: large FOVs are therefore mandatory in order to properly cover the error region associated with the sky localization of a GW trigger. Furthermore, in such large error boxes, there could be many EM transient sources, making any search for counterpart very challenging. This issues, particularly crucial for optical telescopes, are somewhat alleviated in the high-energy part of the spectrum: for instance, gamma-ray telescopes provide usually a large FOV, and the number of sources is not as high as in the optical band. Among the various γ-ray observatories, the *Fermi* satellite is one of the best suited for joint EM and GW observations. *Fermi* is equipped with two instruments: the Gamma-ray Burst Monitor (GBM, [6]), sensitive to the energy range from $\sim$8 keV to $\sim$40 MeV and the Large Area Telescope (LAT, [7]), covering

the energy range from ~ 20 MeV to more than 300 GeV. GBM cover the whole sky unocculted by Earth (FOV ~ 9.5 sr), with an overall median localization error for short GRBs of 8° [8]. LAT has a smaller FOV (~ 2.4 sr) but can provide a much better locazionazion (on-axis 68% containment radius at 10 GeV is 0.8°). If GBM detects a GRB, an Autonomous Repoint Request (ARR) can be issued, and *Fermi* automatically slews to move the GRB into the LAT FOV. The EM detection observation of a transient EM source with *Fermi*/LAT would allow other observatories having narrow FOV (such as, for example, optical telescopes) to follow-up the GW events and obtain complementary informations at other wavelengths: in fact, the small *Fermi*/LAT error region can be rapidly covered with a smaller number of fields (or tiled exposures) and therefore it can be observed with longer exposures, allowing also the identification of faint sources. We report on a preliminary estimates of the rates of coincident high energy EM and GW detections with aLIGO, AdV and the *Fermi* satellite, focusing on NS-NS mergers accompanied by short GRBs.

2. Method

We used simulations to estimate the rates of joint GW and high-energy EM detections and investigated the best strategies for the high energy EM follow-up. We followed these steps:

(i) Construction of a realistic sample of NS-NS merging systems
(ii) Simulation of the GW signals associated to the merger of these systems and estimate their detectability with aLIGO and AdV
(iii) Simulation of the associated EM emissions (short GRBs) and assess their detectability with *Fermi*

For step (i), we generated a sample of synthetic galaxies in the Local Universe up to a maximum distance of 500 Mpc, which is consistent with the expected horizon for NS-NS mergers for AdV and aLIGO. We only considered Milky Way-like galaxies, that provide the major contribution to the NS-NS merger rate [9], and used a constant galaxy density of 0.0116 Mpc^{-3}, the extrapolated density of Milky Way equivalent galaxies [10].
For step (ii), we used the synthetic merging systems available in the database of *The Synthetic Universe* [11][1], based on different synthesis models to account for the uncertainties in the physics of the binary evolution such as, for example, the common envelope phase and the wind mass-loss. Two metallicities are considered, $Z=Z_\odot$ and $Z=0.1\ Z_\odot$, where $Z_\odot$ is the solar metallicity. We considered a $50\% - 50\%$ mix of systems with $Z= Z_\odot$ and $Z= 0.1\ Z_\odot$, accordingly with the bimodal distribution of the star formation in the last Gyr observed by the Sload Digital Sky Survey [12]. The database provides several physical properties of the binary system, e.g. the merging time T_m. If the the sum of T_m and of a randomly assigned starting time is less that the age of the galaxy ($\sim$10 Gyr), we included the merger in our sample. From this sample of merging systems, we randomly extracted binaries in accordance with the merger rates reported in [11], populating our synthetic galaxies. We chose as our reference model the so called "standard model B", that uses the current state of the art description of physical mechanisms governing double compact objects (see [11, 13]). However, to take into account the uncertainty on the merger rate related to the physics of the systems, we also considered the models for which the maximum and minimum merger rates have been estimated: the so called "V12, A and B" (for systems with $Z= Z_\odot$) and the "V2 A and V1 B" (for systems with $Z=0.1\ Z_\odot$). We assumed that the evolution of the merger rate with redshift is negligible within the local universe (up to the maximum distance considered in this work). For each merging NS-NS system, we simulated the expected GW inspiral signals using the "TaylorT4" waveforms, and using the physical properties of the binary (e.g. mass, sky position etc), and we placed them into Gaussian noise and performed a convolution with the

[1] www.syntheticuniverse.org

GW detector responses. We used the sensitivity curves of aLIGO and AdV reported in [14], who describes five possible observing scenarios representing the evolving configuration and capability of the interferometers. We then analyzed the simulated GW signals with matched-filtering techniques, imposing for the detection a signal-to-noise ratio threshold of 12, corresponding to a false alarm rate (below 10^{-2} yr^{-1} [14]. For each simulated GW candidates, we computed an associated sky localization with the tool BAYESTAR [5]. An example of such localization is in Figure 1. We simulated the GeV light curve and spectrum of the afterglow emission of GRBs using GRB 090510 as a template. This choice is motivated by the fact the GRB 090510 is the only short GRB to show emission up to GeV energies and, in particular, to show an extended emission (up to 200 s) at high energies (up to 4 GeV), as detected by the LAT [15]. In order to simulate the possible detection by *Fermi*, the LAT sensitivity to GRBs has been estimated in the energy range 10-1000 keV with the Pass 7 reprocessed instrument response functions of the LAT[2], by assuming that the source spectrum is a Band function.

