DOI: 10.54254/2753-8818/9/20240783

# Application of gravitational wave detection technology in astronomical observations

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**Abstract.** Gravitational waves are waves that propagate through space and time due to the interaction of gravity, representing a completely new physical phenomenon. This article reviews the background and issues of gravitational wave detection, with a focus on the progress of interdisciplinary research. It was not until 2015 that researchers successfully detected gravitational waves for the first time, capturing gravitational wave signals from the merger of two black holes using laser interferometry technology. This breakthrough confirms the predictions of Einstein's general relativity and opens a new chapter in the study of gravitational waves. Gravitational wave detection technology not only provides a new way to observe the universe, but also provides clues for studying the mysteries of the universe such as black holes, dark matter, and dark energy. Gravity wave detection technology also has potential communication application prospects, such as quantum gravity communication and long-distance communication, which brings new possibilities for future communication technology. In the future, there expects to be more success of gravitational wave detection and the continuous contribution of gravitational wave research in unlocking the mysteries of the universe and advancing the forefront of science.

**Keywords:** Gravitational Wave, Black Hole, Dark Matter, Dark Energy.

## 1. Introduction

General relativity is the theoretical basis of the expanding universe model of modern cosmology, which was proposed by Einstein in 1915. General relativity explains gravity as the result of matter and energy bending spacetime, and objects move along this curved spacetime path, called a geodesic. This curvature creates what is known as a gravitational effect, where the "gravitational pull" an object experiences is actually due to the object's motion through curved spacetime. The general theory of relativity successfully explains many celestial phenomena and also predicts gravitational waves. American scientists made an announcement on February 11, 2016, revealing their ground-breaking detection of gravitational waves in September 2015. They achieved this feat using the Laser Interferometer Gravitational-Wave Observatory. These researchers explained that when two black holes merged approximately 1.3 billion years ago, the resulting disturbance generated by the colossal masses' combination reached Earth on September 14, 2015. This event was then identified through advanced Earth-based instruments. Confirming a prediction made by Einstein 100 years ago. Gravitational waves represent a significant consequence of Einstein's general theory of relativity, which represent a completely new physical phenomenon and provide a new perspective for understanding of gravity and

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the structure of space-time in the universe. Gravitational waves are fluctuations that propagate through spacetime due to gravitational interactions. The way they propagate is through the expansion and contraction of spacetime itself. For example, two neutron stars merge, and their motion will cause disturbances in the surrounding space-time, which are like ripples that propagate outward. These fluctuations cause changes in the geometry of space-time, and this change propagates out in the form of gravitational waves. This propagation is similar to how sound waves travel through air, but gravitational waves travel through the curvature of space-time itself.

The detection of gravitational waves is of great significance to both astronomy and physics. First, gravitational waves provide a completely new way of observing celestial bodies. The traditional observation methods of human beings mainly relied on electromagnetic waves, such as visible light and radio waves, while gravitational waves provide an observation method independent of electromagnetic waves, which can break through obstacles that electromagnetic waves cannot penetrate, such as the interior of black holes. By observing gravitational waves, scientists can study the properties and behaviours of extreme celestial bodies such as black holes and neutron stars, as well as various major events in the universe [1]. Secondly, gravitational waves also help to verify the important theory of general relativity. By precisely measuring the speed and nature of gravitational wave propagation, scientists can verify whether general relativity still holds true under extreme conditions. This helps us to better recognize the nature of the gravitational field, thereby advancing the development of physics. In order to detect gravitational waves, scientists have developed a series of sophisticated gravitational wave detectors. The most famous of these are Laser Interferometer Gravitational-Wave Observatory (LIGO) and Virgo. These detectors use laser interferometry to capture gravitational wave signals by measuring tiny vibrations in space caused by gravitational waves passing by the Earth [2].

As a result, the prediction of gravitational waves holds significant importance within the framework of general relativity, representing a completely new physical phenomenon, revealing the deep nature of space-time structure and gravity. By observing and studying gravitational waves, the mysteries of the immense universe can be better understood by human beings, verify physical theories, and carry out more research on celestial bodies and space-time. Continued developments in this field will unlock the mysteries of the universe, while providing new tools and insights.

## 2. Basic principles

From 2015 to today, scientists have developed a variety of gravitational wave detection methods. Among them, space laser interference gravitational wave detection is one of the most commonly used and successful gravitational wave detection methods at present [3]. The laser interferometer gravitational wave detector consists of two long arms, which are perpendicular to each other. Each has power cycle mirrors. The working principle of the detector is as follows: Initially, a monochromatic laser beam, carefully controlled for its frequency, is divided into two beams of equal intensity using a beam splitter. One of these beams is directed into one arm of a detector via reflection, while the other beam is directed into a perpendicular arm through another beam splitter. These two light beams travel to the far end of their respective arms, where they are reflected by mirrors before being redirected to meet at the initial beam splitter, leading to interference. When a gravitational wave passes through this setup, it induces a slight alteration in the length of one of the arms, causing a shift in the phase of the light beam within the interferometer, which is then detected [4]. In this device, assuming that the length of each arm is L, the angular frequency of light is ω0, and the path length of the light round trip is $2L$, so the phase shift caused is the formula below:

$$\varphi(\mathrm{t}) = \omega_0 \mathrm{Tr} = \frac{2}{c}\omega_0 L. \tag{1}$$

Here, Tr is the round-trip time and $c$ is the speed of light. This phase shift is constant and proportional to $L$. When a gravitational wave arrives, it affects the two arms differently – one gets longer while the other gets shorter due to its polarization. This difference in arm length changes the path the light beams take, disrupting their initial coherence for interference. This allows light to reach the photodetector,

