Detection of Gravitational Wave in LIGO and Significance Evaluation

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Abstract. Gravitational wave detection plays crucial role in astrophysics and cosmology, which can prove the theoretical models as well as demonstrate the detail information in the universe. As a concept proposed based on general relativity, it has not been detected until the invention of the most advanced detectors, i.e., Laser Interferometer Gravitational-Wave Observatory (LIGO). In this paper, the state-of-art detection facility LIGO will be discussed in detail. To be specific, the detection principle of gravitational wave as well as the detection facility components and requirements will be illustrated. In addition, the significance of detecting gravitational wave will be clarified. On the path paved by pioneering physicists, this study looks further into the mechanism of the LIGO detection method and the significance of detection of gravitational wave. Moreover, the newest detection results are analyzed, and the corresponding improvements suggestions and future outlooks are presented and proposed accordingly. These results shed light on further exploration of gravitational wave detection.

Keywords: LIGO, gravitational wave, cosmology detection.

1. Introduction

In retrospect, the birth of the idea of gravitational wave happened about 100 years ago in Albert Einstein's theory of General Relativity [1]. It was assumed that it would be produced during violent interaction between massive celestial objects such as black holes or neutron stars [2-4]. By detecting and analyzing it, the scholars believed that they would gain insights into the invisible interaction between black holes or ultimately, the Big Bang. Moving into the 21th century, a method called LIGO has been developed to detect gravitational wave and it has made a successful discovery in 2016 [5-9]. Before further exploring the physics, a few keywords will be demonstrated:

Spacetime. It can be considered to a fabric combining the three dimensions of space with the fourth dimension of time which rises from the General Relativity

Gravitational wave. It can be considered to be ripples in space time caused by violent and energetic processes in universe.

LIGO. It stands for Laser Interferometer Gravitational-Wave Observatory which detects gravitational wave based on principles discussed in Weiss's report

Interferometer. It is an investigative tool used to examine information about an object or phenomenon at a very small scale, the LIGO's interferometers measure a distance 1/10000th the width of a proton.

As discussed above, the pursuit of gravitational wave has been going for about 100 years and it has produced overwhelming results in 2016 using LIGO detection method. However, the LIGO method still has several limitations such as its sensitivity to gravitational wave is limited by quantum nature of light at frequencies between 200 Hz and 10000 Hz etc. [9].

Therefore, this study will focus on discussing the mechanism of LIGO detection and proposing a potential solution to its limitations. Furthermore, this research will discuss the significance of detection of gravitational wave as it has not been particularly clear to the public to raise public awareness and inspire younger generations to carry on the pursuit of truth in the universe. The rest part of the paper is organized as follows, it is split into two sections, one discussing the LIGO detection method and the second investigating the significance of detection of gravitational wave. Combing the results from both sections, a final conclusion will be presented at the end of the paper.

2. Mechanism of LIGO detection method

2.1. Origin of LIGO

In 1960, Rainer Weiss proposed a thought experiment in which three test masses are sitting at the vertices of a right triangle. If beams of light are travelling along the triangle's perpendicular side, the distortion of spacetime caused by gravitational waves would produce a phase difference between beams [4-7]. This thought experiment is then turned into reality in Weiss's paper in 1972 and it is approved for construction in 1990. Now days, the construction is known as LIGO which consists of two km instruments containing three interferometers one in Livingston and the two in Washington.

2.2. Properties of Gravitational wave

As discussed previously above, gravitational wave is a fluctuation in spacetime origin from Einstein's theory of General Relativity. It is predicted that it would be generated by massive accelerating objects similar to the generation of electromagnetic wave by accelerating charges. It can be considered to be a transverse wave which distorts the space. It causes compression of space in one dimension and expansion of space in perpendicular dimension due to its quadrupolar property. As the separation between two points increases, the amount of expansion or compression increases. This particular property implies that the gravitation wave is a strain in spacetime as a strain is defined to be s a change in position divided by separation. In this paper, only the plus-polarized gravitational wave is considered [10]. Calculation of strain is explained in Fig 1. According to the graphs, the strain can be calculated using the formula h=ΔL/L. Here, L represents origin radius of the ring and ΔL represents length of distortion/displacement. The h represents gravitational wave/strain which is constant at any instant in Fig 1. From the equation provided above, a value of h can be calculated which is smaller than 10 to the power of positive 21 as following

