Analysis of Principle, State-of-art Detections and Applications of Gravitational Wave

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Abstract. In recent years, with the development of stable and high-precision measurements, it is now available for human beings to observe gravitational waves based on interferometry. As a matter of fact, the first gravitational signal is obtained contemporarily based on the facility LIGO, which is actually a high-accuracy interferometer with an extremely large signal-noise ratio. On this basis and with this in mind, this study will detailly analyze the principle and detection results of the gravitational wave. To be specific, the state-of-the-art facilities LIGO as well as other advanced detection scenarios are estimated and evaluated with the introduction of the components, searching parameters as well as finding results based on the data retrieving. In addition, the obtained results are analyzed and the possible applications are also discussed. According to the analysis, the current limitations and prospects are proposed. Overall, these results shed light on guiding further exploration of gravitational wave detection.

Keywords: Gravitational waves, laser interferometers, pulsar timing array.

1. Introduction

The concept of gravitational waves was first implied by Albert Einstein in the special theory of relativity as early as 1905. After 10 years, he predicted the existence of gravitational waves in the general theory of relativity in 1916, which suggested that gravity would deform the surrounding space, and the acceleration of a massive object would cause this deformation to spread in all directions like a wave [1]. After this critical theory was proposed, scientists tried to proof of the existence of gravitational waves by understanding the general theory of relativity and developing gravitational wave detecting facilities. With the development of wave-detecting science, scientists are seeking breakthroughs in the field of making instruments that can detect gravitational waves. Gravitational waves were directly detected for the first time in 2015, it was a huge breakthrough in the field of astronomy [2]. The unique penetrability of gravitational waves can bring scientists some information about events in space that happened a long time ago even when the early universe was formed.

On September 14, 2015, Ligo and Virgo in the United States detected a gravitational wave event that produced a 1,000 times smaller swing than an atomic nucleus, called GW150914. The frequency increased from 35 Hz to 250 Hz in 0.2 seconds. It was later identified as 3 solar mass sizes of gravitational waves that radiated by the combination of two black holes of 36 solar masses and 29 solar masses, they combined into a 62 solar mass black hole [3, 4]. The source of this gravitational wave is extremely distant from Earth, about 410Mpc, or 1.3×10^9 light years away. With the first successful cases, more gravitational wave detectors were built or operated in many countries around the world. On October 16, 2017, several observatories around the world announced the first detection of gravitational waves from merging neutron stars. In this study, the principle, component as well as results based on the state-of-the-art facility LIGO will be discussed and analyzed.

2. Basic Description of Gravitational Wave

Gravitational wave phenomena and related topics have become a popular topic for scientific researchers and scientific students to research and lucubrate because it brings new orientations and methods for the scientific field to explore more facts of the universe. As gravitational wave detection technology improves, more events from distant galaxies and the early universe will be discovered and

studied. This paper mainly studies the phenomena of gravitational wave detection and the analysis of the detecting result, including the basic definition of gravitational waves, the detection methods and principles of gravitational waves, as well as the results and applications of gravitational wave detection. The concept of gravitational waves is based on the Lorentz invariance in general relativity. General relativity is Albert Einstein's theory of gravitational interactions between objects, published in 1915, which assumes that all the laws and theories remain constants in any frame of reference in the universe. Einstein proposed that objects with mass exert gravity and that this object must be affecting the space-time around it. Space in the universe is a stretcher plane, and objects with mass distort the space-time around them, while objects around this object are drawn closer to it [5].

When the motion of matter accelerates, or the mass distribution of the material system changes, the degree of distortion of the surrounding spacetime is changed, and when these changes propagate outward from the source of radiation in the form of waves, it is called gravitational waves [6]. The gravitational wave signal detected by humans for the first time came from a black hole merger event, which is one of the gravitational waves produced by an interacting binary system. Other sources of gravitational wave signals that can be detected by humans include supernova explosions and gamma-ray bursts.

