Analysis of the State-of-Art Observations for Gravitational Wave Searching

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Keywords: Gravitational Wave, Detection, LIGO, Universe Exploration.

Abstract: Gravitational wave is one of the most mysterious things in the universe. Proposed by the General Relativity, which is Einstein's theory, this kind of wave is what scholars have long wanted to detect and understand. The essence of gravitational waves is the spatiotemporal disturbance caused by mass motion, propagating at the speed of light, but difficult to detect due to their extremely low intensity. With the development of high-precision measurement technology, especially the application of laser interferometry technology, gravitational wave detection has gradually become a research focus. Gravitational wave detection not only provides new avenues for exploring the universe, but also helps reveal the origin, structure, and properties of extreme celestial bodies such as black holes and neutron stars. These results give some knowledge about gravitational wave and introduces some projects in detecting gravitational wave. There are some projects such as the LIGO, the LISA, Taiji Plan and Tianqin Plan aiming to detect gravitational wave signals.

1 INTRODUCTION

Gravitational wave is a great prediction in Einstein's general relativity, and it is a space-time disturbance caused by mass motion. It travels at the speed of light. Because of the low intensity of its light body, it is difficult to be detected. The detection of gravitational wave began in the 1960s, when Weber used his resonance mass spectrometry detector to do this experiment (Weber, 1960). The detection of gravitational wave is always an important research subject in the field of physics and astronomy, and it gradually become possible because the progress of technology, especially the development of high-precision measurement technologies such as laser interferometers. The earliest proposed gravitational wave dictation scheme in the world was the Laser Interferometric Space Antenna (LISA) program proposed by the European and American Union (ESA&NASA) in 1973 (Martens and Joffre, 2021).

The meaning of detecting gravitational wave is that it provides a brand new observation method, which will uncover so many unknown rules and phenomenon in the university. At present, the domestic and abroad program of gravitational wave detection include the LISA (Hammesfahr, 2001; Jennrich 2009) and the Tianqin program led by Sun Yat sen University (Luo et al., 2016). One can understand the universe deeper by detecting the gravitational wave, including the origin, evolution and structure of the universe, and characters of black holes and neutron stars.

After the concept of gravitational waves was proposed, scientists began to detect gravitational wave. However, because of the restrict of low technique, the early detection experiment has not made substantial progress. Until the beginning of 21 century, the detection of gravitational wave made a breakthrough. In 2015, the LIGO in the USA detected the gravitational wave for the first time. This discovery was hailed as the greatest discovery of physics in 21 century, and the discovery meant that the epoch of gravitational wave had come. After this discovery, LIGO cooperated with the VIRGO Laboratory in European and achieved a series of important results.

Although there are many achievements in detecting gravitational wave, there are still some problems in this detection. The signal of gravitational wave is so weak that it is difficult to be detected, and the detection need high precision instruments. Gravitational wave detection is an expensive project,

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Deng, S.
Analysis of the State-of-Art Observations for Gravitational Wave Searching.
DOI: 10.5220/0013074700004601

In *Proceedings of the 1st International Conference on Innovations in Applied Mathematics, Physics and Astronomy (IAMPA 2024)*, pages 264-268
ISBN: 978-989-758-722-1

which requires a significant amount of manpower, material resources and financial resources. The detection also need to solve some technical challenges including improving the sensitivity of the detector, expanding the detection frequency range, etc. These problems stimulate exploration enthusiasm and innovative spirit of scientists. With the progress of technology and deepening of research, gravitational detection will achieve a greater breakthrough in the future. As a new means and tool for exploring the universe, gravitational wave detection provides an important way for us to uncover secrets of the universe. It is believed that gravitational wave detection will bring us more surprise and discoveries with the continuous research.

The author's motivation for writing this paper mainly originated from a strong interest in exploring cosmic science and curiosity about the unknown world. The author believes that the detection of gravitational wave can promote human progress and it is an obvious evidence of the General Relativity. The structure of this paper shows as follows. In the second part, the author gives some descriptions about gravitational wave. The third part is about some principles and facilities aiming to detect the gravitational wave. The content of forth part is the state-of-art results. In the fifth part, the author introduces some limitations and prospects about this detection. The sixth part is the conclusion.

