The Detection Scheme and Applications of Gravitational Waves

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Abstract. In recent years, gravitational waves have already attracted attention as the gateway to a new era in physics since they were first directly detected and observed. This paper summarizes the development of gravitational waves from the first proposed to the present and the main observation methods, as well as the main uses and significance of the detection of them. To be specific, in this paper, the most popular laser interferometer technique for the detection based on Michelson interferometer is discussed, and several purposes of the detection of gravitational waves are given. The detection signatures are available to adopt to the analysis of the collision of binary star systems. Gravitational radiation or primordial gravitational radiation can carry more information about black holes or the Big Bang than electromagnetic waves. The gravitational wave astronomy created by gravitational waves has opened a new horizon for astronomers to explore the universe, and the detection of them is an integral part of the future development of physics and astronomy. To sum up, these results shed light on guiding further exploration of gravitational waves detection as well as applications of them.

Keywords: Gravitational wave; detection schemes; LIGO.

1. Introduction

Gravitational wave (GW), a wave produced in an orbiting binary star system, which is a valuable piece of evidence to verify relativity. Jules Henri Poincare suggested that gravitational waves travel at the speed of light. Most famously, Einstein stated the basic concepts of gravitational waves in 1916 [1]. In the century that followed, many physicists have joined their efforts in detecting gravitational waves. In 1974, physicists from Princeton University demonstrated the existence of them by observing the orbital period decay of the first pulsing binary star system [2]. This was an indirect way to detect the existence of gravitational wave. Ggravitational wave create a new way for scientist to study the universe, provide a perspective beyond the electromagnetic wave. What's even more remarkable is that gravitational waves interact so weakly with matter, i.e., providing clear information of the universe [3].

In the 1950s, Joseph Weber attempted to design experiments to detect gravitational waves, he designed a giant aluminum rod to detect gravitational radiations when they resonated at the same frequency, the main body of the device is a solid aluminum cylinder about 3 feet in diameter, about 5 feet in length and about 3.5 tons in weight. Stick around in the middle of the cylinder on the surface of the small block is piezoelectric element, it through internal vibration produces output voltage, such as those that will be gravitational waves excited vibration [4]. However, the earth’s vibrations caused by earthquakes and weather interfered with the experiment. Make it difficult to tell whether the vibrations were caused by gravitational waves or not, and the experiment ended up with no verifiable results. Until 2015, the gravitational waves have finally been directly observed for the first time by LIGO, on September 14, 2015, at 5:51 am (ET), both LIGO labs, which located at Hanford and Livingston respectively, picked up the gravitational wave signal of two objects colliding, detected by the first activation of both labs after a five-year upgrade. This tiny change creates a typical interference in laser light [5].

The observed gravitational waves came from binary black holes, and the information carried by the radiation has led to many discoveries in astrophysics, contributed to astronomical observations, proved that black hole binaries exist and emitting gravitational radiation means that this binary merge at the current age scale of the universe. The black holes in GW150914 are the remnants of massive stars that formed in an environment with only about half the amount of elements heavier than helium in our solar system [6]. Gravitational waves have been a high-profile field of physics in recent years, this essay aimed to summarize the technique using Michelson interferometer to detect GWs, and explain how the detection of GWs applied in astrophysical, astronomical observations. This paper firstly gives an explanation of the basic principle of gravitational waves, then reviews the detection principle of Michelson interferometer, and discusses the applications as well as limitations of gravitational radiations detection.