$$\Delta L < 4 \times 10^{-18}\ metres \tag{1}$$

$$h = \frac{\Delta L}{L} < 10^{-21} \tag{2}$$

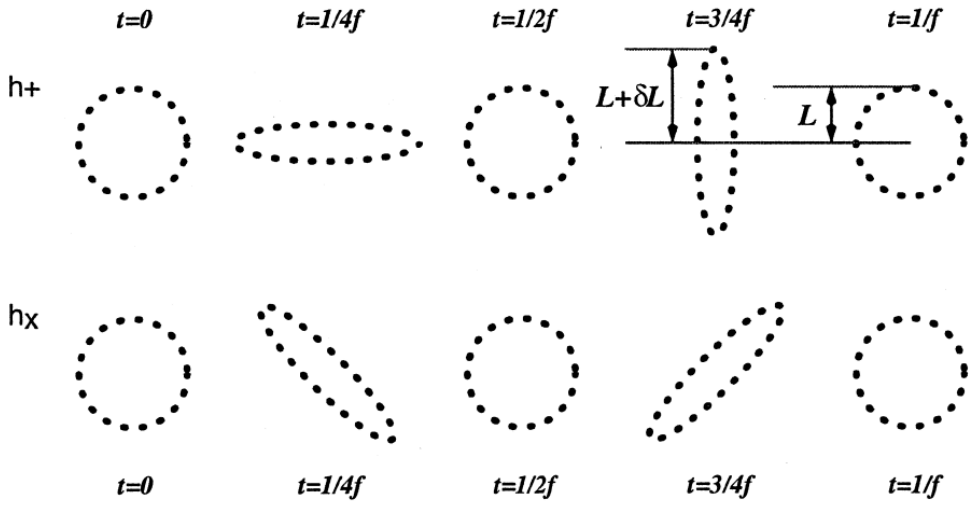


Fig. 1 The two polarizations of gravitational waves.

2.3. Principles of laser interferometer

In the Laser Interferometer Gravitational-wave Observatory, there are two laser interferometers located 3000 kilometres apart for detection of gravitational waves. As discussed previouly in the Key word sections, a LIGO interferometer is a specific type of interferometer that can measure a distance 1/10000th the width of a proton which is at the scale of 10^{-21}. To understand how this is achieved, fundamental principles of interferometers have to be discussed. Interferometers work by merging two

or more sources of light to create an interference pattern which can be measured and analysed [12]. The basic interferometer consists of a laser, a beam splitter, a series of mirrors and a photodetector which are arranged as shown in Fig. 2

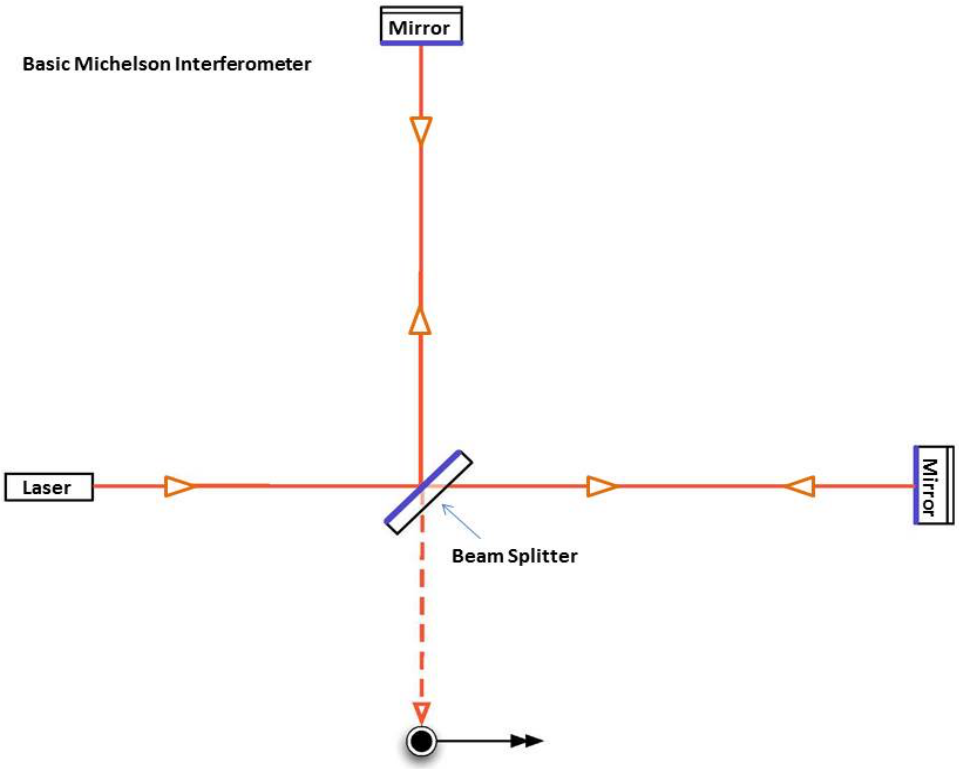


Fig. 2 Basic Michelson Laser Interferometer.

