The triggering of electromagnetic observations by gravitational wave events

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Abstract. The prospects for the observation of electromagnetic emissions by gravitational wave sources first detected using a network of interferometers are discussed. Various emission mechanisms and detection techniques for compact binary inspirals are studied to show that the pointing ability of gravitational wave observatories and the efficacy of electromagnetic detectors can be combined to predict that counterpart detections are improbable for the Initial interferometers, possible with Advanced LIGO detectors, and likely with an Advanced detector in Europe. Results from a new position estimation algorithm for unmodeled sources are also presented, and are discussed in the context of the observation of counterparts to burst sources of gravitational radiation.

INTRODUCTION

It has been shown [1, 2] that the coherent operation of the international network of interferometric detectors that are presently being commissioned will result in greatly improved detection efficiencies for transient gravitational wave (GW) events. In addition, the phase information of the GW signal incident of the network will allow to estimate the position of its source. Searching for an electromagnetic (EM) counterpart to a GW event with good position information could provide a wealth of information about the thermodynamics of the source and about its host galaxy (assuming an extra-galactic event), which would complement admirably the information about the source dynamics that is carried by the GW.

Only limited attention has been given in the past to this important problem, both from the point of view of the expected EM signature of strong sources of gravitational radiation, and from the point of view of the optimal estimation of the position from GW data. I review in this paper some of the literature related to this subject. I first treat the case of compact binaries coalescences, for which more guidance is available from the astrophysics and the dynamics of the coalescence than for more general burst sources with poorly constrained waveforms (e.g. supernovae), which are discussed in the last section of this paper.

BINARY COALESCENCES

A fairly extensive discussion of the prospects for the observation of EM counterparts triggered by the detection of the GW from the inspiral of a compact binary is presented

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in [3]. The "chirp" signal from the inspiral is known with enough precision that an optimal matched filter can be used to search the GW data, allowing the observation of the coalescence of an optimally oriented double neutron star binary out to 25 Mpc (425 Mpc) with a signal-to-noise ratio of 10 with a single Initial LIGO (Advanced LIGO) interferometer. Detection rate estimates can be found in [4].

The simplest way to estimate the position of the coalescing binary is to measure the arrival time of the GW signal in all interferometers, and to triangulate the source. A more efficient approach is to analyze coherently the data from all interferometers, so that the source position is included in the list of parameters that are fitted to the data. This approach has been analyzed in detail by [2]; from their results, the size of the 2σ error box (95% coverage) for a network formed by the LIGO Hanford, LIGO Livingston, and Virgo interferometers (the HLV network) is expected to be

$$\Delta\Omega = \frac{7.4 \times 10^{-4}\ \mathrm{sr}}{|\cos\theta|} \left(\frac{12}{\rho_N}\right)^2, \tag{1}$$

where θ is the angle between the normal of the HLV plane and the direction of the source, and where ρ_N is the amplitude signal-to-noise ratio for a *coherent* analysis.

Eq.(1) can be inverted to find at what distance the error box of a coalescing binary fits into the field of view of a given EM telescope. Assuming a double neutron star binary seen face-on along the line $\theta = 0$, the error box will fill the 3.4 deg^2 field of view of the ROTSE-III robotic telescope [5] at a distance of 20 Mpc for the HLV network. With Advanced LIGO detectors in America and the Initial Virgo detector, this distance reaches 60 Mpc. Assuming that Virgo were also upgraded to the Advanced LIGO level, the distance would achieve 400 Mpc; at this distance, ~ 10 events per year can be expected (according to the standard model of [4]). It is noticeable that while upgrading Virgo to the Advanced LIGO level does not greatly improve the distance reach of the LIGO-Virgo network, it significantly improves the ability to locate the GW source. Advanced interferometers in America and in Europe would allow the observation of black hole-neutron star binary coalescences out to 300 Mpc with error boxes of ~ 0.25 deg^2, which is the size of the fields of view achievable with 8-meter class telescopes, or with the Chandra X-ray Observatory. At this distance, the expected event rate is ~ 0.2 per year (according to the standard model of [4]). Other examples are given in [3, Table 1].

These observational prospects all assume that there is an EM counterpart to double neutron star or neutron star-black hole binaries that is bright enough to be detected at the distance where a significant rate of GW events can be expected. At least three models have been proposed in the literature for these EM counterparts. In the first one [6], it is argued that the interaction between a neutron star and its strong field ($B \gtrsim 10^{15}$ G) companion leads to the formation of a stellar wind which powers coherent radio emissions, and to a relativistic wind extracting orbital energy to produce a X-ray flash. Both EM signals would be emitted during the *inspiral* phase of the binary coalescence, i.e., before the merger of the two stars, but the radio signal could be considerably delayed with respect to the GW signal due to interstellar dispersion. The radio signal could be seen out to ~ 100 Mpc with the VLA, for instance.

