Chapter 47
What's Next for VST: Electromagnetic Follow-Up of Gravitational Waves Events

A. Grado, E. Cappellaro, S. Piranomonte, E. Brocato, M. Branchesi, S. Covino, S. Campana, F. Getman, G. Greco, L. Nicastro, E. Pian, E. Palazzi, L. Stella, and G. Stratta on behalf of a larger collaboration

Abstract A big step forward in the long-standing quest for gravitational waves (GWs) will be made next year when the LIGO and VIRGO collaborations will start regular operations of their sensitive, upgraded interferometers. It is crucial that the electromagnetic counterparts of GW events are securely identified, a difficult task because of the large size of error box expected to be returned by the interferometers (dozens to hundreds of square degrees). Our group is tackling the challenge by organizing a follow-up campaign covering the widest possible range of the electromagnetic spectrum. The optical counterpart will be covered by the VST thanks to its characteristics. The sensitivity and optical quality of the telescope will allow us to probe faint transients (e.g. kilonovae and short GRBs) that are among the most promising GW source candidates.

A. Grado (✉)
INAF-Osservatorio Astronomico di Capodimonte, Via Moiariello 16, 80131, Naples, Italy
e-mail: agrado@na.astro.it

E. Cappellaro
INAF–Osservatorio Astronomico di Padova, vicolo dell'Osservatorio 5, 35122, Padova, Italy

S. Piranomonte • E. Brocato • L. Stella
INAF – Osservatorio Astronomico di Roma, Monte Porzio Catone (RM), Italy

M. Branchesi • G. Greco • G. Stratta
Università degli studi di Urbino, Urbino, Italy

S. Covino • S. Campana
INAF – Osservatorio Astronomico di Brera, Milan, Italy

F. Getman
INAF-Osservatorio Astronomico di Capodimonte, Via Moiariello 16, 80131, Naples, Italy

L. Nicastro • E. Palazzi
INAF-Istituto di Astrofisica Spaziale e Fisica Cosmica, Bologna, Italy

E. Pian
Scuola Normale Superiore, Pisa, Italy

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47.1 Introduction

Direct detection of gravitational waves may become a reality in the coming years when a worldwide network of advanced versions of ground-based GW interferometers will start to operate [6, 11]. Besides representing a direct test of general relativity, the detection of GWs allows insight into radiation processes, explosion mechanisms and stellar structure in a way that is independent of absorption and propagation effects that often plague electromagnetic (EM) observations. GWs make possible to investigate the inner regions of astrophysical objects not accessible with photons at all the wavelength (optical, infrared, X, γ).

There is no doubt that to really exploit the huge efforts devoted to the detection of GWs, it is crucial that their electromagnetic counterparts are securely identified. The Italian National Institute of Astrophysics (INAF) has signed the MoU with LIGO-Virgo collaboration (LVC) thus recognising the need of a joint institutional effort to maximize the scientific return of these campaigns. The Italian observing facilities will include national telescopes directly controlled by INAF (e.g. CITE, TNG, REM, SRT, ASTRI, etc.) and large telescopes accessible through consortia (VST, VLT, LBT, CTA). In particular the VST equipped with the OmegaCam camera [8, 17] will play a major role due to his wide field-of-view (FOV), optical quality and angular resolution. We plan to use part of the INAF-VST and INAF-OmegaCam guaranteed observation time to activate a transient search immediately after an alert from the GWs Observatories is issued.

47.2 Gravitational Waves Sources

The Einstein's theory of The General Relativity predicts that mass distributions with time-varying mass quadrupole moments produce GW. These waves are oscillating perturbations of space-time travelling at the speed of light. GWs represent a unique way to investigate the interior regions of extremely dense astrophysical objects. Up to now, no direct GW detection has been obtained, even if indirect evidence has been found to explain the orbital evolution of the binary pulsar PSR B1913+16, [25]. The direct detection of GWs will open a new window in astronomy and the expectations of the scientific community is obviously extremely high.

To this end, a large effort is currently under way by Virgo [6] and LIGO [5] experiments in order to improve the detector sensitivity by a factor of 10 in the 40–1,000 Hz range and even by a larger factor at 10–40 Hz. In terms of detectable sources this means to increase their number by a factor of 1,000.

