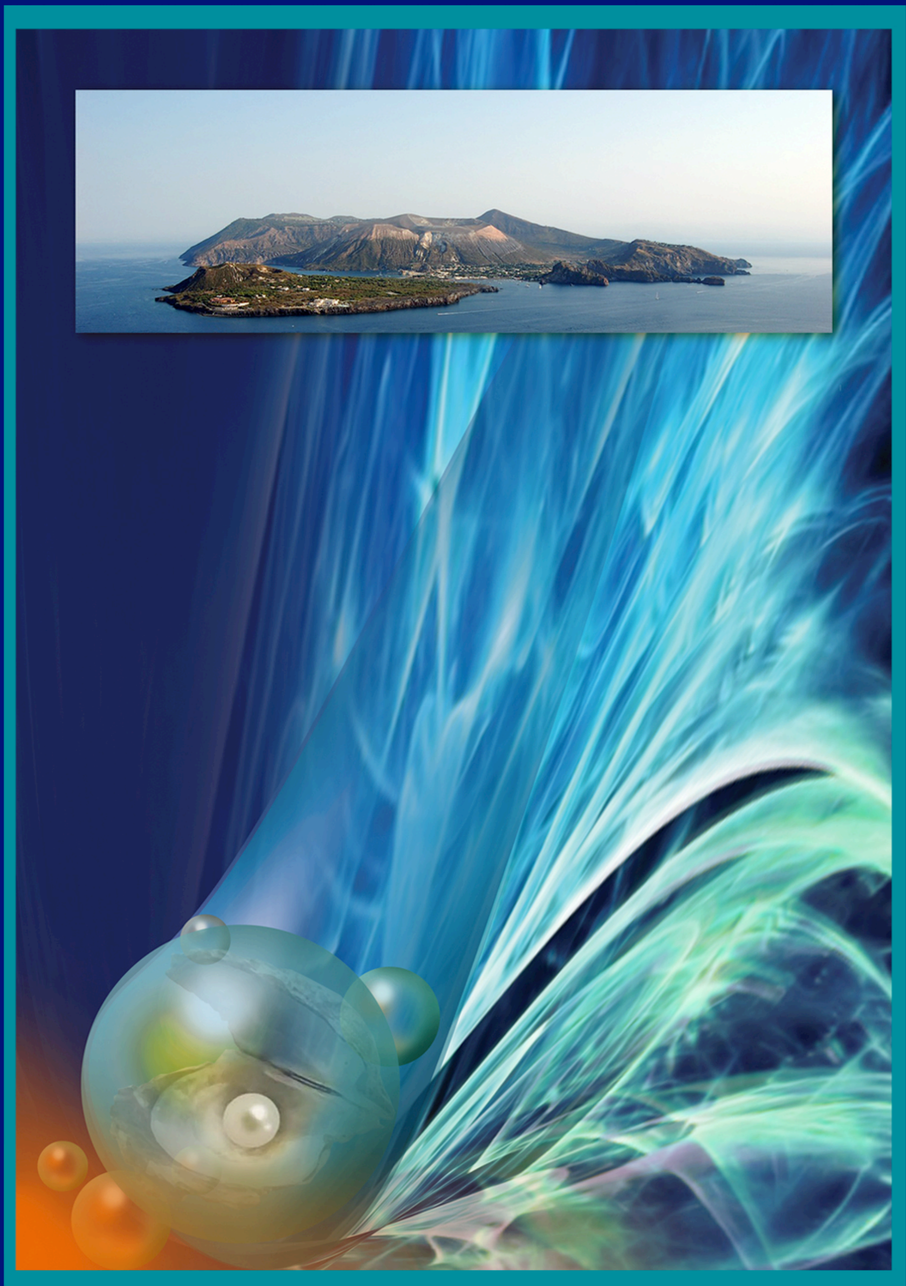
ISTITUTO NAZIONALE DI FISICA NUCLEARE
Laboratori Nazionali di Frascati

FRASCATI PHYSICS SERIES



Vulcano 2014

Frontier Objects in Astrophysics and Particle Physics

Editors:
R. Fusco Femiano, G. Mannocchi, A. Morselli, G. Trinchero

FRASCATI PHYSICS SERIES

Series Editor

Rossana Centioni

Technical Editor

Debora Bifaretti

Cover by Claudio Federici

Volume LVIII

Istituto Nazionale di Fisica Nucleare – Laboratori Nazionali di Frascati
Divisione Ricerca
SIDS – Servizio Informazione e Documentazione Scientifica
Ufficio Biblioteca e Pubblicazioni
P.O. Box 13, I-00044 Frascati Roma Italy
email: sis.publications@lnf.infn.it