The laser is connected to the beam splitter and then to the two mirrors in large perpendicular tubes of same length. As a beam is emitted from the laser, it is split into two beams at the beam splitter, first beam is reflected in direction towards the mirror in the y axis and the reflected back from the mirror to the beam splitter. A second beam is transmitted by the beam splitter in direction to the mirror in x-axis and then reflected by a mirror at the end of the tube back to the beam splitter.

As the two reflected beam meet at the beam splitter and enter the photodetector, two results could be observed. First observation is that there is no light detected in photodetector as total destructive interference occurs if the distance travelled by both beam is same, implying that they are out of phase by one pi. Second observation being there is no light, a little light or light as bright as original laser beam detected at the photodetector as a range of interference occurs including partial destructive or constructive and total constructive or destructive interference. It occurs when the two beams travel different distances implying that they are out of sync.

Linking back to the idea of gravitational waves, it is defined as a strain in space which stretches objects in one direction and compresses them in the perpendicular direction. If gravitational wave interacts with the interferometer, more precisely the two perpendicular tubes, it would stretch the tube A in x axis by amount of 10^{-18} and compresses the tube B in y axis by same amount at an instant t1. As a result, tube A would have different length compared to tube B, consequently, the two light beams would travel different distances, become out of sync and produce a partial destructive or constructive interference when merged together. The result is that light is detected at photodetector.

However, as the gravitational wave stretches and compresses the two tubes in a periodic motion, there would be time in which tube A is compressed and tube b is stretched and time when tube A and tube B return to their normal lengths therefore the two beams shift in and out of alignment and undergoes a range of interference over time. As a result, a flicker of light is observed.

2.4. Challenges in LIGO

The basic principle of detecting gravitational wave using interferometer seems to be straightforward but there are still several problems remaining to be solved. First challenge being the degree of precision required for the interferometers. As discussed previously, the change in L caused by gravitational wave is less than 10 to the power of negative 18 which is 1/10000th the width of a proton. To be able to detect this change in length, the interferometer must have a high sensitivity. The requirement of high sensitivity leads to a second challenge which is the presence of background noise.

In order to increase sensitivity of interferometer, the effect of background noise must be reduced. Common types of background noise experienced in LIGO are quantum sensing noise, seismic, thermal and radiation-pressure noise, which could produce a flick of light in observation similar to the ones produced by gravitational wave [8]. To solve the two challenges, the LIGO interferometer has implemented some other components in the structure. In pursuit for high sensitivity, quantization imposes the most significant barrier [13]. In solution of eliminating noises, the idea of frequency bands of gravitational waves must be understood. Gravitational waves come in different frequencies, the ground-based interferometer such as the LIGO interferometer can only detect gravitational waves between 1 to 10^4 Hz.

This detection band of LIGO can be further divided into two ranges for analysis of noises. For high frequency range of LIGO's detection band (10Hz to 7000Hz), dominant source of noise is quantum fluctuations in arrive rate of detected photon. The fluctuation origin from Heisenberg's uncertainty principle as behavior of photon is unpredictable and random, resulting in a different time of arrival. To minimize the effects of different arrival time, a large number of photons has to be emitted from the laser source thus a high output power of the laser is required.

To increase output power of the laser, two mirrors are incorporated in the two tubes to reflect the light back into the system to increase the laser power from 20 kW to 100 kW. At lower frequencies (Below 150 Hz), seismic, thermal and radiation-pressure noise is the most dominant. To eliminate these type of vibrations, active and passive damping systems are implemented [14].

In active damping system, a Seismic Isolation (ISI) system Is introduced which contains sensors to detect frequencies of vibrations caused by environmental factors, then a signal is sent to a computer to generate countermotion to cancel vibrations simultaneously. It is similar to the principle of noise-cancelling headphones. In passing damping system, a 4-stage pendulum called "quad" is implemented as illustrated in Fig. 3. The reflecting mirrors are suspended at the end of four pendulums so that the vibrations not called in active damping system can be absorbed (seen from Fig. 4). In addition, due to the large mass of the mirrors, the effect of vibration is minimized according to the Law of Inertia [15].

