Unveiling The Gravitational Waves: Nature, Detection and Applications

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Abstract. The detection of the gravitational wave has shifted the general understanding in physics by providing a piece of evidence for Theory of general relativity. Further, it has opened a new window for scientists to observe the universe and discovery new mechanism. The gravitational waves are incredibly faint by the time they reach earth and there are various sources of noise that causes interference in the gravitational wave signals. However, it would be challenged to isolate these noises in practice. The article will first explain the fundamentals of the gravitational waves, for example, the origin and nature of the gravitational waves. Secondly, the article will explain the approach that scientists took to detect the gravitational wave, which is the famous Laser interferometer gravitational-wave observatory. Finally, the future application of gravitational waves for future astrophysical research on the infant universe is also provided. This article will explain the above by previous hypothesis and recent research in physics.

Keywords: Gravitational wave; Interferometer; Black hole; General relativity.

1. Introduction

The Gravitational wave is a fundamental concept in Einstein's theory of general relativity. These waves are made by the acceleration of massive astral bodies in the universe. They function like ripples on the surface, but instead of water they interfere with the spacetime, and they pass on energies in the vast cosmos. Specialized Instruments for the detection of gravitational waves are invented by the scientists such as the Laser Interferometer Gravitational-wave Observatory (LIGO). The discovery of gravitational waves would help human to reveal more of the expansive cosmos by its unique physical identities [1].

The origin of the gravitational waves can be traced back to the time when Albert Einstein first postulated his hypothesis of general relativity in 1915. It altered Newton's theory of Gravity which he explained gravity as a curvature of the space time which is created by the motion of massive object and therefore generates the gravitational waves. In 2015, the LIGO detected signals from the gravitational waves. The gravitational wave was produced by the merger of two blackholes 1.3 billion light-year ago [2]. This provided compelling evidence for Einstein's Theory of General relativity. The LIGO is an extraordinary invention specifically for the detection of gravitational waves. The LIGO is a remarkable fusion of engineering, technology and modern physics that contributes to the exploration of the gravitational waves in a sophisticated approach [3]. The gravitational waves play a crucial role for supporting human's discovery of the vast universe. The gravitational waves would help people to observe and study cosmic phenomena that are not easily detectable through traditional way, because of the distinctive physical property of the gravitational wave. For example, the penetration of the gravitational waves inside the universe. The future utilization of gravitational waves can help human to widen their understanding of the immense universe.

In this essay, section 2 will introduce the origin and nature of the gravitational waves. Section 3 will outline the process of detecting gravitational waves and working principles of the LIGO. Section 4 will explain the future applications of the gravitational wave in the broad physics field in terms of their nature.

2. Nature of the Gravitational Waves

Differently with Newton's Theory of Gravity whereas Einstein's Theory of gravity define gravity as the curvature of spacetime. Massive objects will cause the 4-dimentional space-time to curve. Like the image below, the larger the mass of the object, the more the "fabric" of the space time curves. The curvature of the massive supergiant such as the Sun will create a sink of the "fabric of the spacetime". This will cause the earth or planet around it to orbit around itself. However, if the stars have similar mass to each other, they will spin around each other, then the gravitational wave will be produced [4]. For example, when two black holes are in a binary system and they are orbiting to each other, their spins and motions can also generate gravitational waves. As they move and spin, they cause fluctuations in the curvature of spacetime that radiate away in the form of gravitational waves. As the black holes orbit each other, they lose energy in the form of gravitational radiation, which causes their orbits to gradually decay, eventually leading to a merger.

Gravitational waves propagate as disturbances in the fabric of spacetime itself. They are waves of curvature that move at the speed of light, approximately 299,792 kilometres per second. This property ensures that gravitational wave signals reach people from the most distant corners of the cosmos, allowing people to observe events that occurred billions of years ago. Gravitational waves have a strong penetration due to its nature—weak interaction with matters. This is because it doesn't need a medium like water or air, but it is created by the curvature of spacetime itself. When it travels through the universe it would only cause a minuscule distortion of spacetime. Unlike the electromagnetic waves, gravitational waves cannot be absorbed. They can pass through substances with barely any absorptions [5]. This means that it can be reflected or refracted. Illustration of massive object in the spacetime is shown in Fig. 1.

