Special Topic: Gravitational Wave Astronomy

First direct detection of gravitational waves

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We are living in the fabric of spacetime as Albert Einstein explained in his theory of general relativity. Gravity is the curvature of the spacetime. Einstein’s theory predicts not only that spacetime can warp, but that it can carry ripples of gravitational waves (GW), which are transverse waves of spatial strain that travel at the speed of light. They are generated by time variations of the mass quadrupole moment of the source. At that time, Einstein thought that GW signals were too weak to be detected.

The solutions of the field equations of Einstein’s general relativity also show spacetime singularities that today we know as black holes. The advance in theoretical work in general relativity and breakthroughs in numerical solutions of general relativity made it possible to model Binary Black Hole (BBH) mergers and to accurately predict their gravitational waveforms. However, there were no direct detections of GW and of black hole mergers until the 100th anniversary of Einstein’s prediction of the existence of GW.

On 11 February 2016, LIGO Scientific Collaboration together with VIRGO collaboration announced the first direct detection of GW by the Advanced LIGO detectors at Hanford, WA (H1), and Livingston, LA (L1) [1]. The signal from this event, GW150914, appeared first at L1 and about 6.9 ms later at H1 on 14 September 2015. The signals were so strong that they were visible in the raw data as shown in Fig. 1. The combined signal-to-noise ratio was 24. The signal was a ‘chirp’ signal, whose frequency increased from about 35 Hz to 150 Hz over 0.2 s. The amplitude reached the maximum at this point, followed by a few cycles of ring-down. From these basic features, it was concluded that the signal came from a pair of black holes spiralling together and merging. The waveform corresponded to an initial binary system consisting of a primary black hole with a mass of about 36 solar masses and a secondary black hole of about 29 solar masses. The inferred luminosity distance to the event is about 420 Mpc. This marked the first observation of a binary black hole merger, and the first direct observation of a black hole being formed.

During the first observation run (O1) [2], Advanced LIGO identified two confirmed GW signals, GW150914 and GW151226, and one candidate GW signal, LVT151012, with 87% possibility of astrophysical origin. All the observations are consistent with the predictions of general relativity. The inferred rate of BBH mergers based on those observations is 9–240 Gpc$^{-3}$yr$^{-1}$, which gives confidence that future
observing runs will observe many more BBHs.

The first direct detection of GW confirmed the theory of detection, and gave us a sensitivity calibration that allows us to make firm predictions of the benefits of sensitivity improvement. It opened the era of GW astronomy. The Advanced LIGO detectors are ground-based detectors with 4-km arm length. A strain sensitivity of better than $10^{-23}/\sqrt{\text{Hz}}$ was achieved around 100 Hz during O1. Above 100 Hz, the sensitivity is limited by quantum shot noise. Below 100 Hz, technical noise sources are dominant, of which most are understood, but some are not fully explained. A three-times improvement to reach the design sensitivity will increase the event rate for the type of sources already detected by 27 times allowing statistical studies to begin.

The design for the next-generation ground-based detectors started well before the detection of GW signals [3–5]. With improved sensitivity, tens of thousands of events per year will be detectable. With a sensitive detector in the southern hemisphere, it will be possible to determine the source direction sufficiently well that, for stronger signals, their host galaxies will be identifiable, allowing the GW to be used to study cosmology and test the theory of dark energy. The first observation surprised us by the unexpectedly large number of binary black holes in the universe. As sensitivity in this new spectrum increases, more and more surprises can be expected.

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REFERENCES