2. Descriptions of Gravitational Wave

In general, the more mass there is in space, the more space-time is distorted by mass. In general relativity, when anything accelerates through spacetime, the accelerating object creates gravitational waves. The physical meaning of the intensity is the ratio of the distortion of space-time caused by gravitational waves to the flat space-time metric. Unlike electromagnetic waves, the transmission of GM without being affected by any obstacles, such as any types of gases or cosmic dusts. It also bends or distort space-time as the gravitational wave travel through it. This paper mainly discuss the case of linearized gravity, and define the metric perturbation in the global vacuum approaching flat spacetime [7]. By which one considers a small perturbation over a fixed Minkowski background $\eta\mu\nu \equiv \mathrm{diag}(-1,+1,+1,+1)$, one derives

$$g_{\mu v}(x) = \eta_{\mu v} + h_{\mu v}(x), \quad \left|h_{\mu v}(x)\right| \ll 1 \tag{1}$$

After a series of formula derivation, the concrete can refer to Chiara Caprini's Cosmological Backgrounds of Gravitational Waves [7]

$$G_{\mu v} \equiv R_{\mu v} - \frac{1}{2}\eta_{\mu v}R = \frac{1}{2}(\partial_\alpha \partial_\mu \bar{h}^\alpha_\mu + \partial^\alpha \partial_\mu \bar{h}_{v\alpha} - \Box\bar{h}_{\mu v} - \eta_{\mu v}\partial_\alpha \partial^\beta \bar{h}^\alpha_\beta) \tag{2}$$

$G_{\mu\nu}$ can always be written as:

$$G^{(L)}_{\mu v} = -\frac{\Box\bar{h}_{\mu v}}{2} \tag{3}$$

Gravity is the least powerful of the four fundamental forces, so gravitational waves are very weak [2]. Therefore, phenomena such as the collision of stars are not enough to observe gravitational waves, only the collision of massive binary neutron stars, black hole merger and other phenomena can radiate strong gravitational waves. These radiations carry enough energy to shift relative distances between places on Earth. And LIGO [8], a typical Michelson laser interferometer, is designed to capture these gravitational waves.

3. Detection Scheme: Laser Interferometer

Laser interferometers, similar to the Michelson interferometer used to test special relativity, are the most popular method for detecting gravitational waves. At the center of laser interferometer is a beam splitter,which extends out two light storage arms at right angles to each other and at equal distances.In order to avoid interference of experimental data caused by air molecule jitter in the cavity, the test mass of each interferometer must be placed in a vacuum, and the diameter of the vacuum pipe between the test mass of each arm is 1.2 meters [8], where a sketch is presented in Fig. 1.

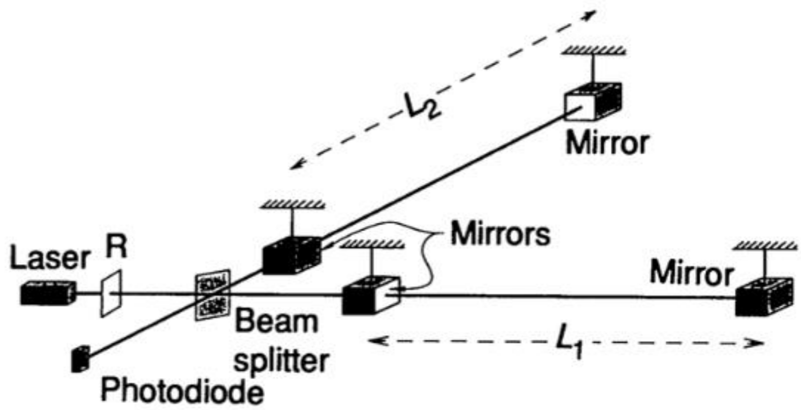

Fig. 1 The simple structure of laser interferometer.

Each of the two arms has a Fabry–Pérot interferometer [9]. For the best detection of low-frequency gravitational waves, the length of the arms of the detector should be at least tens of kilometers. However, it is not practical to build large-scale laser interferometers on Earth. Therefore, the Fabry–Pérot interferometer has solved this problem by allow light to travel back and forth in the arm to increase the effective light path, which could be understood as folding the arms of the Michelson interferometer so that the length of the folded arms can be built on the ground, also ensures high laser power in the interferometer and reduces power loss. When a laser shots the light to beam splitter, the light travels along the two arms, and when it is brought back together by reflection, the two beams interfere. When two beams are stacked, the peaks and valleys correspond, and the resulting peaks and troughs are two beams stacked together so the amplitude increases and the total wave strength is stronger. This is constructive interference. If the crests correspond to the troughs when the two beams are stacked, and the dislocation of the peaks and valleys is eliminated, the wave strength will become weak, which is destructive interference.