In the recent years a number of theoretical studies predicted that the most promising GW sources are expected to be emitted by extremely dense binary systems such like neutron stars (NS) and black hole (BH) systems during their coalescent phase (NS-NS or NS-BH). With the expected sensitivity of advanced LIGO and Virgo network is reasonable to foresee that this kind of sources can be detected within 200 Mpc (NS-NS) and 400 Mpc (NS-BH) [2]. According to the predicted rate of 1 event/week for these binary systems coalescence [1, 2] the unexplored GW astronomy is about to begin soon.

Other sources are expected to produce transient GW signals as well. Among them perturbed NS and BH [15, 16] and the core collapse of massive stars [21]. The event rate of core collapse supernovae (CC-SNe) is of the order of 100–1,000 events per year within a distance of 100 Mpc [10]. However, the number of CC-SNe, as well as for perturbed NS and BH, detectable by the advanced GW detectors is highly uncertain [3, 4, 20] owing to uncertainties in the amount of energy emitted in GWs.

It is worth noticing that CC-SNe explosions emit both gravitational wave and MeV neutrinos (e.g. SN 1987A [27, 28]). Therefore the contemporaneous detection of their GW, MeV neutrinos and EM signals will provide a unique tool to study the physics of such explosive events and open the era of the multi-messenger astronomy.

47.3 The GW Sources in the EM Window

How likely is it to observe the EM counterparts of GW events? In the current understanding the massive binary systems are thought to be the strongest GW emitters and these sources are expected to have an EM counterpart. The progenitors of long gamma-ray bursts (LGRBs) are thought to be due to the collapse of massive stars ("collapsars", e.g. [12, 29]). On the other hand and more promising for the GW detection, the short GRBs (SGRB) seems to be generated by the coalescence of NS-NS or NS-BH systems [7]. In spite of the extensive studies of GRBs from ground and space, a clear identification of the progenitors is still missing. A coincident detection of a GW signal from a SGRB will represent a strong evidence that the coalescing process of NS-NS or NS-BH system are the real origin of these high energy phenomena.

In this scenario the source orientation will play a fundamental role. SGRB observed in gamma-rays and hard X-rays will be in a face-on configuration. When the relativistic jets slows-down due to the interaction with the interstellar matter, GRBs will be visible as an afterglow radiating also at soft X-rays, optical and radio frequencies with a progressively larger beaming angle [18, 30]. When a GRB is observed off-axis, the emission at lower-energies (i.e. from radio to X with no emission in gamma-rays) is indeed expected to be the only signal from the jet that will reach the observer, generating the so-called "orphan afterglows". Mergers of compact objects likely to generate GWs, are believed to produce also the so-called kilo nova radiation, i.e. the isotropic thermal emission expected in the optical/IR bands powered by the radioactive decay of heavy elements [22]. The kilonova emission appears days to weeks [19, 22] after the merger and remains bright for a similar time (Fig. 47.1). The kilonova emission can provide information of the merger processes, as the light curves depend on the mass, velocity and geometry of the ejecta, while their opacity and spectral feature probe the ejecta composition. As discussed in the previous section, other possible sources of GWs exist, but the energy released as gravitational radiation is highly uncertain and are of minor interest for the EM follow-up.

