

FIRST OBSERVATIONS OF GRAVITATIONAL WAVE SIGNALS*

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A century after their prediction by Albert Einstein, gravitational waves were registered directly on Earth for the first time by the two detectors of the Laser Interferometer Gravitational-wave Observatory (LIGO). A short description of gravitational wave phenomenon is given and the extraordinary sensitivity of the detector required to measure gravitational radiation is pointed out. Basic principle of the laser interferometric detector is presented. The detection of the first signal that originated from merger of two black holes is described. Finally, results of the recent searches for other sources of gravitational waves than the binary black hole coalescence are summarized.

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1. Introduction

Einstein demonstrated that his theory of general relativity predicts existence of gravitational waves [1]. It took several decades of theoretical research before this phenomenon was completely understood. Taylor and Weisberg indirectly confirmed existence of gravitational radiation through observations of the orbital decay of the binary pulsar 1913 + 16 [2]. It took several more decades before instruments sufficiently sensitive to detect gravitational wave signals were designed and built. Like electromagnetic waves, the gravitational waves propagate with the speed of light, they have two polarizations and they carry energy [3, 4]. The dimensionless amplitude of a gravitational wave signal is approximately given by

$$h \simeq \frac{2G}{c^4 r} \ddot{I}, \quad (1)$$

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where G is Newton's constant, c is velocity of light and \ddot{I} is the second time derivative of the quadrupole moment. Simple estimates show that measurable gravitational waves cannot be generated on Earth. Study of the sources of gravitational waves reveals that there is a wealth of astrophysical sources of gravitational radiation [4]. However, they can only be detected with instruments capable to measure displacements of a fraction of a diameter of the proton. The pioneer in the effort to detect gravitational waves was Joseph Weber. Starting in the 1960s, Weber built a series of bar detectors. These were heavy metal cylinders of length ~ 1 meter. Weber's bars were not sufficiently sensitive to detect gravitational wave signals. Moreover, their sensitivity was limited to a narrow band. The idea that led broad band detectors to be much more sensitive was to use laser interferometry. In figure 1, a simplified diagram of a laser interferometer is presented. In the 1990s, two laser interferometric gravitational wave detection projects were funded: LIGO [5] and Virgo [6]. The LIGO and Virgo detectors conducted observations from 2002 through 2010 imposing astrophysically interesting upper limits on amplitude of gravitational waves from various sources. After the upgrades, the Advanced LIGO started working in September 2015 and during its first observational run the detectors made first detections of gravitational wave signals. The upgraded Advanced Virgo detector is expected to join soon the LIGO observations.

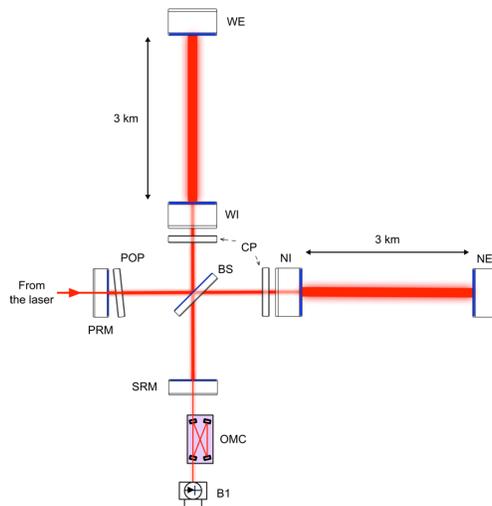


Fig. 1. Laser interferometric gravitational wave detector. A gravitational wave propagating orthogonally to the detector plane and linearly polarized will have the effect of lengthening one arm and shortening the other. The output photodetector (B1) records these differential cavity length variations (Courtesy Virgo Collaboration).

2. First gravitational wave signals detected

On September 14, 2015, the two LIGO interferometers made the first direct detection of a gravitational wave signal. The signal was first observed at the LIGO Livingston Observatory, and then 7 ms later at the LIGO Hanford Observatory. The signal was identified by an on-line signal search algorithm within 3 minutes from its arrival at the detectors. The observed signal was very strong with the signal-to-noise ratio of 24 [7].