ISBN 978-88-86409-63-6

VULCANO Workshop
Frontier Objects in Astrophysics and Particle Physics
2014

Vulcano Workshop 2014

Frontier Objects in AstroPhysics and Particle Physics

Dark Matter

Cosmology and Astroparticle

Astrophysics and Cosmology

Particle Physics and Interactions

Cosmic Ray origin, Gamma and Neutrino Astronomy

Neutrinos

Cosmic Rays

Future Projects

* Slides are available at https://agenda.infn.it/conferenceOtherViews.py?view=nicecompact&confId=7266

Frascati Physics Series Vol. 58 (2014)
Frontier Objects in Astrophysics and Particle Physics
May 18-24, 2014

OBSERVATIONAL PROSPECTS IN THE ELECTROMAGNETIC DOMAIN OF GRAVITATIONAL WAVE SOURCES

Marica Branchesi on behalf of
the LIGO Scientific Collaboration and the Virgo Collaboration
INFN, Sezione di Firenze, I-50019 Sesto Fiorentino;
Università degli Studi di Urbino Carlo Bo, I-61029 Urbino, Italy

Abstract

A new exciting frontier of observational astronomy will soon start to be explored: the current upgrade of gravitational wave ground-based detectors, LIGO and Virgo, should make possible to observe gravitational wave signals for the first time. Expected sources of gravitational waves include the most energetic astrophysical events such as the merger of neutron stars and/or black holes and the core collapse of massive stars. These events are believed to produce electromagnetic transients, like gamma-ray bursts and supernovae. The simultaneous use of electromagnetic facilities and gravitational-wave detectors will give the unique opportunity to catch the electromagnetic signatures of gravitational wave sources and to observe the same source with different messengers (GW and photons). The paper outlines the challenges, opportunities and strategies to develop and carry on multi-messenger searches.

1 Introduction

In the next decade the new generation of ground-based gravitational wave detectors, the advanced LIGO [1] and advanced Virgo interferometers [2, 3], will come on-line and will observe the sky as a network with the aim to directly detect for the first time gravitational wave (GW) signals. Detectable astrophysical sources can be divided into two classes on the basis of their emitted signals: transient and continuous sources. The former emit signals with a duration in the detection band significantly shorter than the observation time and which cannot be re-observed, the latter emit quasi-periodic waves whose frequency changes slowly. Transient GW signals are expected to be emitted from the coalescence of binary systems of compact objects (COs), neutron stars (NS) and/or stellar mass BHs [4, 5] and core-collapse of massive stars [6]. Continuous GW signals are expected from spinning NSs if they are not perfectly symmetric around their rotation axis.

The initial LIGO and Virgo observations have not detected gravitational-wave signals, but they have estimated upper limits on the source rate and on GW emission amplitude. The search for GWs from compact binary coalescence with total mass between 2 and 25 solar masses, for example, have given cumulative rate upper limits of the binary coalescence of binary neutron star, neutron star- black hole and binary black hole systems of 1.3×10^{-4}, 3.1×10^{-5} and $6.4 \times 10^{-6} \mathrm{Mpc}^{-3} \mathrm{yr}^{-1}$, respectively [7]. These rates are two to three orders of magnitude above the astrophysically predicted ones. The detection probability will dramatically improve with the advanced detectors which will provide a factor of ten increase in sensitivity over the initial detectors, corresponding to a factor of thousand increase in the number of detectable sources. Tens of binary coalescence per year are expected to be observable [8].

GW searches for 195 known targeted pulsars [9] with initial LIGO and Virgo made it possible to place upper limits on the rotational energy loss due to the emission of GWs, and thus on the NS ellipticity . For the Crab and Vela pulsars, the results constrain the fraction of rotational energy loss to less than about 1% and 10%, respectively, of their spin-down luminosities.

The advanced GW detectors are expected to come on-line in 2015 [10]. Their sensitivity should make it possible to observe GW signals by opening a new window in the (astro)physical study of gravitational collapse, explosion mechanisms, and ultra-dense matter stellar structure. The simultaneous availability of sensitive GW detectors and ground-based and space electromagnetic

(EM) observatories will allow scientists to use powerful multi-messengers, GWs and photons, to probe the most energetic events in the Universe.

