Analysis the Principle and State-of-Art Observations for Gravitational Waves

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Abstract: Gravitational wave searching is one of the key issues for astrophysics. This study provides a comprehensive exploration of the fundamental principles of gravitational waves, detection techniques, and their applications in astrophysics, with an in-depth outlook on future research directions and technological advancements. The article first analyzes the theoretical foundation of gravitational waves, tracing their origin in general relativity and detailing the diverse gravitational waves, including compact binary coalescence, unpredictable, continuous, and burst gravitational waves. It then delves into the working principles and technological challenges of detection systems for gravitational waves, like LIGO and Virgo, focusing on the various noise sources that affect detector sensitivity within the 10 Hz to 10 kHz frequency range. The article also summarizes significant gravitational wave detection events, such as GW150914, and discusses their profound significance for astrophysical research. The introduction of deep learning technologies, such as convolutional neural networks, is anticipated to further optimize the identification and classification of gravitational wave signals, providing more powerful tools for astrophysical research.

1 INTRODUCTION

In 1916, the renowned physicist Einstein published a groundbreaking paper on general relativity. He concluded that only the third type of wave carries energy, because the condition precisely eliminates the existence of waves that cannot carry energy. Through exchanges and cooperation with De Sitter, Nordström, and Schrödinger, Einstein discovered a mathematical error in his derivation and abandoned the coordinate condition. This led to the identification of two types of waves: longitudinal and transverse waves. Although longitudinal waves do not carry energy, they can still be considered as apparent entities without using single-mode coordinates, because in a field-free system (flat Minkowski metric), longitudinal waves can be eliminated through coordinate transformations. Ultimately, Einstein discovered plane transverse gravitational waves (Weinstein, 2016). In 2015, the Laser Interferometer Gravitational-Wave Observatory (LIGO) used two advanced detectors, i.e., H1 in Hanford, Washington, and L1 in Livingston, Louisiana, to observe gravitational wave signals. This observation is considered the beginning of the era of gravitational wave astronomy. The most convincing discovery was the event GW150914 (the fusion of two black holes). It was the result of LIGO's use of Optical resonators that are coupled together to enhance the sensitivity of interferometer transducers (Abbott, et al., 2016).

Gravitational waves have become a new tool for exploring the universe. In the study of dark matter (DM) and primordial black holes (PBHs), impact of gravitational lensing on gravitational waves signals can cause deflection, amplification, or time delay. This allows for the distinction between dressed primordial black holes and ordinary primordial black holes by studying the distribution of dark matter around primordial black holes (Lin, et al., 2025). Gravitational waves are often produced by binary mergers and are observed through a network of cutting-edge gravitational wave detection systems. The first type of gravitational wave is called ground-based gravitational wave. LIGO and Virgo have collaborated on the observation of ground-based gravitational waves. For example, during the first observation run (O1) from September 12, 2015, to January 19, 2016, Advanced LIGO detected gravitational waves resulting from three binary black hole combinations. From November 30, 2016, to August 25, 2017, Advanced LIGO conducted O2. On August 1, 2017, Advanced Virgo also began

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observing gravitational waves. Improvements were made to the gravitational wave detectors at different stages of observation to enhance sensitivity and reduce scattered light noise (Abbott, et al., 2019). The second type of gravitational wave is called space-based gravitational wave. On December 3, 2015, the European Space Agency launched the LISA Pathfinder (LPF) to demonstrate the end-to-end free fall of test masses (TMs), laying the experimental foundation for future space-based gravitational wave (GW) observatories like LISA (Armano, et al., 2016).

This paper aims to analyse the fundamental principles of gravitational waves and the description and understanding of gravitational wave observations. Subsequent sections will cover the definition and principles of gravitational wave generation, gravitational wave detection devices and their principles, recent observational results and phenomena, current limitations in gravitational wave research, and future prospects.

2 DESCRIPTIONS OF GRAVITATIONAL WAVE

First, one can understand the basic properties of gravitational waves by introducing the fundamentals of gravitational waves in linearized gravity. To make the situation more realistic, one needs to first study the globally vacuum spacetime, where the two polarization components of gravitational waves are reflected by the transverse-traceless gauge. These two components can be regarded as two independent waveforms (seen from Fig. 1) (Flanagan & Hughes, 2005).