3. Detection of LIGO

Since the development of detection technology on gravitational waves science, a variety of detection technologies using different principles have been applied to scientific research, the two most widely used detection methods are laser interferometer and pulsar timing array [7]. The first instruments to detect gravitational waves in GW150914 were two laser interferometers which are in Livingston and Hanford. Typically, a single laser interferometer cannot get accurate results, two or more instruments are needed to confirm the accuracy of gravitational wave events. Because two laser interferometers in different geographical locations will produce a time difference when they receive the gravitational wave signal, and this tiny time difference helps researchers determine the direction, location, and size of the gravitational wave source. The basic principle of laser interferometers is related to the stretching and compression of space by gravitational waves. The large area of the instrument is mainly composed of two vacuum tubes several kilometers long, and the two vacuum arms are 90 degrees perpendicular. A laser is shot and refracted by the prism at the intersection to the other end of the vacuum tube. When the laser reaches the other end of the vacuum tube, it will be reflected by the mirror back to the laser emission point. Since the two vacuum tubes are precisely the same length, the two lasers will return to the intersection point at the same time [8]. A sketch of the principle for LIGO is shown in Fig. 1.

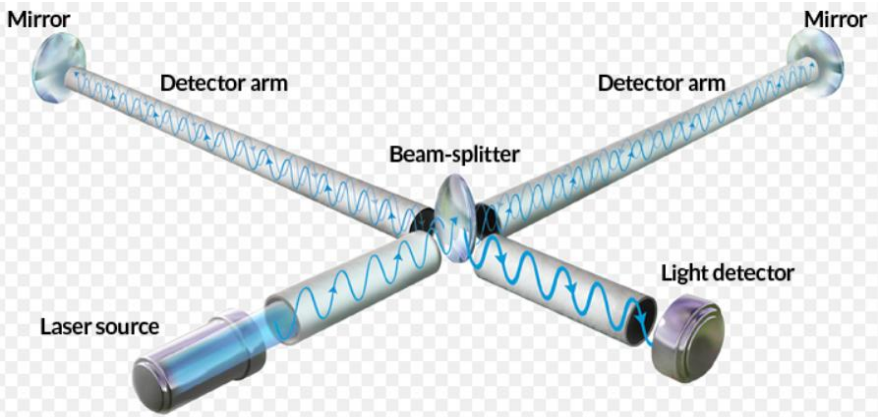


Figure 1. A sketch of the LIGO.

Under the characteristics of lasers, destructive interference occurs when two laser beams intersect (Fig. 2). So in the absence of a gravitational wave passing through, the detector will not detect any points of light. However, when gravitational waves pass through the vacuum tube, they change the

length of the tube by a very small extent, making one tube longer and the other shorter. Due to the change in size, the two laser beams no longer intersect at the same time, so there is no longer a complete destructive interference, some laser spot would be detected.

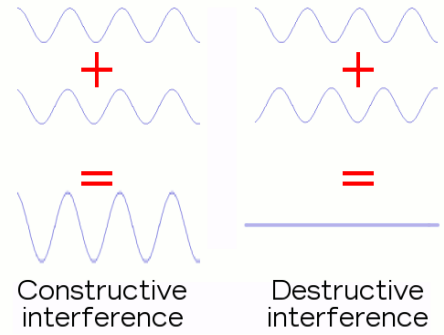


Figure 2. A sketch of two laser beams intersect.

However, the ground-based laser interferometers already in use are only sensitive to high-frequency gravitational waves (10hz, 104hz), and due to the size of the facilities that can be built on Earth, it is not feasible to greatly expand the instrument area in order to detect gravitational waves in a wider range of frequencies. Another widely used technique for detecting gravitational waves is the Pulsar Timing Array (PTA), which is a magnetized rotating neutron star that regularly emits pulses due to its magnetic field direction (radiation beam) being different from its rotation axis (Fig. 3). However, not all pulsars are suitable for PTA, in more than 3,000 pulsars that have been discovered, only 400 of them have very stable rotation periods. Normally, the observatory will detect the pulse of multiple pulsars for a long time, and when gravitational waves pass through, the time of the pulse to reach the Earth will change. This method is often used to detect most of the low-frequency gravitational waves (nHz), which are emitted by events associated with the early formation of the early universe [9].