2 Electromagnetic Emission from Gravitational Wave Sources

The discovery of the EM counterpart of a GW signal will be a key ingredient to characterize the astrophysical source and maximize the science return of GW observations. It would increase the confidence in the astrophysical origin of the GW signal. It would give a precise localization and potentially lead to the identification of the host galaxy. GW and EM radiations will provide complementary insight into the progenitor (mass, spin, distance, etc.) and the environment physics (temperature, density, redshift), giving a complete picture to understand the engines that power the double-messenger emission, e.g [12, 11]. The GW/EM observations compared with theoretical models will shed light on a plethora of open questions including the birth and evolution of CO and the Equation of State of matter at extreme densities in the stellar crust and interiors of NS.

The merger of NS-NS or NS-BH, and the core collapse of massive stars are expected to produce the gamma ray bursts (GRBs) and supernovae (SN). GRBs release a huge amount of energy (up to 10^{53} erg isotropic-equivalent energy [13]) within a few seconds that results in a hot, highly relativistic fireball, which undergoes internal dissipation and leads to gamma-ray prompt beamed emission. The fireball evolves later into a blast wave as it decelerates against the external medium, producing an afterglow emission [14] visible in X-rays, optical, radio, and in some cases gamma rays. The afterglow emission can last minutes, hours, months after the prompt emission and it can be observed over a wider viewing angle. According to the traditional classification schemes GRBs are divided into long GRBs and short GRBs on the basis of the prompt emission duration. While for the long GRBs, SN emission in the same location of the GRB strongly support the core-collpase of massive star as progenitor [15], for the short GRBs there are some observational evidences that indicate the NS-NS and NS-BH merger as possible progenitor. Their association with older stellar populations and the larger distance to the host galaxy centers compared to long-GRBs are in good agreement with predictions for the binary NS system distribution, see [16].

The merger of COs is also expected to emit [17], an isotropic optical/infrared thermal short-lived emission, called "kilonova", powered by the radioactive decay of heavy elements synthesized through rapid neutron capture in the sub-relativistic merger ejecta [18, 19, 20]. The Hubble Space Telescope follow-up of the short GRB130603B showed the first observational tentative evidence of kilonova emission [21] by observing, 9 days after the prompt emission, an excess in the near-infrared consistent with kilonova predictions.

The NS-NS (NS-BH) mergers are expected to be detectable by the advanced detector network up to the range (location- and system orientation-averaged distance) of 200 Mpc (400 Mpc) with corresponding likely rate of $40\mathrm{yr}^{-1}$ ($10\ \mathrm{yr}^{-1}$) [8]. The core-collapse of massive stars, due to the small energy emitted in GWs, are expected to be detectable within our Galaxy [6], and out to larger distances of 1 Mpc to tens of Mpc in more optimistic scenarios e.g. [22, 23].

The most promising EM counterpart emission is expected to be associated with NS-NS and NS-BH merger. Figure 1 shows the optical emissions expected for a source at a distance of 200 Mpc. The solid lines represent the brightest and faintest on-axis (whose narrow relativistic jet points towards the observer) short GRB observed afterglows [24]. The afterglow brightness decays rapidly as a power law $t^-\alpha$ with α in the range 1 to 1.5 [13]. The small-dashed lines represent the synthetic off-axis afterglows of GRBs [25] with energy jet of 10^{50}erg, jet angle of 0.2, observer angle of 0.4, and a uniform interstellar medium density of $10^{-3}\mathrm{cm}^{-3}$ (bottom line) and $1\mathrm{cm}^{-}3$ (top line). The dashed lines represent three different models of kilonova emission. The Piran et al. (2013) kilonova is a bolometric light curve obtained for a BH-NS merger with NS mass of $1.4\,\mathrm{M}_{\odot}$, BH mass of $10\,\mathrm{M}_{\odot}$, and iron opacity. The curve represents an upper-limit to the true R-band luminosity since it assumes that all of the bolometric luminosity is emitted in the R-band. The Metzger et al. (2010) kilonova is a blackbody emission for an ejecta mass of 10^{-2} solar mass, and iron opacity. The Barnes & Kasen (2013) assumes an ejecta with low velocity (0.1 c) and mass (10^{-3} solar mass), and lanthanides opacities.