Subsequently, one considers the definition of gravitational waves in a finite region of spacetime. Although gravitational waves cannot be distinguished from the time-varying near-zone fields produced by external sources in a finite region, they can be approximately defined when the wavelength of the gravitational wave is much smaller than the characteristic length of the background metric.

Next, one will further understand the types of gravitational waves from the perspective of their origins. The first type is compact binary coalescence gravitational waves, which are produced due to the merger of binary stars. Specifically, after rotating for a certain period, the two stars will merge, during which gravitational waves are generated. The second type is stochastic gravitational waves, which produce a relatively weak gravitational wave signal. This signal has no specific waveform and is difficult to detect. The name originates from the randomness of its waveform. The third type is continuous gravitational waves, which are generated by the rotation of a compact massive object, such as a neutron star. Due to the asymmetry of the massive object, the rotation of the massive object produces gravitational waves carrying weak energy. The fourth type is burst gravitational waves. The gravitational wave signal is difficult to detect due to modelling difficulties, which are due to the origin of burst gravitational waves: the non-spherical collapse of a star (Ray, et al., 2024).

To better understand gravitational waves and their characteristics, one compares them with electromagnetic waves (though there are essential differences between the two). First, both have wave-like properties: electromagnetic waves are vibrations of the electromagnetic field in spacetime while gravitational waves are tiny propagating ripples in the curvature of spacetime itself. The main difference lies in the ease of detection; gravitational waves are difficult to detect, while electromagnetic waves are relatively easy. Second, gravitational radiation is primarily produced by the collective motion and mutual interference of macroscopic masses, i.e., celestial bodies in the universe, microscopic charge motion is responsible for generating electromagnetic waves, forming incoherent superpositions of waves with a dipole structure in the wave zone.

Similarly, the interaction of electromagnetic waves with matter is significant, whereas gravitational waves propagate freely in the universe. The ratio of wavelength to source size is exactly the opposite for the two, which also leads to the fact that electromagnetic waves can be used for imaging, while gravitational waves cannot. Therefore, based on these differences, it can be found that the two also complement information about astrophysical sources, which can provide effective methods for subsequent astronomical research (Le Tiec & Novak, 2017).

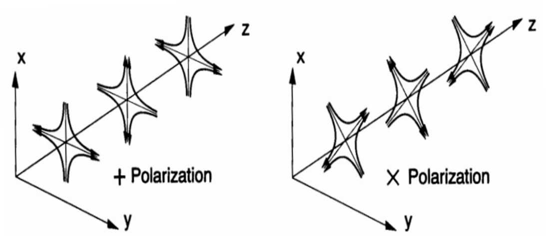

Figure 1: Lines of force for a purely + GW (left), and for a purely x GW (right)Figure kindly provided by Kip Thorne (Flanagan & Hughes, 2005).

3 PRINCIPLES AND FACILITIES

Wave Observatory (LIGO) has achieved a significant breakthrough in the field of gravitational wave detection, especially with the first direct detection of the gravitational wave event GW150914. This detection was made possible by the two advanced detectors, LIGO and Virgo, which began observations from September 2015 to August 2017. Let's delve into the LIGO detectors. LIGO detectors utilize Michelson interferometers, which rely on changes in the phase of light to indirectly measure the strain amplitude of gravitational waves. The test masses (mirrors) within the detectors are designed to be in a state of "free fall," allowing them to respond freely to the minute displacements caused by gravitational waves without being affected by other environmental interferences.