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creating a signal. The strength of this signal depends on the difference in path length and the intensity of the gravitational waves. When the researchers detected this signal, it meant they had successfully detected gravitational waves.

## 3. Applications of gravitational wave detection

According to the current gravitational wave detection technology, scientists can conduct in-depth and multi-faceted research on various astronomical phenomena in outer space. The following article will discuss some specific applications of gravitational wave detection.

### *3.1. Applications on black holes*

As the carrier of information, gravitational waves can provide information that electromagnetic waves cannot provide. Let us observe celestial bodies and the universe through gravitational waves. The gravitational wave observations can determine the mass, spin and luminosity distance from the earth of these binary black holes [5]. According to Einstein's general theory of relativity, mass and energy cause space-time curvature, and objects moving in curved space-time will generate gravitational waves. For a black hole, it is extremely curved space-time would cause a stronger gravitational wave signal. When two black holes merge, they produce a strong gravitational wave signal that can be picked up by gravitational wave detectors. Therefore, the detection of gravitational waves can be used to confirm the black hole merger event. At the same time, by analysing the frequency and amplitude changes of the gravitational wave signal, scientists can measure the mass and spin of the black hole. This provides important clues for understanding the formation mechanism and evolution of black holes.

The frequency, amplitude and shape of the gravitational wave signal all contain information about the black hole. The observed gravitational wave signal usually appears as a tone with gradually increasing frequency, which is due to the high-speed rotation of the black hole merger. Therefore, the mass of the black hole can be deduced from the frequency of the gravitational wave signal. In a gravitational wave merger event, the mass of the black holes is related to the total mass after the merger and the ratio of the two black holes' masses. By analysing the frequency evolution of the gravitational wave signal, the masses of the two black holes before the merger can also be deduced [6].

A black hole's spin describes how it spins, similar to the rotation produced by the Earth's rotation. The spin can be divided into two directions: positive spin and negative spin, corresponding to the cases where the spin axis of the black hole is consistent with the direction of motion orbit and opposite respectively. The shape of the gravitational wave pattern carries clues about the black hole's rotation. This rotation influences the gravitational wave's frequency, phase, and overall shape. Through the examination of these aspects in the gravitational wave signal, scientists can make estimates regarding the black hole's degree of spin.

The validity of the previously mentioned application was demonstrated through the actual event known as GW150914. In 2015, LIGO made its inaugural detection of a gravitational wave signal. This signal originated from the collision and merger of two black holes, each approximately 30 times the mass of the sun. This event was given the name GW150914. By analysing the gravitational wave signal, scientists obtained key parameters such as the mass and spin of the black hole merger event [7]. Observations of GW150914 confirmed the existence of black hole mergers and provided important information about the black hole's mass and spin. This also verifies the potential value of gravitational wave detection technology in the study of black holes.

### *3.2. Applications on dark energy and dark matter*

Being a revolutionary scientific tool, gravitational wave detection technology not only brings new breakthroughs to astrophysics, but also has important significance in the study of dark energy and dark matter in the cosmos.

Dark matter and dark energy are unknown energies and matter that make up about 95 percent of the universe. The relationship between gravitational waves and dark energy together with dark matter is that the space-time curvature of gravitational wave propagation is affected by all matter and energy,

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including dark matter and dark energy. Therefore, by observing gravitational wave signals, one can indirectly understand the nature of these mysterious components in the universe.

Dark matter does not interact with light, so it cannot be directly detected by traditional electromagnetic wave observation methods. Gravitational waves can be affected by dark matter through the curvature of space-time that propagates [8]. Because the distribution of dark matter will affect the propagation path and speed of the gravitational wave signal, thus leaving traces in the gravitational wave detection. By analysing the signals from multiple directions observed by gravitational wave detectors, scientists can study the distribution of dark matter in different locations, and similarly, they can also find dark matter with abnormal distribution.

Dark energy is the driver of the accelerating expansion of the universe, but its nature remains a mystery. The propagation speed and trajectory of gravitational waves are affected by the curvature of space-time, and dark energy will affect the curvature of space-time. By observing the propagation of gravitational waves, one can indirectly understand the influence of dark energy on space-time. Gravitational wave observers can capture gravitational wave signals of different frequencies, and these signals can be used to measure changes in the propagation speed of gravitational waves. By comparing signals at different frequencies, scientists can explore whether dark energy affects the speed of gravitational waves [9]. Therefore, researchers can comprehend the involvement of dark energy in the universe's expansion.