2 DESCRIPTIONS OF GRAVITATIONAL WAVE

The gravitational wave was firstly mentioned in General Relativity, and it is a type of time and space ripples caused by some huge gravitational sources. The gravitational wave propagates in the form of waves, and the speed of it is the light speed. Gravitational wave can be defined by this equation (Yang, 2023):

$$\frac{\partial^2 u}{\partial t^2} = a^2 \frac{\partial^2 u}{\partial x^2} \tag{1}$$

The generation of gravitational wave needs fast changes of mass distribution, such as the rotation, approaching or merging of binary star systems. During these processes, violent movements and changes in mass and energy generate gravitational waves that propagate at the speed of light in a vacuum. Gravitational wave barely interacts with other matters in the universe, so it is challenging to detect it. However, these slight fluctuations contain some information of their sources, such as the mass, energy and direction. This information is important to scientists, because it can help us have a deeper understand of the evolution of the universe, and they can also offer the character of some massive objects such as neutron stars and black holes. Information about gravitational wave could even uncover the secret of dark matter and dark energy.

Although detection of gravitational wave is a very difficult task, scientists have made some progress through persistent efforts and the design of sophisticated instruments. These signals make us hear the voice from deep universe. Gravitational wave is not only the confirmation of General Relativity, but also it brings the infinite possibility to do more research and update technology. With the progress of detective technology and new discovery of gravitational wave, one can further reveal characters of extreme objects. Scholars even want to use gravitational wave for cosmic navigation, find new energy sources or achieve a brand-new information transmission mode.

3 PRINCIPLE AND FACILITY FOR OBSERVATION

The principle and facility for observation of gravitational wave dictation constitute a sophisticated system. This system is designed to capture and study the tiny space-time perturbations created by the accelerating motion of massive objects in the universe. Detailed introduction of principle and facility for observation are discussed as following.

Gravitational wave can cause tiny transformation, and this transformation can be detected by precise equipment. The basic principle of gravitational wave detection is influence on the two remote parts of the detector. When gravitational waves pass by, the plane perpendicular to them will be in a state of continuous stretching and shrinking, that is, longitudinal stretching when transverse contraction, and longitudinal contraction when transverse stretching. This kind of transformation will lead to tiny change between these two parts of detector, and then the detector sends signals to researchers. By measuring this transformation, one can indirectly know gravitational wave is here.

The most used detective facility is the Laser Interferometric Gravitational-Wave Observatory (LIGO). LIGO consists of two detectors located thousands of kilometres apart, and each detector contains two laser interferometers perpendicular to each other. Laser beam is sent to two interferometers and then reflected. When gravitational wave gets through this detector, it will cause the phase of the laser to change. One can determine the existence and character of gravitational wave via this phase change. To increase the sensitivity of detector, LIGO uses highly stable optical and mechanical systems, and it is in a place that keeps away from cities and other man-made disturbance. LIGO also need numerous data processing and analysis to extract real signal of gravitational wave from the noise. LIGO-Virgo reduces the distance and position of GW170817 to 40±8Mpc, which is approximately 30deg2 in the sky (Collaboration and Aasi 2015; Acernese et al. 2015). Except for the LIGO, there are some other gravitational detectors under construction and operation. The Laser Interferometer Space Antenna (LISA) plans to use the Interferometer network consisted of man-made satellites to conduct long-distance detection. LISA's telescope research team conducted index analysis and decomposition of the telescope (Livas and Sankar, 2016; Sankar and Livas 2014; Livas and Sankar 2015). What is more, there are still some gravitational wave detection methods based on pulsar time difference and astronomical observations are also being studied. These methods are based on different principles and technologies, and these methods detect the gravitational wave indirectly by measuring the interaction between this kind of wave and the substance.

In conclusion, the principle of gravitational wave detection is measuring the effect of gravitational waves on the space between two distant positions, and using sophisticated detectors to capture this kind of tiny changes.