Overall, LIGO detectors exhibit high sensitivity, particularly in the frequency range of 100 to 300 Hz. This good broadband response is beneficial for measuring astrophysical sources of different masses. The simultaneous observation by two detectors compensates for the directional sensitivity deficiency of the interferometers and enhances the ability to locate signals. The LIGO detectors ingeniously isolate the test masses from ground vibrations. The increased circulating laser power makes quantum noise controllable. The use of optical resonators in the detectors enhances signal strength and the measurable range of signals. Thus, it is not difficult to understand the principle of gravitational wave detectors, which convert spacetime perturbations into measurable signals. The introduction and process of LIGO and Virgo detectors are as follows: The LIGO data sampling rate is 16, 384 Hz, while the Virgo data sampling rate is 20 kHz. Calibration is required to convert the interferometer photodiode output into strain data. The detectors record hundreds of thousands of auxiliary channels. Fourier domain analysis is used for LIGO-Virgo data. Fast Fourier Transform (FFT) is employed to convert time-domain data into frequency-domain data. Subsequently, Tukey window functions are applied to reduce spectral leakage. The data is then whitened and finally bandpass filtered to enhance signals in specific frequency bands. Non-stationarity can occur in the data, and one needs to assess the non-stationarity of the data using wavelet transforms and discrete wavelet packet transforms as given in Fig. 2 (Abbott, et al., 2020). The physical parameters of gravitational waves can be estimated using Bayesian theorem, Markov Chain Monte Carlo (MCMC), and nested sampling algorithms, while the waveform can be determined using numerical relativity waveform models (Abbott, et al., 2020).

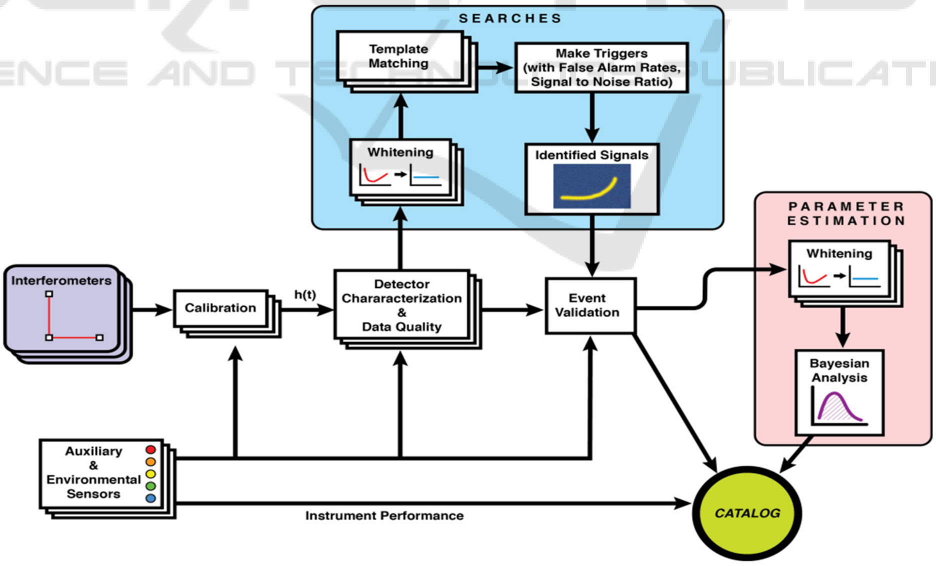

Figure 2: A sketch of the searching process (Abbott, et al., 2020).

4 STATE-OF-ART OBSERVATIONS

Since the LIGO-Virgo Collaboration (LVC) reported the gravitational wave detection results from the O1 and O2 phases, including the highly significant event GW150914, numerous research institutions and scholars have conducted multiple gravitational wave detections in recent years. One will now introduce each of the gravitational wave detection events and their attributes one by one.The first event is GW170121. As the most confident newly discovered binary black hole merger event, it has a probability of astrophysical origin exceeding 0.99, which almost certainly indicates that it is a genuine astrophysical event. The event's inverse false alarm rate (IFAR) is approximately 2.8×10^3, signifying that the expected frequency of similar signals generated solely by noise under similar observational conditions is extremely low.

The second and third events are GW170304 and GW170727. Both are newly discovered events with high confidence levels, each with an astrophysical origin probability close to 0.98. This suggests a high likelihood that they are of astrophysical origin. The IFAR values of these two events are similar, both around 370 O2, indicating their high significance against the noise background. The fourth event is GW170425. With a probability of around 0.77 for astrophysical origin and an IFAR of approximately 29 O2, GW170425 is a newly discovered event with a moderate confidence level. Although its confidence level is slightly lower than the aforementioned events, it still has a relatively high probability of being an astrophysical event. The fifth event is GW170202. This event has a probability of astrophysical origin of about 0.7 and an IFAR of around 6 O2 (Schmidt, 2020). It is a candidate event with a certain level of confidence. Among all the newly discovered events, it is at a medium confidence level, yet it still has a high probability of being an astrophysical event. The sixth event is GW170403. As a candidate event close to the detection threshold, GW170403 has a probability of about 0.55 for being of astrophysical origin, with an IFAR of roughly 5 in O2. Although its confidence level is relatively low, it still has a certain probability of being an astrophysical event and is worth further investigation (Venumadhav, et al., 2020).