### *3.3. Application on communication*

The application of gravitational wave detection technology in the field of communication is a novel and potential field, although it is still in the research and exploration stage, it has aroused people's interest.

Gravitational wave detection technology can provide a new communication channel for quantum communication. Since the propagation of gravitational waves is subject to the curvature of space-time, quantum gravitational communication can use the change of the propagation path of gravitational waves to realize the encoding and transmission of communication signals. This approach may increase the security and reliability of communication, because changes in the propagation path of gravitational waves are difficult to eavesdrop and interfere.

Gravitational wave propagation is not limited by the propagation of electromagnetic waves, so it can theoretically be used to achieve long-distance communication. Gravitational waves can pass through most substances, such as planets, stars, etc., without being affected by them, so as to realize communication across large distances in the universe [10].

Gravitational wave detection technology can be used to monitor natural disasters or environmental changes. By observing changes in gravitational wave signals, crustal movement, seismic activity, etc. can be monitored in real time, and early warning signals can be issued in advance, thereby helping to reduce losses.

### *3.4. Ongoing Problems*

There are also certain problems in the detection of gravitational waves. In a space interferometer, the relative orbital motion between the satellites causes the length of the interfering arms to vary, resulting in unequal lengths between the interfering arms. The instability noise of the laser frequency is considered to be an important noise source in the laser interferometer, and its size is proportional to the jitter degree of the laser frequency and the length difference of the interference arm [10]. But noise will affect and reduce the accuracy and sensitivity of gravitational wave detection. Therefore, in order to reduce laser noise, the length of the two arms of the interferometer should be precisely controlled to reduce the difference and improve the accuracy of detection.

## 4. Conclusion

Gravitational wave technology represents a significant development in the field of modern science, which has deeply influenced multiple fields such as astronomy, physics, and communication technology. By analysing the frequency evolution and waveform of gravitational wave signals, scientists can measure the mass and spin of black holes, providing new clues for studying the formation mechanism, evolution process, and interaction with other celestial bodies of black holes. With the continuous progress of gravitational wave detection technology, people are expected to delve deeper into the mysteries of black holes in the future. In addition, gravitational wave technology has provided us with a new tool to explore the field of dark matter and dark energy at presence in the cosmos, which account for the vast majority of energy and matter in the universe, but are still full of mysteries to this day. The study of gravitational waves can indirectly understand their properties and distribution, thereby better understanding the evolution of the universe. In the field of communication, gravitational wave technology also has potential application prospects, including quantum gravity communication and long-distance communication, which bring new possibilities for future communication technology. Despite the technological challenges faced by gravitational wave research, such as laser noise suppression and interference management, this field still has enormous potential and will continue to drive the forefront of science, providing new opportunities for humans to reveal the mysteries of the universe and verify physical theories. The rapid development of gravitational wave science will continuously deepen people's understanding of the universe and nature, laying a solid foundation for future exploration and innovation.

**References**

[1] Zhao Wen, Zhang Xing, Liu Xiaojin, et al. (2017). Gravitational waves and sources of gravitational waves. Progress in Astronomy, 35(3), 316-344.
[2] David Shoemaker. (2020). Gravitational wave astronomy with LIGO and similar detectors in the next decade. Asto2020 Science White Paper, 51(3).
[3] Wang Yunyong, Zhu Xingjiang, Liu Jian, et al. (2014). Laser Interferometer Gravitational Wave Detector. Progress in Astronomy, 32(3), 348-382.
[4] Wang Zhi, Sha Wei, Chen Zhe, et al. (2018). Preliminary design and analysis of telescope for space gravitational wave detection. Chinese Optics, 11(1), 131-151
[5] Cao Zhoujian. (2018). From gravitational wave detection to multi-messenger astronomy including gravitational waves. College Physics, 37(2), 10.
[6] Zhou, Yu. (2021). Gravitational wave detector discovers the strongest black hole merger event so far. Science News, 023(S01), 30-30.
[7] Zhang Yifang. (2019). The verification of gravitational waves on general relativity and eight possible tests of negative matter as a unified dark matter-dark energy. Journal of Yunnan University: Natural Sciences Edition, 42(2), 285-290
[8] Zhang Yifang. (2019). The verification of gravitational waves on general relativity and eight possible tests of negative matter as a unified dark matter-dark energy. Journal of Yunnan University: Natural Sciences Edition, 41(2), 285-290.
[9] Zhang Xin. (2019). Research progress in dark energy cosmology. Journal of Liaoning University: Natural Sciences Edition, 46(2), 97-108.
[10] Liu Heshan, Gao Ruihong, Luo Ziren, et al. (2019). Absolute distance measurement and communication technology in space gravitational wave detection. China Optics, 12(3), 486-492.