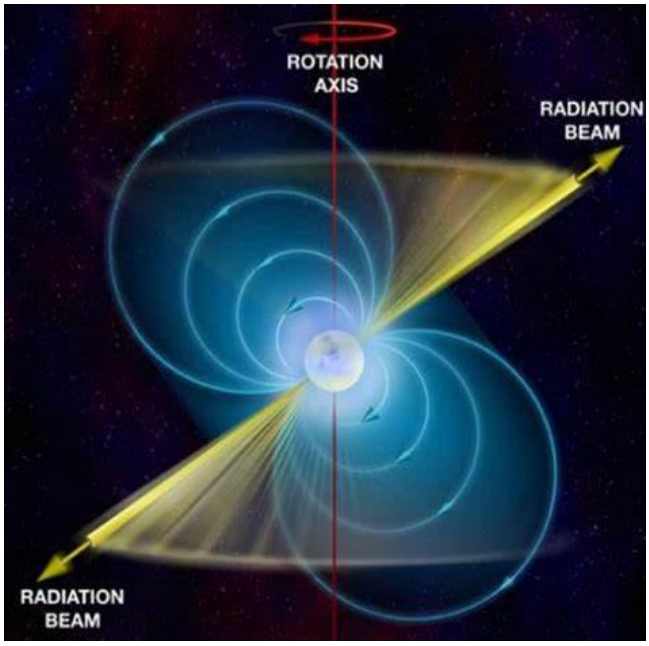


Figure 3. Rotation axis.