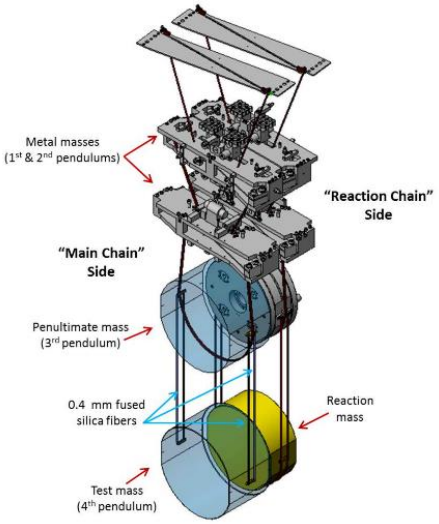


Fig. 3 4-stage pendulum system with the reflecting mirror (test mass) suspended at the end.

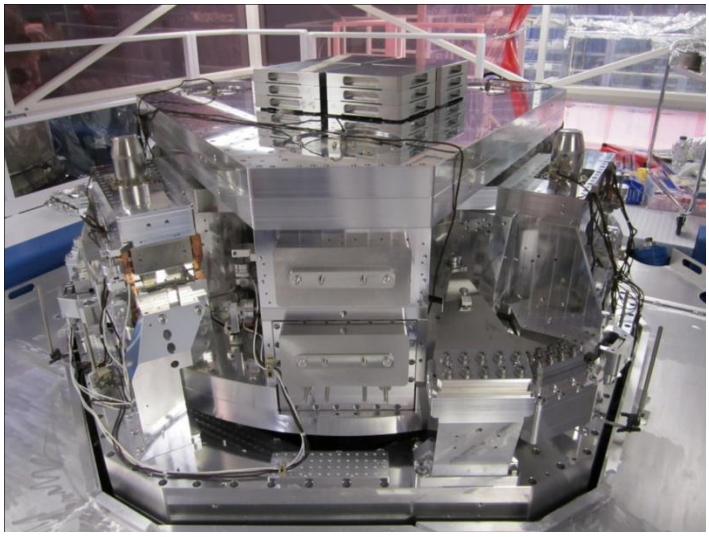


Fig. 4 The ISI system for active damping.

Besides the methods described above to eliminate noises, other conditions are established to further reduce the effect of noises hence increase the sensitivity. A vacuum environment is introduced in the tubes which has an air pressure that is one-trillionth of the air pressure at sea level [15]. One reason of implementing a vacuum environment is to eliminate the Brownian motion of air particles. The constant bombardment of mirrors by randomly moving air particles causes oscillation which leads to change in distances that two beams travel. Second reason of operating in vacuum is to prevent contact of laser or mirror with dust. When dust is present on the path of laser beam, it causes some of the beams to scatter and these scattering can be misinterpreted as flicker of light. In worse scenario, the laser will incinerate the dust and cause damage to the mirror. At last, in a vacuum environment, laser beam can be reflected many times without being absorbed to increase laser power, therefore a high sensitivity can be reached.

3. Significance of Detection of Gravitational Waves

With the understanding of the complex mechanism that LIGO use to detect gravitational wave, it is worth to know the significance of detection. As discussed previously gravitational waves are ripples in fabric of spacetime which are produced by massive, accelerating celestial bodies such as black holes. Before the detection of gravitational wave, the two primary ways of exploring the universe is by detecting electromagnetic radiation and examining subatomic particles. The EM radiation and subatomic particles are considered to be messengers of information which provide different but complementary view of the Universe.

Similar to EM radiation and subatomic particles, gravitational wave is a messenger of information from the Universe which provides new evidence that complements the analysis made by detection of EM radiation and provides addition evidence that is unable to be retrieved in form of EM radiation. For example, the collision of two black holes can only be detected by examining gravitational waves as it does not emit EM radiation as light cannot escape the gravitational pull of black hole. The other reason for detecting gravitational wave is that the gravitational wave does not interact with matter strongly. Unlike EM radiation, it travels through the Universe utterly unchanged to produce the most accurate information of the events occurred in the distant galaxies. Overall, the detection of gravitational waves symbolizes a new era in astronomy as the exploration of space can take an utterly new direction into a new world. At last, the researchers believe that the detection of gravitational waves could eventually reveal the secret of the Big Bang.

4. Conclusion

In conclusion, the structure of LIGO interferometer has been illustrated and the principle of detecting gravitational wave in LIGO has been discussed. The challenges that LIGO faces have been tackled in different angles through elimination of background noises. In the discussion on the significance of detecting gravitational wave, the gravitational wave detection method has been compared with the EM radiation detection method, the two major advantages in gravitational detection method have been listed and explained. However, more research into the analysis of gravitational wave and the assistance of gravitational wave in explaining inflation and Big Band can be carried out in future. Overall, these results offer a guideline for gravitational wave detection.

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