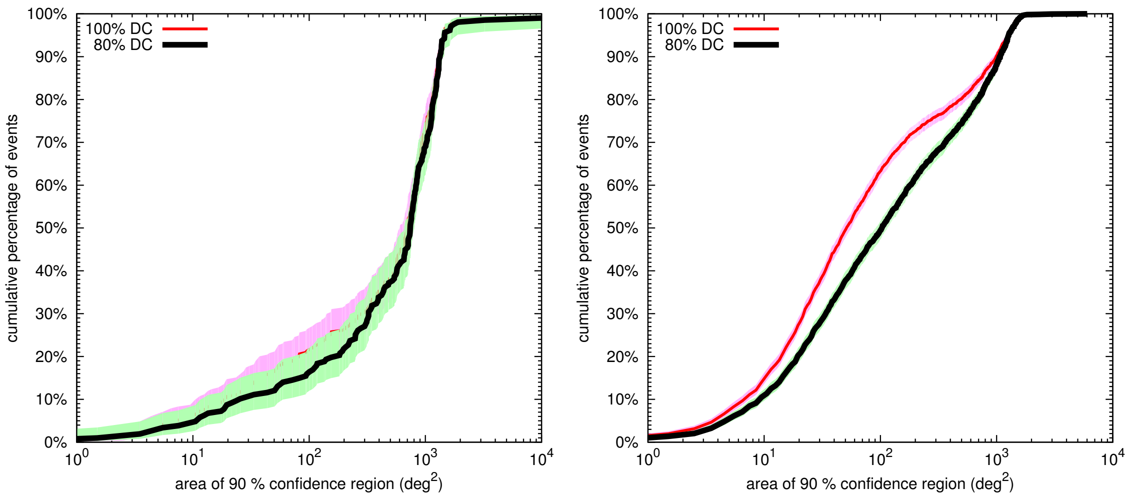

Figure 1. Preliminary results on the simulation of GW localization (i.e. the step ii described in the text). Cumulative histograms of sky localization areas of the 90 % confidence region in the 2016-2017 (left) and in the design (right) scenarios. The shadowed regions enclose the 95 % confidence intervals accounting for sampling errors. The Standard model B of [11] and a 50%-50% combination of systems with Z= $Z_\odot$ and Z= 0.1 $Z_\odot$ have been considered.

3. Results and Conclusions

We report here some preliminary results on this study. We have run our simulations and processed the results for GW and high-energy EM detections, showing the capability of localizing NS-NS binaries for the initial and design configuration (See Fig. 1 for an example). As far as the localization is concerned, our simulations show that ∼0.01 (0.5) NS-NS mergers will be localized within 20° in the initial(design) configuration.

We also estimated the number of joint GW/EM detections per year. Our simulation show that ∼0.3 sGRB will be detected per year, while the number of joint GW/EM detections are expected to be 0.003 (0.07) in the initial (design) configuration.

These results are still partial, as we are working on studying how various uncertainties of different origin can affect our results.

[2] http://www.slac.stanford.edu/exp/glast/groups/canda/archive/p7rep_v15/lat_Performance.htm

However, NS-NS mergers are among the most promising sources for GWs, and if association with GRBs will be proven, we will have a totally new insight into the physics of compact ojects.

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References

[1] LIGO Scientific Collaboration, Aasi J, Abbott B *et al* 2015, Classical and Quantum Gravity, 32, 074001
[2] Acernese, F, Agathos, M, Agatsuma, K *et al* 2015 *Classical and Quantum Gravity* **32** 024001
[3] Metzger and Berger E 2012,*ApJ* **746** 48
[4] Berger E 2014 *ARAA* **52** 43
[5] Singer L, Price L, Farr B *et al* 2014 *ApJ* **795** 105
[6] Meegan C, Lichti G, Bhat P *et al* 2009 *ApJ* **702** 791
[7] Atwood W, Abdo A, Ackermann M *et al* 2009 *ApJ* **697** 1071
[8] Evans P, Osborne J, Kennea J *et al* 2016 *MNRAS* **455** 1522
[9] O'Shaughnessy R, Kalogera V and Belczynski K 2010 *ApJ* **716** 615
[10] Kopparapu R, Hanna C, Kalogera V *et al* 2008 *ApJ* **675** 1459
[11] Dominik M, Belczynski K, Fryer C *et al* 2012 *ApJ* **759** 52
[12] Panter B, Jimenez R, Heavens A and Charlot S 2008 *MNRAS* **391** 1117
[13] Dominik M, Belczynski K, Fryer C *et al* 2013 *ApJ* **779** 72
[14] The LIGO Scientific Collaboration, the Virgo Collaboration, Abbott B *et al* 2013 *Preprint* arXiv:1304.0670
[15] Ackermann M, Asano K, Atwood W *et al* 2010 *ApJ* **716** 1178