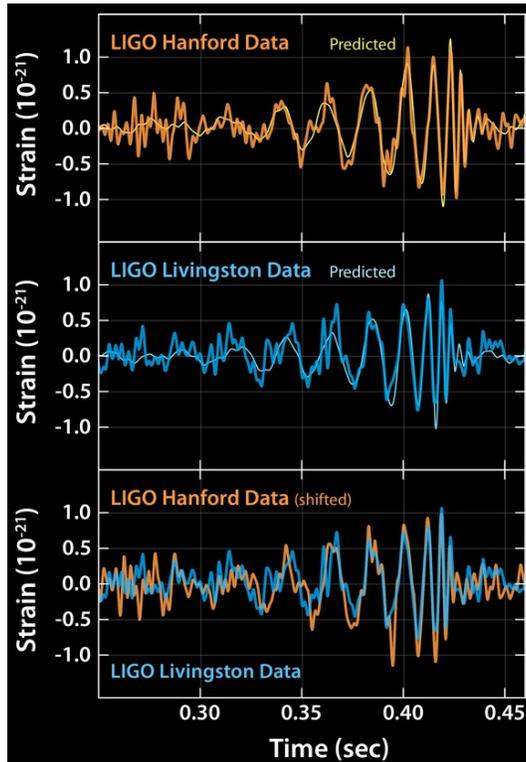


Fig. 2. Plots of the first signal of gravitational waves detected by the twin LIGO observatories. The top two plots show data received at Livingston and Hanford, along with the predicted shapes for the waveform from Albert Einstein's general theory of relativity. Time is plotted on the X -axis and strain on the Y -axis. Strain represents the fractional amount by which distances are distorted. The bottom plot compares data from both detectors. The Hanford data have been inverted for comparison, due to the differences in orientation of the detectors at the two sites. The data were also shifted to correct for the travel time of the gravitational wave signals between Livingston and Hanford (Courtesy Caltech/MIT/LIGO Laboratory <https://www.ligo.caltech.edu/image/ligo20160211a>).

Parameter estimation pipelines were used to determine that the gravitational wave signal was emitted from the merger of two black holes with masses of $36M_{\odot}$ and $29M_{\odot}$. The newly created black hole had a mass of $62M_{\odot}$, meaning that the total energy of gravitational wave emitted was equivalent to $3M_{\odot}c^2$. The system was 1.3 billions light years away from us when it merged. The measured gravitational wave signal, GW150914, from the two LIGO detectors is displayed in figure 2. The detected signal agrees very well with predication of Einstein's general theory of relativity at all three stages of the evolution of the binary: *inspiral*, *merger* and *ringdown*. The measured signal enabled several additional tests confirming validity of general relativity in a highly non-linear regime [10]. The peak amplitude of GW150914 is $h \sim 10^{-21}$ which corresponds to a displacement of the interferometers' arms of $\Delta L \sim 2 \times 10^{-18}$ m. In addition to GW150914, during Advanced LIGO's first observing run, a second black hole coalescence was observed (GW151226) [8] and a third black hole coalescence candidate event was also recorded (LVT151012), although its statistical significance was not high enough to claim a detection [9].

3. Searches for other gravitational wave signals in O1 data

The data collected by the advanced LIGO detectors during the first observational run are searched for other potential astrophysical sources of gravitational wave signals: coalescence of compact binaries involving neutron stars, supernovae, rotating neutron stars and stochastic background. These other searches have not resulted in any detections so far. Nevertheless, interesting upper limits were obtained:

- With 90% confidence, the merger rate is constrained to be less than $12600 \text{ Gpc}^{-3}\text{yr}^{-1}$ for binary-neutron star systems and less than $3600 \text{ Gpc}^{-3}\text{yr}^{-1}$ for neutron star–black hole systems [15].
- For a broad range of non-BBH transient gravitational-wave sources rate density upper limits are stricter than those previously published by an order of magnitude [14]. The dimensionless energy density of gravitational waves is constraint to be $\Omega_0 < 1.7 \times 10^{-7}$ with 95% confidence, assuming a flat energy density spectrum in the most sensitive part of the LIGO band (20–86 Hz) [13].
- For broadband point sources, upper limits on the gravitational wave energy flux per unit frequency are in the range of $F_{\alpha,\Theta}(f) < (0.1\text{--}56) \times 10^{-8} \text{ erg cm}^{-2} \text{ s}^{-1}\text{Hz}^{-1} (f/25 \text{ Hz})^{\alpha-1}$ depending on the sky location θ and the spectral power index α . For extended sources, we report upper limits on the fractional gravitational wave energy density required to close the Universe of $\Omega(f,\Theta) < (0.39\text{--}7.6) \times 10^{-8} \text{ sr}^{-1} (f/25 \text{ Hz})^{\alpha}$ depending on Θ and α [12].

- For the Crab and Vela pulsars, less than $\sim 2 \times 10^{-3}$ and $\sim 10^{-2}$ of the spin-down luminosity is being lost via gravitational radiation, respectively (assuming the distance is precisely known and using the fiducial moment of inertia of 10^{38} kg m^2) [11].

4. Conclusion

The pioneering observations presented in this paper mean that for the first time, a gravitational wave signal was registered by a detector on Earth and for the first time, the merger of two black holes into a single black hole was observed. The black hole that resulted from the merger was consistent with the Kerr solution of Einstein's equations. The significance of this discovery is that general relativity has been tested in extreme gravity regime where the gravitational field is strong and dynamical. Also, as a result of these observations a new field was born, the **Gravitational Wave Astronomy**.

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