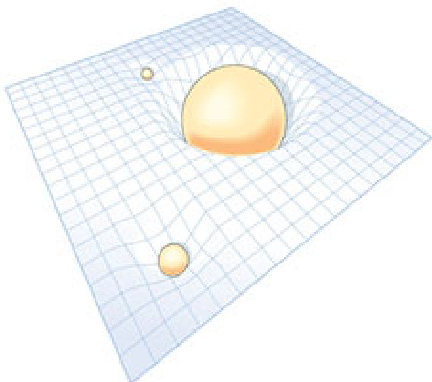

Fig. 1 Massive object will create greater curvature of spacetime [5].

3. Detection of the Gravitational Waves

3.1. History and Discovery

In 1915 Albert Einstein predicted the Gravitational wave by his idea of General relativity. He explained that large, massive objects like stars or blackholes will accelerate and merge with each other, then the merging will release energy as gravitational wave which sends through the space. But at that time there wasn't any evidence to support this hypothesis. In the 1960s as scientists wanted to further explore and find evidence about the gravitational waves, so they started to develop a more sensitive instrument that are able to detect some very subtle distortion in spacetime caused by the gravitational waves. Michelson interferometer was invented to deal with the problem. This built a foundation for the development of detectors. In the 1990s the LIGO project was initiated by the scientist for detecting the gravitational waves. The LIGO project set 2 identical interferometers in 2 different places—Hanford, Washington and Livingston, Louisiana. These interferometers will collaborate with the Virgo interferometer in Italy for the detection of the gravitational waves [6].

September 14, 2015, LIGO received a tiny, gentle signal from the passing gravitational waves. After this they tried to convert it into audio waves and analyses them. After the wave-origin analysis they announced that the interferometers detected the gravitational waves from the merging of 2 black holes. They discovered that the black holes were approximately 30 times the mass of the Sun and have a distance of a billion-light year away. They fused together giving off a huge amount of energy which is approximately three solar masses by Einstein's equation $E = mc^2$. After the first detection in 2015, the LIGO and Virgo have continued to receive more gravitational wave signals from the universe, which was made by some astrophysical events. For example, the neutron star collisions and the black hole mergers. These give evidence and supports for the scientists to explore the universe.

With respect to the further discovery of the universe scientists are planning to expand the global network of gravitational wave discovery. The KAGRA in Japan and the future LIGO in India will improve the accuracy of the gravitational wave localisation and produces more comprehensive results for research of the gravitational waves [7].

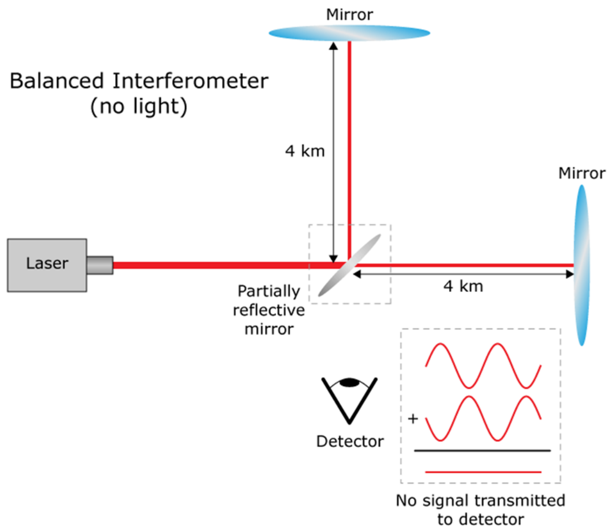

Fig. 2 The basic setting up of the single LIGO interferometer [8].

3.2. Working Principle of the Interferometers

LIGO consists of two identical interferometers—one located in Hanford, Washington, and the other in Livingston, Louisiana. Each interferometer has a long, L-shaped vacuum chamber with arms several kilometres in length. At the end of each arm is a mirror that reflects the laser beam. The basic setting up of the LIGO interferometer is shown in Fig. 2 [8].

The basic interferometer setup of the device is the following. For the laser beam emission, there is laser to emit a continues beam of lights which will split into two equal parts at the bean splitter at the corner of the L-shaped arms. The beams will pass down both of the arms. For the arms and mirrors, the arm will change its length while the gravitational wave passes through. To increase the sensitivity for the change in length—It is designed to be as long as possible. The light beams will bounce back and forth between the mirrors. Notably, at the junction of the arms the laser beams will recombine, and this will be detected by a photodetector. The wave of the combined wave would either be a constructive interference or cancel out each other (destructive interference), and this will inform whether the length of the arms has changed or not. In other words, whether there is a gravitational wave passing through or not [9].