To effectively identify the signals detected as gravitational waves and give the location of the wave source, LIGO has two detectors in Livingston, Louisiana, and Hanford, Washington, USA. At 5:51 a.m. (EDT) on September 14, 2015, both detectors picked up signals simultaneously [10]. The confidence level was as high as 5.1 standard deviations before it was proved to be the first observation of gravitational waves. Gravitational waves travel at the speed of light, with wavelengths inversely proportional to frequency, without changing the speed of the waves. LIGO's long arms, which are four kilometers long, are sensitive to the frequency of gravitational waves emitted by the merger of binary neutron stars or black holes.

4. Applications of Detecting Gravitational Waves

Historically, scientists used to study the universe entirely by relying on electromagnetic radiation and subatomic particles passing through neutrinos. And many cosmic events, such as the collision of black holes, take place that electromagnetic waves are difficult to detect. Gravitational waves offer a perspective on such events [3]. In addition, gravitational waves can travel unhindered through long distances in the cosmos, carrying a lot of information that scientists have detected. There are several applications of gravitational waves.

4.1. Process of Massive and Supermassive Binary Black Hole

The merger of massive black holes can produce a powerful source of gravitational waves. The frequency is inversely proportional to their mass, so it's lower, but the amplitude is higher [11], and since observing black hole mergers through electromagnetic waves can provide very limited information, astronomers hope to study the process of black hole mergers and geometric information by analyzing the observed gravitational waves, and thus test general relativity. The waveforms of gravitational waves provide information for the geometry of space-time near the black hole.

4.2. Early Stage of the Big Bang

Because gravitational waves are penetrating that they pass unimpeded through the early plasma soup to record events early in the Big Bang, scientists believe there is such a "gravitational background radiation," known as the primordial gravitational wave.

4.3. Detection of Structural Matter in Neutron Stars

Detection of the gravitational radiation emitted by neutron stars, and their spectra, can be used to analyze the structure of neutron stars and the equation of state. The fundamental state of nuclear matter inside a neutron star can be detected by positive detecting gravitational waves emitted by magnetic deformations [11].

4.4. S Prove Einstein's General Theory of Relativity

As a matter of fact, GR is currently the only theory of gravity that is mathematically and physically possible, and provides a clear alternative prediction for the waveforms produced by the merger of two black holes [11] and measuring gravitational waves precisely allows scientists to test general relativity and Einstein’s equations more thoroughly. Detecting gravitational waves will also help quantum mechanics. If wave-particle duality is used to predict gravitational waves, then gravitational waves will exist as particles, gravitons. Once quantum mechanics and general relativity are combined through gravitational waves, scientists will eventually be able to achieve a grand unified theory, which would be one of the highest achievements in the history of science.

5. Limitations and Future outlooks

The first successful detection of gravitational waves on September 14, 2015 was a major scientific breakthrough. However, the laser interferometer method for detecting gravitational waves still has limitations. First, because gravitational waves are so weak, the amount of space they distort as they pass through the laser interferometer is so small that the laser beam generated by the optical path difference can only be detected by a very small change in the optical detector. Therefore, the construction of laser interferometer gravitational wave detector requires extremely high measurement accuracy, and the observatory equipment needs to be constantly updated and maintained to ensure the length accuracy of the interferometer. Secondly, the existence of noise will also affect the detection accuracy of laser interferometer. There are many types of noise, here mainly mentioned two types of noise, seismic noise and radiation pressure noise. For seismic noise, ground vibration noise is mostly generated by micro earthquake, weather, sea wave movement, industrial production and so on [12]. The ground vibration will directly cause the interferometer to move along with the ground vertically. Moreover, such ground vibration noise has the most serious impact on the interferometer in the low-frequency part and is also the most difficult to avoid. Radiation pressure noise refers to the photon moving in the interferometer arm hits the test mass surface and causes the mirror to be under pressure and change its position [13]. In case to reduce the influence of noise by laser interferometer, it is necessary to first figure out the noise source, determine the sensitivity of the detector to the noise, and then study different methods to reduce the corresponding noise source.