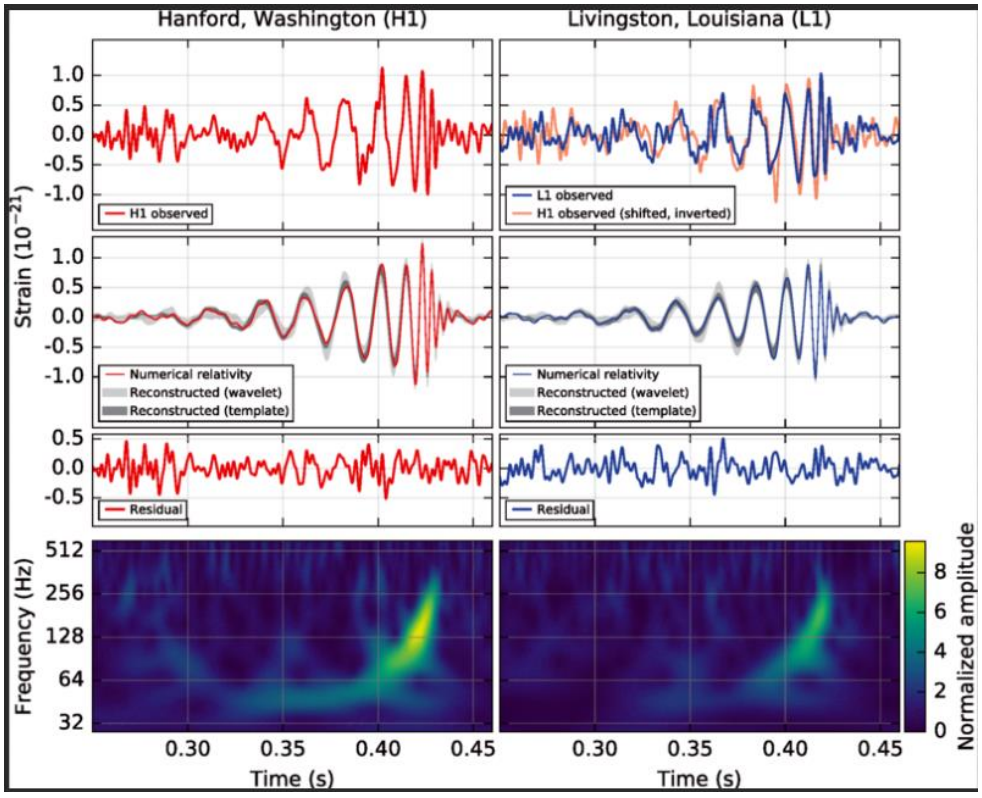


Figure 4. Detection results of LIGO.

Gravitational wave detection has developed rapidly in the past decade, during which several important achievements have been made in the fields of binary black hole mergers, binary neutron star mergers, and blackhole-neutron star mergers. On September 14, 2015, Ligo and Virgo observatory detected a gravitational wave event from 1.3 billion light years away. This is the first time humans have received a gravitational wave signal, This signal is the gravitational wave radiation by the merger of two black holes, the signal frequency covering 35hz to 250hz. As presented in Fig. 4, Ligo and Virgo are ground-based laser interferometers, Ligo consists of two detectors, one in Livingston(L1) and the other in Hanford(H1). There was a 7-millisecond lag between the two detectors detecting the signal, which is the same speed that light travels between the two detectors.

4. Other Detector

Another event verified the correctness of the general theory of relativity and confirmed the nature of gravitational waves such as their propagation speed. On August 17, 2017, the Ligo Observatory detected gravitational waves radiating from a binary neutron star merger event, which has been named GW170817. Besides the gravitational waves, a short gamma-ray burst was detected, which was confirmed to have come from the same binary neutron star merger event. Fig. 5 shows the gamma rays observed by the Fermi Space Telescope in the U.S., the gravitational wave signals observed by the Ligo laser interferometer, and the gamma rays observed by the Integral Space Telescope in Europe. The two space telescopes observed the gamma-ray burst two seconds after the gravitational wave signal peaked.

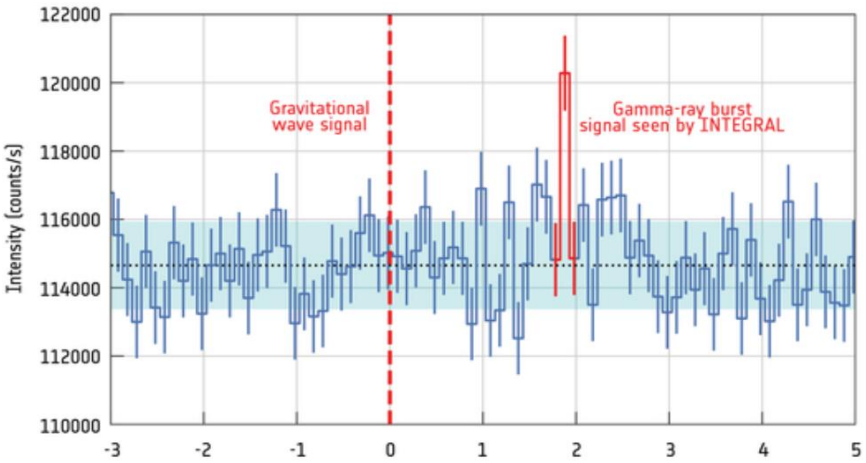


Figure 5. Gamma ray observed by the Fermi Space Telescope.