The gravitational wave will cause an oscillation in the spacetime, so it will change the length of the interferometer's arms when it is passing through it on Earth. This will change the interference pattern. For example, if one arm gets longer while the other gets shorter, the interference pattern will shift. The LIGO then continues to detect the interference pattern. The changes in the pattern will reveal the specific properties of the source of the gravitational waves eg. Amplitudes and frequencies. The data of the waves will be analysed by the scientists to demonstrate the source of the gravitational wave. For instance, the masses and spins of the merging black holes---By making comparison of the signals with theoretical works, the scientists can predict the astrophysical events that have created the gravitational waves.

3.3. Future Applications of the Gravitational Waves

The high penetration nature of the gravitational wave allows people to measure signals made by the infant universe. The stochastic gravitational wave background contains vital information about the beginning of the universe, which is the time when the universe explodes and expand---The Big Bang events. This information can provide insights into the overall structure and evolution of the universe. About 380,000 years ago the cosmic microwave background was emitted from the big bang [10]. The cosmic microwave background (CMB) is a barrier for the earlier signals made from the beginning era of the universe, because the signals that's carried by the photons were erased by the extremely hot plasma in the infant universe. Yet, for the gravitational waves, the CMB is not a barrier, but it is rather a window. As the gravitational waves have a relatively long wavelength and high penetrating power, this would maintain its passing of signals in the universe and eventually, the LIGO detector. Therefore, the gravitational waves could open a new era for scientist's discovery of the universe as it has given a new perspective to observe the universe thoroughly—From the very beginning.

4. Conclusion

The gravitational waves were born by the merger of astral bodies, and this was explained by Einstein's theory of general relativity. When two similar massive bodies spin and causes fluctuation of the spacetime—which generates the spacetime. The high penetration nature of the gravitational waves and the similar speed to light will allow scientist to observe the very beginning of the universe by the signals. There were challenges for the detection of the gravitational waves such as the sensitivity of the instrument for the tender signal of the gravitational waves. Therefore, scientists developed a project called the LIGO. The setting up of the interferometer in multiple places around the earth allows them to collaborate and verify the transmit of the gentle gravitational waves. The interferometer works in a tactic way. It applies the property of wave—constructive and destructive interference to detect any changes in the pattern that is potentially caused by the gravitational waves. In the future there will be more gravitational detectors to be invented and put in use. Comparing to the detectors now, the detectors would have a significant development for wider detection zone and sensitivity. This means that there will be more possibility to receive gravitational waves far from Earth. Especially receiving the signals from the Primordial gravitational waves would help people to understand the phenomenon of the beginning and evolution of the universe. In conclusion, the gravitational waves will provide an advance and effective tool for Scientists to analyze and discover the vast cosmos.

References

[1] Ezquiaga, J.M, Zumalacárregui, M. Dark energy in light of multimessenger gravitational-wave astronomy. Front Astron Space Sci, 2018, 5: 44.

[2] Aasi, J., et al. Search for gravitational waves from binary black hole inspiral, merger, and ringdown in LIGO-Virgo data from 2009–2010. Physical Review D 2013, 87(2): 022002.

[3] Thorne, K.S. (1995). Gravitational waves. arXiv:gr-qc/9506086.

[4] Abbott, B.P., Abbott R., Adhikari R., et al. LIGO: the laser interferometer gravitational-wave observatory. Reports on Progress in Physics, 2009, 72(7), 076901.

[5] Miller, M.C., Yunes, N. The new frontier of gravitational waves. Nature, 2019, 568(7753), 469-476.

[6] Barish, B.C., and Rainer W. LIGO and the detection of gravitational waves. Physics Today, 1999, 52(10): 44-50.

[7] Li Yeming. On the proof of length contraction effect in the theory of relativity. Journal of Nanning Normal University, 2022, 39(3): 158-160.

[8] Feng Shi-meng. A deduction method of mass-velocity relationship in special theory of relativity. College Physics, 2021, 40(6): 32-35.

[9] Cao Zhoujian, He Xiaokai. Using gravitational wave to test general relativity. SCIENTIA SINICA Physica, Mechanica & Astronomica, 2018, 48(7): 079806.

[10] Zhang Tianrong. Gravitational wave and black hole. Nature Magazine, 2016, 38(2): 87-93.