5 LIMITATIONS AND PROSPECTS

Noise sources in the frequency range of 10 Hz to 10 kHz can interfere with the sensitivity of long-baseline interferometric detectors. These noise sources comprise fundamental noise sources (seismic noise, thermal noise from test masses, suspension systems, and coatings), as well as quantum noise. Let’s first take a specific look at seismic noise. Seismic noise (<10 Hz) is associated with periods of extreme weather (such as storms), which limits the low-frequency performance of detectors because the gravitational field of disturbances cannot be shielded. Next is suspension thermal noise, which mainly comes from two aspects: one is the mechanical dissipation inside the suspension system material, manifested as random vibrations caused by Brownian motion; the other is due to the thermodynamic properties of the suspension material, such as the thermal expansion coefficient, which causes tiny temperature fluctuations in the environment to be transferred to the system, thereby generating thermoelastic noise. The third type is mirror and coating thermal noise. Mirror thermal noise mainly comes from three mechanical loss mechanisms in the fused silica substrate: surface loss, thermoelastic loss, and bulk loss. Coating thermal noise mainly comes from the multilayer dielectric coating structure on the test mass used to achieve high reflectivity. The last one is quantum noise, which is the fundamental noise source that limits most frequencies in the LIGO detection band (Hammond, et al., 2014).

For the future, the outlook is as follows. Since the successful monitoring gravitational waves has opened up new avenues in astrophysics, one needs more advanced technology to continue detecting, and it is hoped to conduct more pulsar timing array experiments. One will also further apply CNNs to determine whether the gravitational wave signals appearing in the data stream are originating from binary black holes or binary neutron stars. Because the rate of events is much higher than astrophysical expected, one needs realistic mock data challenges (MDCs) to collect data. One needs to ensure that the results remain interpretable and that one fully understands why a given confidence level is calculated, thereby implementing two feasible machine learning methods, i.e., Logistic Regression (LR, a simple machine learning model that works by converting the input feature vector into a probability) as well as Multilayer Perceptron (MLP, multiple layers of neurons transform the input feature vector into the output probability for each prediction class) (Ashton, et al., 2025).

6 CONCLUSIONS

This article systematically analyzes the fundamental principles of gravitational waves, detection techniques, and their applications in astrophysics, and provides an in-depth outlook on future research directions and technological improvements. Specifically, the article first reviews the theoretical foundation of gravitational waves, covering their origin in general relativity and the different types of gravitational waves, including compact binary coalescence gravitational waves, stochastic gravitational waves, continuous gravitational waves, and burst gravitational waves. Next, the article provides a detailed introduction to the working principles and detection techniques of detectors such as LIGO and Virgo, focusing on the impact of noise sources in the frequency range of 10 Hz to 10 kHz (such as seismic noise, suspension thermal noise, mirror and coating thermal noise, and quantum noise) on detector sensitivity. The article also summarizes the main achievements in gravitational wave detection in recent years, such as the discovery of important events like GW150914, and discusses the significant importance of these discoveries for astrophysical research. In addition, the article explores the potential applications of gravitational waves in the study of dark matter and primordial black holes, as well as the gravitational lensing effect of gravitational wave signals. Looking to the future, with the advancement of technology and the conduct of more pulsar timing array experiments, gravitational wave detection will become more accurate and efficient. Meanwhile, the application of deep learning technologies (such as CNN) will further enhance the ability to identify and classify gravitational wave signals. Finally, the significance of the research lies in systematically summarizing the current status and challenges of gravitational wave detection, providing direction for future technological improvements and scientific research. By conducting an in-depth analysis of the properties of gravitational waves and detection techniques, this article paves new ways for astrophysical research, especially in understanding extreme astrophysical events and dark matter in the universe.

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