On January 5, 2020, Ligo observed a gravitational wave signal produced by the merger of an 8.9 solar mass black hole and a 1.9 solar mass object. The object was later identified by astronomers as a neutron star [10]. In addition, Weiss, Barry, and Thorne, three American scientists who made outstanding contributions to the construction of the Ligo detector, were awarded the 2017 Nobel Prize in Physics. Before the success of gravitational wave detection technology, scientists relied on electromagnetic radiation such as visible light, ultraviolet light, and infrared light to detect the universe. However, these waves are only a small segment of all waves and can provide scientists with very limited information. Gravitational waves are not affected by any medium, it is extremely penetrating and decays very slowly as they pass through the galaxy. It can provide scientists with cosmic information far beyond the detection distance of electromagnetic radiation. Because of the special property gravitational waves carried, many people are looking forward to it as a future means of interstellar communication. One of the reasons GW150914 has created a huge impact in the scientific field is the new information it brings to the field of black hole detection. Until 2015, humans have relied on electromagnetic radiation generated by black holes accreting interstellar material to detect black hole mergers, but this method has not been able to understand the detailed process of black hole mergers. Scientists can use the detected gravitational wave patterns to analyze and study the process, and it is possible to get a detailed process of the black hole merger event. These results can be used to verify the General relative theory and other theories and bring new information to the study of cosmic evolution and galaxy evolution.

Similar to the ground-based laser interferometer mentioned above the limitations of the scale of building observation equipment on the ground. As the largest ground-based laser interferometer, Ligo Observatory is already a large instrument in ground facilities, but the gravitational wave detection it can achieve is still limited to the range of 10hz to 103hz, and a larger scale laser interferometer is needed to detect gravitational waves at lower frequencies. The pulsar timing array, which focuses on low-frequency gravitational wave detection, is also limited and can detect gravitational waves at frequencies between 10^{-9} and 10^{6}. Gravitational wave signals between the two observable frequencies' range still require other advanced detection techniques to receive them.

On this basis, scholars came up with the idea of moving the laser interferometer geographically to remove the scale limitations due to the size of the Earth and its spherical arc. The European Space Agency is leading a mission called Laser Interferometer Space Antenna (LISA), which will launch three spacecraft in an "L" shape similar to a ground-based laser interferometer that also emits lasers to detect gravitational waves. The LISA mission is still in its exploratory phase, with a formal spacecraft launch expected in the early 2030s. The scientific idea of the project is that due to the significant extension of the laser arm, the detectable gravitational wave frequency can reach 0.1mhz-1hz, and it may be possible to detect ultra-compact binaries and supermassive black hole mergers. LISA Pathfinder is a test spacecraft launched in 2015 to investigate whether noise in space can meet LISA's detection needs. The test spacecraft successfully completed its mission in 2017, indicating

that the key difficulties of the LISA mission are likely to be overcome. In the field of gravitational wave detection, scientists are committed to exploring more gravitational wave frequency signals that have not been successfully received, and if the LISA mission is successfully put into operation, many cosmic events will be discovered for the first time or studied in greater depth. This field is very new compared to other signal detection fields and still has great prospects for development.

5. Conclusion

As a field that has developed rapidly in the past decade, gravitational waves and their detection and application have brought new information and research directions to the exploration of the universe. As the definition of gravitational waves has become more precise, different gravitational wave detection techniques have been applied to observatories in various countries. Because of the unique nature of gravitational waves, the detection of events in this field may bring information to astronomy about events that have never been understood before. Gravitational waves are special in the field of detection of black holes and events in the early universe, but they are still limited in the current level of scientific development. Different frequencies of gravitational waves correspond to events of different properties and periods, and the current laser interferometers and pulsar timing arrays still have incomplete coverage of gravitational wave frequencies. If laser interferometers in space can be used and eliminate interference, scientists could detect gravitational waves in a wider range of frequencies. Research on the topic of gravitational waves helps to raise awareness of a topic that brings important information to current astronomical research and holds great promise.

To sum up, this study introduces the principle of gravitation wave detection and investigates the state-of-the-art facilities as well as discusses the advanced results. To be specific, the components and detection scenarios of LIGO are evaluated and estimated. The current observation results are based on the different facilities and the detection results are demonstrated. In addition, the current defects as well as drawbacks are also mentioned. Besides, the corresponding suggestions are proposed accordingly. Overall, these results offer a guideline for further exploration of gravitational wave analysis.

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