4 STAET-OF-ART RESULTS

The most advanced gravitational wave detections are reflected in multiple aspects, and these detections not only deepen the understanding of cosmology, but they also promote the rapid development of related detection technologies. In the field of gravitational wave detection, scientists have achieved unprecedented precision and sensitivity. The Taiji plan adopts laser interference method, which establishes connections between satellites through lasers. When the gravitational wave signals pass through the detector, these signals will cause temporal and spatial bending, thereby changing the distance of the beam transmitted between the two measurement points. By using a high-precision laser interferometer to read out this distance change, the inversion of gravitational wave signals can be achieved (Luo, et al. 2020; Luo, et al. 2021). In the aspects of accumulation and analysis of observational data, there has been many gravitational wave detection such as LIGO and Virgo, etc. These projects have accumulated numerous observational data, and via deep analysis into these data, scientists not only have verified the prophecy of general relativity, but multiple gravitational wave sources have been discovered, which include extreme celestial phenomena such as black holes or neutron star mergers. These observational conclusions uncover the most mythical and extreme cosmological phenomena in the universe.

Table 1: Median values of the distributions of parameter estimation uncertainties for multiband BBHsa (Zhao et al. 2023).

GW detector	$\Delta\Omega_{90\%}$	σ_{dL}/d_L	σ_{Mc}/M_c	σ_η
LISA-Taiji	8.2×10^{-1}	1.1×10^{-1}	3.4×10^{-6}	5.5×10^{-3}
AMIGO	1.1×10^{-1}	7.5×10^{-2}	4.5×10^{-7}	4.7×10^{-4}
ET-CE	5.7×10^{-3}	1.8×10^{-3}	1.6×10^{-3}	2.5×10^{-3}
LT-AMIGO	5.4×10^{-1}	5.8×10^{-2}	1.5×10^{-7}	3.0×10^{-4}
LT-ET-CE	1.5×10^{-1}	1.3×10^{-3}	4.7×10^{-8}	1.5×10^{-4}
AMIGO-ET-CE	4.9×10^{-4}	1.1×10^{-3}	2.4×10^{-7}	7.9×10^{-5}
LT-AMIGO-ET-CE	4.6×10^{-5}	1.1×10^{-3}	2.9×10^{-8}	6.1×10^{-5}

Scientists have successfully captured multiple important gravitational wave by using the most advanced gravitational wave detector. The LIGO-Virgo team observed a gravitational wave signal from the merger of two black holes named GW190412. This signal has extremely high scientific value, and it shows the powerful abilities of gravitational wave detector when it is measuring a complex cosmological phenomenon. By analysing this signal, scientists could measure some cosmological characters of the black hole system, such as distance, mass, distribution and rotating speed, etc. As can be seen from the Table 1, the Space Gravitational Wave Detector Network (LT AMIGO-ET-CE) of LISA, Taiji, AMIGO, ET, and CE can improve parameter estimation accuracy by two orders of magnitude (Zhao et al. 2023).

With the continuous advancement of detection technology and improvement of data processing capabilities, scientists are gradually uncover the mystery of gravitational wave universe. Future projects of gravitational wave detection will more concentrate on the collaborative development of multi band and multi messenger astronomy. By combining data from different wave bands, astrophysical processes in the universe will be understanded more comprehensively, which will offer a deeper and comprehensive cosmology for humans, and will promote further development of disciplines such as astronomy and physics.

To sum up, the most advanced consequences of detection of gravitational wave are reflected in the breakthroughs in detection technology, accumulation and analysis of observative data and capture of important gravitational wave signals, etc. These consequences not only deepen understanding of human, but they also offer valuable data and theoretical support for scientific researches in the future.