One way to avoid some of the noise coming from Earth is to put gravitational wave detectors into space, and LISA Pathfinder, launched in 2015, has shown that noise in space is low enough to be 100 times more than required. ESA's Laser Interferometer Space Antenna [14], a collaboration with NASA, is a laser interferometer built in space to detect gravitational waves. It is expected to launch to the Sun-Earth Lagrange point in 2037. LISA has three arms 2.5 million kilometers long, forming an equilateral triangle in space, and a long enough arm length represents the more sensitive the probe is to gravitational waves. Therefore, LISA is expected to find more low-frequency gravitational wave signals that cannot be detected by ground-based observatories, and bring new discoveries in gravitational wave astronomy. The orbit of LISA is given in Fig. 2 [15].

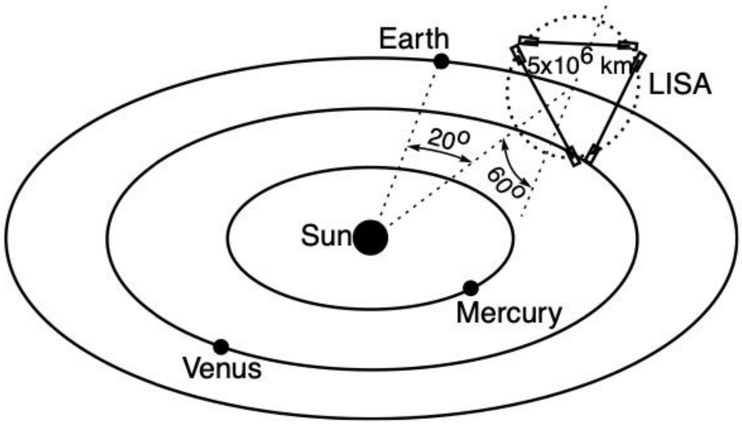

Fig. 2 The display of orbit of LISA.

There are still several other ground laser interferometers has been put into use or under construction, such as Virgo which belong to European Gravitational Observatory and had joined LIGO in 2017; The GEO600, a 600m-long laser interferometer jointly built by Germany and the United Kingdom in the south of Hanover, Germany, has been in operation since September 18, 2015. The KAGRA in Japan which has two special characteristics, First, the underground location reduces seismic noise. Second, KAGRA's test masses mirror used is sapphire, which can effectively overcome low temperature working (~20K), thus reducing thermal noise [8]. The Taiji, a China's space gravitational wave detection program similar to LISA, plans to put three satellites in earth orbit in space millions of kilometers apart. Building more gravitational-wave detectors could help verify the gravitational signals faster and more accurately. The successful detection of gravitational waves in 2015 is just a prologue to gravitational wave astronomy. In the future, scientists will be able to detect denser signals from, more diverse sources of gravitational waves, wider range of frequencies, which will help scientists study the universe in greater depth.

6. Conclusion

In summary, this paper discusses the concept of gravitational waves, the development process since it was proposed, the main detection principles and methods and instruments, and the use of gravitational waves detection. In general, take LIGO, which went into operation and detected gravitational waves for the first time, as an example. The main detection principle of gravitational waves is laser interferometer, with a Fabry–Pérot interferometer inside each arm. Using the principle of laser interference, a gravitational wave can be directly detected by disturbing the surrounding space as it passes by. The main applications of gravitational waves are to verify general relativity, and to help study the merging of binary star systems such as black holes. However, the laser interferometers needed to detect gravitational waves have a lot of noise interference effects, but these will be reduced by more methods in the future, such as building laser interferometers in space to reduce noise effectively. Gravitational wave astronomy opens up a new perspective for the observation of the universe, and the detection of gravitational waves is an indispensable path for the development of science. In the future, gravitational waves will bring scientists more new discoveries.

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