Another possibility is that the optical counterpart to a binary coalescence is powered by the radioactive decay of the material ejected from the disrupted merging neutron

star(s) [7]. Numerical simulations have shown that maybe as much as 10% of the star material is ejected during the merger [8], although recent work with more realistic approximations to General Relativity have given smaller fractions [9]. The emission was estimated by [7] to be primarily in the UV, and even at 1 Gpc, at peak luminosity the R band magnitude should be smaller than 20.

Finally, it has been theorized in the context of (short) gamma-ray bursts that binary coalescences could be the generator of the relativistic blast wave that is popular for explaining the long wavelength counterparts to gamma-ray bursts. While it is conceivable to look for a direct association between GW signals and gamma-ray bursts [10], the large distances involved weaken the prospects for GW detection. On the other hand, as argued by [11], a possibly large fraction of binary coalescences might fail to produce a gamma-ray burst, but still power an afterglow. Interpolating from long duration bursts, [12] estimate that the R magnitude of the afterglow of a short gamma-ray burst should be around 19 at 1 Gpc, while its X-ray flux should be $\sim 10^{-11}$ erg cm^{-2} s^{-1}. Consequently, the afterglow should be detectable in both bands.

All in all, these numbers show that a number of models predict bright enough EM afterglows from binary coalescences for their detection with existing telescopes. The real challenge will most likely be to identify the counterpart in a large field where more than one variable objects might be present. Given these considerations, I reproduce here the conclusion of [3] that EM counterpart observations to binary coalescences are unlikely with the initial detectors (rate $\sim 10^{-4} - 10^{-2}$ yr^{-1}), possible with Advanced LIGO detectors ($\sim 10^{-3} - 10^{-1}$ yr^{-1}), and likely with an Advanced detector in Europe ($\sim 1 - 100$ yr^{-1}), where the range in predicted rates results from uncertainties on the rate of binary mergers in the Universe [4].

BURST SOURCES

Burst GW sources with poorly predicted waveforms pose a significantly different problem than binary inspirals for signal detection and position estimation. In general, due to their misalignment, each interferometer of the network measures a different combination of the two polarizations of the GW signal, so that an unambiguous comparison of the measured signals to estimate the source position is often hard to achieve. I have recently proposed a generalization of the power detectors for GW bursts [13, 14] that was designed to provide good position estimates.

Numerical simulations have been performed to estimate the position error of this new algorithm for the HLV network. The signal was a random realization of a band-limited white noise process, different for each realization of the noise background. The signal was 62.5 ms long, with significant power only between 125 Hz and 150 Hz. The plus and the cross polarization waveforms were independent, but the plus polarization had four times more power (on average) than the cross polarization. For signals injected along the northern hemisphere normal of the HLV plane with a network signal-to-noise ratio of 13.4, approximately 50% of the trials lead to unusable position estimates (errors $\gtrsim 10$ degrees), but $\sim 25\%$ of the trials had errors smaller than one degree (see [14, Fig. 5]). Assuming that the GW source emits a quantity E of energy in gravitational

radiation, a network signal-to-noise ratio of 13.4 places the source at a distance $r \sim 70$ kpc $(E/10^{-7}M_{\odot}c^2)^{1/2}$ for Initial LIGO and Virgo, and ten times farther for Advanced detectors in America and in Europe.

To interpret these results in terms of supernovae, one can look at the simulated signals I used as very rough approximations to the GW signal from the collapse of a core in a supernova explosion (e.g., the GW signals from the simulations in [15] have $E \sim 8 \times 10^{-8}M_{\odot}c^2$, durations of a few tens of milliseconds, central frequencies between 100 Hz and 1 kHz, and bandwidth of $\sim$hundreds of Hz). Assuming as above that only $10^{-7}M_{\odot}c^2$ is radiated in GW, the initial HLV network should only be able to locate supernovae that are in our galaxy. An advanced network, however, should be able to locate accurately supernovae that occur in the local group. If significantly more energy is radiated in gravitational radiation during a supernova than this, the rate of locatable supernovae might increase to a level where it is significant. With mean maximum absolute B magnitude around -17, the EM counterparts should be easily detectable for collapses within the reach of the GW network.

To conclude, aside from the improvement of the sensitivity of the world wide network of interferometric detectors, the observation of an EM counterpart to a GW event will require the improvement of GW data analysis techniques, in terms of error box sizes, but also in terms of speed, as many afterglows might be rapidly dimming. Also, better theoretical guidance regarding what to expect from a GW event in terms of EM radiation could be used to design more efficient EM searches for the large error boxes that will be produced by GW observations and that will have to be scanned efficiently.

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