The above emissions can be detectable with sensitive instruments. Each of them require an adequate plan of observational epochs to detect and follow the light curves (flux vs time). A GW event, which is observable independently of the system orientation, is more likely to be associated with an isotropic kilonova and off-axis GRB signals than an on-axis GRB afterglow. The rate of on-axis GRBs with respect to off-axis depend on the jet beaming angle, whose value is poorly constrained so far [18, 26].

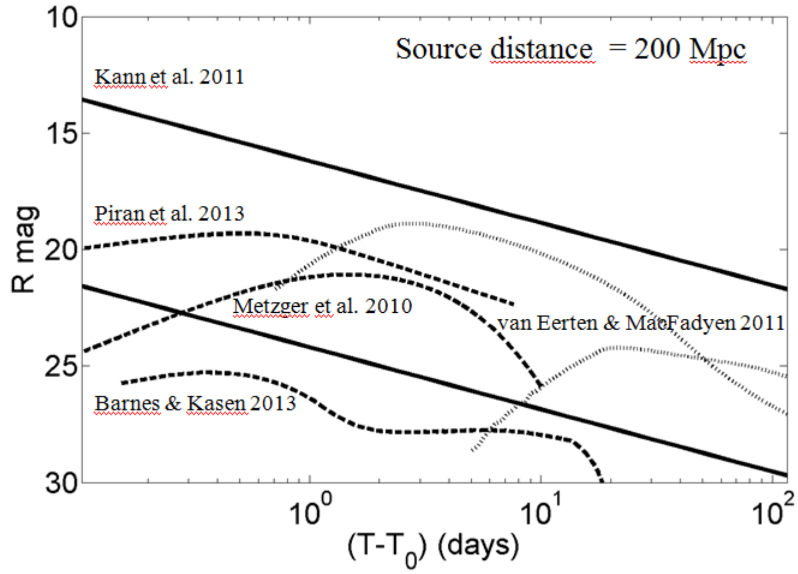


Figure 1: *Optical R-band emission expected from a NS-NS and NS-BH merger at a distance of 200 Mpc. The coalescence of NS-NS and NS-BH is the most promising source of GW transient signals*

3 Multi-messenger searches

On the basis of the emission timescales, two types of searches have been developed to detect the GW and EM signals associated with the same astrophysical source: the *"electromagnetically triggered search"* and the *"electromagnetic follow-up of GW events"*. The former search uses the EM detections to perform the GW analysis, the latter uses the GW candidate events to trigger EM observations.

The most promising analysis able to associate the GW event with the prompt emission of a GRB is the *"electromagnetically triggered search"*, which searches for GW signals in temporal and spatial coincidence with the observed GRBs [27, 28]. This search can be used to investigate the nature of a single gamma-ray event, e.g. [29], and also for statistical studies over the GRB population [27, 28].

Vice versa, a prompt identification of GW candidates will allow astronomers to organize EM-follow up observations able to detect GRB afterglow, kilonova and supernova emissions. The Virgo and LIGO collaborations (LVC) have developed low-latency GW pipelines to detect compact binary coalescence [30] and unmodeled GW bursts. The pipelines generate alerts for significant GW-candidate events and send alerts in low latency. The first EM follow-up program (Dec 17 2009 to Jan 8 2010 and Sep 4 to Oct 20 2010) was performed during the last LIGO/Virgo science run [31]. The off-line analysis [32, 33] of the GW data alone showed no evidence of an astrophysical origin for the GW candidates identified by the low-latency pipelines. All the detected EM transients were consistent with the EM background [34, 35]. The 2009-2010 EM follow-up program was a great exercise to point out all the challenges to search for an EM counterpart.

The main challenge is the sky location uncertainty associated with a GW signals. The sky position is mainly evaluated by "triangulation" using the arrival time delay between detector sites and it is of order of several tens to hundreds of square degrees. These sky areas are larger than the field of view of the majority of the EM telescopes. Thus, adequate observational strategies, which use tiling of many telescopes and/or galaxy targeting, need to be developed. Furthermore, in large sky area there are many contaminating transients not associated with the GW event, which need to be removed to detect the EM counterpart.