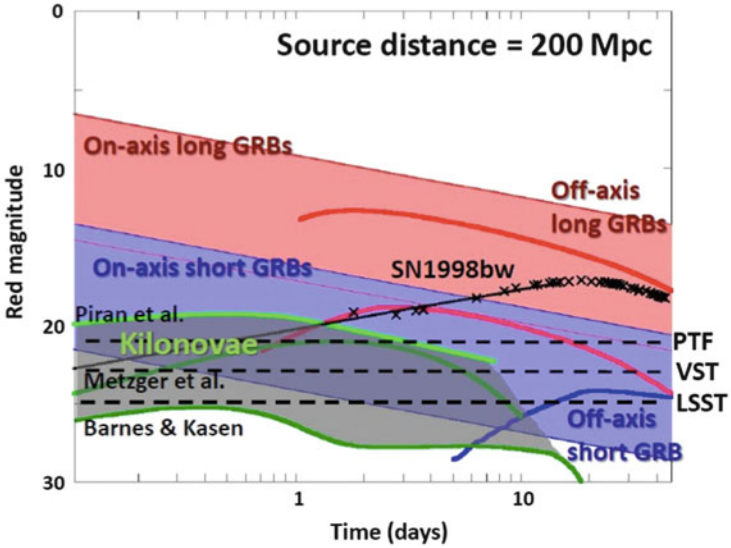

Fig. 47.1 GRB afterglow, kilonova and supernova R-band emissions as function of time from the GW emission. The *blue* (*red) band* indicates the region occupied by the observed on-axis short (long) GRB afterglows [13, 14]. The *blue (red) lines* indicate examples of off-axis afterglows of short (long) GRBs (modeled by [26]). The *grey band* is the region of the kilonova model [19, 22]. An example of GRB-associated SN emission is shown by *solid black line* (*black asterisks*; observation of SN 1998bw by [9]). The VST, PTF and LSST limiting magnitude for 80 s in r band for point sources with S/N 10 are indicated by *black dashed-lines*

47.4 Observations of Electromagnetic Counterpart of Gravitational Wave Events

To identify the EM counterpart of GW events at least two critical issues have to be addressed: (i) the determination of the GW source position and (ii) the short time before sources fade out. The GW trigger will be passed to the EM telescopes with a large positional uncertainties ranging from tens to hundreds square degrees. At the same time the high sensitivity of the advanced GWs detectors will access a large volume of the Universe. These two characteristics of GWs detection require, for the EM follow up, the use of both wide field of view and medium to large effective area telescopes. For what concern the time constraints the Fig. 47.1 shows the expected on- and off- axis afterglow emission from both long and short GRBs in the R-band as a function of time as well as all the quoted possible sources discussed in Sect. 47.3. One may appreciate that these sources will be observable only for few days by using medium to large sized telescopes. The VST meets all the requirements [8] needed for an effective follow-up of GWs.

The LIGO and Virgo collaborations (LVC) have engaged in a program of low-latency gravitational wave data analysis to generate triggers for significant GW candidates and share them with astronomical institutes which signed a MoUs with the LVC. INAF has signed the MoU and we are in the phase of set-up the hardware, software and observational facilities to react to such triggers and begin the observing campaigns aimed at identifying their possible optical counterpart. In particular the area surveyed by VST and its tiling strategy will be dictated by the GW signal direction (sky-position probability maps) and the telescope pointing constraints. Our initial strategy is to survey up to $100\,\mathrm{deg}^2$ chosen as those sky map pixels with the highest probability to contain the GW source. We plan to perform the survey in two filters (g,r bands) and in three epochs, that is $t_0 + (0.1 \div 1)d$, $t_0 + (1 \div 3)d$, $t_0 + (20 \div 40)d$ where t_0 is the time of GW detection and d stays for day. The temporal sampling is chosen allowing for the rapid evolution of the expected GWs counterpart. Whenever suitable past archival images of the same field will be available, the transients can be identified already from the first epoch of the survey. Otherwise we will need a comparison with the second epoch for objects with rapid luminosity evolution (e.g. GRBs) or with the third epoch for slower evolving transients (e.g. SNe). Our immediate objective is to identify as early as possible all transients in the sky map area and select among them the best candidate for GWs counterparts [23, 24]. These will be further scrutinized by mean of dedicated photometric and spectroscopic observations at all wavelengths exploiting all the facilities controlled and/or participated by INAF. The VST needs approximatively one night of observation to cover $100\,\mathrm{deg}^2$ in two filters with a limiting magnitude of 22.5 for point-like sources with S/N 10. This is what is required for the detection of faint transients in the local Universe.

47.5 Conclusions

There is no doubt that the detection of EM counterpart of GW signals will be one of the most challenging projects for space and ground based observatories. The INAF astronomical community is working to collect the human and financial resources to contribute to this effort. We plan to take advantage of the availability of the VST observational facilities and of the wide experience in the Time Domain Astronomy of the Italian community.

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