5 LIMITATIONS AND PROSPECTS

In the journey of exploring the profound mysteries of the universe, as a unique and powerful observation method, gravitational waves have been attracting endless exploration of scientists since the General Relativity was proposed. However, the road of detecting gravitational wave is not flat. Gravitational wave, which is the tiniest fluctuation in the universe, is difficult to be detected. The intensity of gravitational waves is extremely low. Even the most intense celestial events such as black hole collision or neutron star merger occurring in the universe, the gravitational wave signals that produced by these events are almost negligible when they reach Earth. The tiny characteristic make the detector of gravitational wave must have extremely high sensitivity and accuracy, with which the detector could capture signals from the deep universe. What is more, there are obvious limitations on underground gravitational wave detection. Nowadays, ground-based detectors such as the LIGO located in the United States mainly rely on high-precision laser interferometry technology to detect gravitational waves. Limited by ground noise and experimental scale, these detectors can only measure high frequency gravitational signal, but these detectors cannot touch the richer mid to low frequency range. Gravitational waves in the mid to low frequency range usually contain deeper and more meaningful cosmological and physical principles, but these waves are difficult to be captured by existing technology.

The interaction between gravitational waves and matters is so tiny that gravitational waves can penetrate almost any substance without loss, but this character makes the detection of gravitational wave more difficult. To solve these problems, scientists must improve the accuracy and sensitivity of detectors. In the Taiji Plan, The Institute of Mechanics of the Chinese Academy of Sciences and other core participating units have made major breakthroughs in pico laser interferometry technology, high-precision weak force measurement technology and other aspects, built a nano radian laser capture and tracking integrated ground simulation system, and developed the first photoviscous interferometer prototype in China (Luo, et al. 2020; Luo, et al. 2021). Detection of gravitational wave will uncover more secretes from the universe. Extreme celestial bodies such as black holes and neutron stars are important resources of gravitational wave. By detecting gravitational wave signals generated by these celestial bodies, scientists can gain a deeper understanding of the internal structure and motion patterns of these celestial bodies, thereby revealing the most fundamental physical laws in the universe.

The development of gravitational wave detection technology will drive common progress in relative field. The application of laser interferometry technology, high-precision measurement technology, etc. in gravitational wave dictation, not only promotes development of these technologies themselves, but it also offers vital technology support and reference for other scientific fields. This interdisciplinary integration and interaction will inject new vitality into scientific research and technological development

6 CONCLUSIONS

The gradual promotion of gravitational wave detection means that human understanding the deep structure of the universe reached an unprecedented level. From the theoretical argumentation to experimental verification, this process not only shows the hardship and glory in scientific exploration, but also it shows the power of interdisciplinary collaboration and technological innovation.

With the application of advanced detection technologies such as high precision laser interferometer and pulsar timing array (PTA), scientists successfully captured gravitational wave signals from the deep universe. These signals carry valuable information about the merger of dense binary systems, and uncover some important events in the early universe. In terms of detection technology, laser interferometry plays a crucial role in gravitational detection due to its extremely high sensitivity and accuracy. The successful operation of detectors such as the LIGO confirmed the existence of gravitational wave, and it also offered scientists some new ways to do some research on extreme astrophysical phenomena. As an emerging detection method, the PTA makes scientists detect the persistent gravitational wave background in the universe because this method has a unique ultralow frequency detection capability, which further broadens the perspective of gravitational wave research.

The success of gravitational detection is not only an important confirmation to the General Relativity, but this success also brings new chances and challenges for cosmology and physics. Gravitational wave detection makes scientists explore the mysteries of the universe in an unprecedented way, uncover physical characters of extreme celestial bodies such as black holes and neutron stars, and find the evolution process in the early universe. As a unique information carrier in the universe, its propagation characteristics enable us to penetrate the obstruction of interstellar media to obtain information which cannot be transferred by electromagnetic waves. These characteristics offer new perspective and tools to cosmological researches. With the promotion of detection technologies, a brand new age of astronomy will be opened up. More advanced detectors will detect weaker and father gravitational wave signals, and these detectors will uncover more secretes about the universe. These detections will promote the deep researches in basic physics, the understanding of the structure of spacetime, the essence of gravity, and other related issues.

In conclusion, the development and application in technology of gravitational wave detection is the crystallization of human wisdom and innovative spirit. The detection not only reveals deep secretes of the universe for us, but it also injects new vitality and motivation to cosmology and physics.

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