4 Electromagnetic Follow-up of Gravitational Wave Candidate Events in The Advanced Detector Era

Since the advanced LIGO and Virgo network will continue to consist of three sites (until additional detectors come on-line in Japan and possibly in India, 2022+) the GW events will continue to be typically localized into regions of tens to hundreds of square degrees [10]. The detection of relatively faint rapid transients in large sky areas and the identification of a unique counterpart will require hierarchical searches: 1) sensitive wide-FOV (about 10 sq. degrees) telescopes able to cover the entire GW sky localization area, 2) "Fast and smart" software to rapidly detect and classify transient events, and select a sample of candidate counterparts, 3) larger telescopes and spectroscopic follow-up to characterize the candidates, see e.g. [34, 36].

In 2012 LVC agreed on the policy to share significant GW candidates. "Until the first four GW events have been published, triggers will be shared promptly only with groups of astronomers who have signed a Memorandum of Understanding (MoU) with LVC". At the end of 2013 a call for proposals to sign MoUs was opened and it received high participation. Currently about sixty astronomer groups, agencies and astrophysical institutions are involved in the LVC EM follow-up program with about 150 instruments, which will cover the entire accessible EM spectrum and which are distributed worldwide. The call for MoU will be renewed every year. The field of multi-messenger astronomy is ready to enter a new and exciting era.

5 Acknowledgments

M. Branchesi acknowledges financial support from the Italian Ministry of Education, University and Research (MIUR) through grant FIRB 2012 RBFR12PM1F.

6 References

References

1. G.M. Harry for the LIGO Scientific Collaboration, Classical and Quantum Gravity **27**, 084006 (2010).
2. F. Acernese *et al.*, Virgo Technical Report VIR-0027A-09, https://tds.egogw.it/ql/?c=6589 (2009)
3. T. Accadia *et al.*, Virgo Document VIR-0128A-12, https://tds.ego-gw.it/ql/?c=8940 (2012)
4. A. Abramovici, Science **256**, 325 (1992)
5. C. Cutler & K.S. Thorne, General Relativity and Gravitation **72** (2002)
6. C.D. Ott *et al.*, ApJ **768**, 115 (2013)
7. J. Abadie *et al.*, Phyiscal Review D **85**, 082002 (2012)
8. J. Abadie *et al.*, Classical and Quantum Gravity **27**, 173001 (2010)
9. J. Aasi *et al.*, ApJ **785**, 119 (2014)
10. J. Aasi *et al.*, arXiv:1304.0670
11. B.S. Sathyaprakash & B.F. Schutz, Living Reviews in Relativity **12**, 2 (2009)

12. I. Bartos *et al.*, Classical and Quantum Gravity **30**, 123001 (2013)
13. E. Nakar, Physics Reports **442**, 166 (2007)
14. P. Meszaros, RPPhys **69**, 2259 (2006)
15. J. Hjorth & J.S. Bloom, Cambridge Astrophysics Series **51**, 169 (2012)
16. E. Berger, NewAR **55**, 1 (2011)
17. L.-X. Li, B. Paczyński, ApJ **507**, L59 (1998)
18. B.D. Metzger *et al.*, MNRAS **406**, 2650 (2010)
19. T. Piran, E. Nakar & S. Rosswog, MNRAS **430**, 2121 (2013)
20. J. Barnes, & D. Kasen, ApJ **775**, 18 (2013)
21. N.R. Tanvir *et al.*, Nature **500**, 547, 2013
22. C.L. Fryer & M.S. Warren, ApJ **574**, 65 (2002)
23. A.L. Piro & E. Pfahl, ApJ **658**, 1173 (2007)
24. D.A. Kann *et al.*, ApJ **734**, 96 (2011)
25. van Eerten & MacFadyen, ApJ **733**, L37 (2011)
26. Coward *et al.*, MNRAS **425**, 2668 (2012)
27. J. Abadie *et al.*, ApJ **760**, 12 (2012)
28. J. Aasi *et al.*, Physical Review Letters **113**, 011102 (2014)
29. J. Abadie *et al.*, ApJ **755**, 2 (2012)
30. J. Abadie *et al.*, A&A **541**, A155 (2012)
31. J. Abadie *et al.*, A&A **539**, A124 (2012)
32. J. Abadie *et al.*, PhysRevD **85**, 122007 (2012)
33. J. Abadie *et al.*, PhyRevD **85**, 082002 (2012)
34. J. Aasi *et al.*, ApJS **211**, 7 (2014)
35. P.A. Evans *et al.*, ApJS **203**, 28 (2012)
36. L.P Singer *et al.*, ApJ **776**, L34 (2013)