Acceleron Aerospace Journal || AAJ.11.2106-2466
Volume 3, Issue 6, pp (670-678)
Review Paper
E-ISSN- 2583-9942 || DOI: 10.61359/11.2106-2466

The Role of Gravitational Waves in Understanding the Cosmic Evolution and The Underlying Physics of The Universe

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Abstract: The field of gravitational wave research has rapidly evolved since the first successful detection in 2015, marking the beginning of a new era in astrophysics. This paper reviews the current state of gravitational wave detection and explores the future directions that promise to advance our understanding of the universe. We discuss the advancements and limitations of current ground- based observatories, such as LIGO and Virgo, as well as the pivotal role of upcoming third- generation detectors like the Einstein Telescope and space-based missions like LISA. Key areas of development are identified, including improvements in, cryogenic technologies, extended frequency coverage, and integration with multi-messenger astronomy. The paper also highlights innovative approaches, such as machine learning for real-time signal processing and the potential of atom interferometry for novel detection methods. this paper aims to provide insights into how the next generation of gravitational wave research will unravel new astrophysical phenomena and test the boundaries of general relativity, ultimately deepening our understanding of the cosmos.

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1. Introduction

The term “gravitational wave” was first derived from Albert Einstein's general theory of relativity in 1916. One year after developing the field equations of General Relativity, Einstein predicted the existence of gravitational waves. He observed that the linearized form of the weak-field approximation admits wave solutions, specifically transverse waves of spatial strain that propagate at the speed of light. These waves are generated by time-varying mass quadrupole moments within the source. However, Einstein also recognized that the resulting gravitational wave amplitudes would be extraordinarily small, posing a significant challenge for detection [2], [6].

Gravity is the engine behind many processes in the universe, and much of its action remains unknown. Opening a gravitational window on the universe allows us to dive deeper into its mysteries. Gravity has its own messenger—gravitational waves. These ripples in the fabric of spacetime travel at the speed of light and have opened a new window for exploring the universe. Gravitational waves interact weakly with matter and travel largely undisturbed over cosmological distances, enabling us to explore the formation of black holes, redshifts, and events prior to the epoch of cosmic reionization.

The term “gravitational” in “gravitational waves” stems from the fact that these waves result from gravitational interactions. The term "waves" reflects how these disturbances propagate outward from their source in oscillating wave patterns, much like ripples on a water surface when an object is dropped into it. The discovery of the binary pulsar system PSR B1913+16 by Hulse and Taylor, and the subsequent observation of its energy loss by Taylor and Weisberg, demonstrated the existence of gravitational waves [2]. Efforts to detect gravitational waves began with Weber and his resonant mass detectors in the 1960s, followed by an international network of cryogenic resonant detectors. Interferometric detectors were first suggested in the early 1960s and the 1970s. With further improvements, this led to the development of long-baseline broadband laser interferometers with higher

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****** Received: 05-November-2024 || Revised: 27-November-2024 || Accepted: 28-November-2024 || Published Online: 30-November-2024.

sensitivity. By the early 2000s, a set of initial detectors was completed, including TAMA 300 in Japan, GEO 600 in Germany, the Laser Interferometer Gravitational-Wave Observatory (LIGO) in the United States, and Virgo in Italy. These detectors collectively conducted joint observations from 2002 through 2011, setting upper limits on various gravitational-wave sources while evolving into a global network. In 2015, Advanced LIGO became the first of a significantly more sensitive network of advanced detectors to begin observations [4]. The first detection of gravitational waves occurred on September 14, 2015, by the LIGO detectors. The event, designated GW150914, was the result of two black holes merging approximately 1.3 billion light-years away. This groundbreaking moment in astrophysics marked the first direct observation of gravitational waves, as well as the first confirmed detection of a binary black hole merger. These breakthroughs were achieved through our initial method of exploring the universe: electromagnetic radiation, which traces the interactions of baryonic matter. However, most of the universe is invisible to electromagnetic observations. Gravitational waves enable us to see farther on astronomical scales, offering unparalleled insights into the universe. Gravitational waves, the real engine of the universe, allow us to probe deeper into the cosmos than ever before. Laser interferometry, a standard tool for such measurements, has been under development for over 30 years.

Observations of the universe through electromagnetic waves, combined with theoretical models, suggest that the most valuable portion of the gravitational wave spectrum lies within the frequency range of approximately 0.1 MHz to 100 MHz, accessible to a space-based interferometer. This frequency band provides crucial insights into binary star system formation within the Milky Way and the history of the universe, extending to redshifts around $z \approx 20$. It enables the study of gravitational forces in dynamic, strong-field regimes and phenomena at energy scales of the TeV range, relevant to the early universe. The eLISA mission will be the first to explore the entire universe using gravitational waves, advancing the scientific goal of understanding "The Gravitational Universe." The Next Gravitational Observatory (NGO), a concept studied by ESA for the L1 mission selection, serves as the reference model for the eLISA mission.

One key reason for choosing gravitational waves over electromagnetic waves to study the universe is their unique advantages, which reveal information inaccessible through traditional electromagnetic observations. Unlike electromagnetic waves, which are oscillations of the electromagnetic field propagating through spacetime, gravitational waves are oscillations of spacetime itself. While electromagnetic waves typically result from the combined emissions of individual electrons, atoms, or molecules, leading to incoherent signals, cosmic gravitational waves arise from the large-scale movement of immense masses or energy associated with oscillating, nonlinear spacetime curvature. These waves reflect highly organized, bulk motions rather than the random emissions of individual particles.

Gravitational waves interact extremely weakly with matter, allowing them to pass through dust, gas, stars, and other celestial bodies without being absorbed or scattered. Electromagnetic waves, on the other hand, can be blocked, absorbed, or scattered by matter, making it difficult to observe certain regions of space. Gravitational waves also allow us to observe events that are invisible or extremely difficult to detect with electromagnetic waves. For instance, black holes, which do not emit light and are thus invisible to electromagnetic telescopes, produce strong gravitational waves during their violent mergers, which are now detectable. Similarly, while neutron star collisions emit some electromagnetic radiation, their gravitational wave emissions provide additional insights into the dynamics of these collisions and the properties of the involved objects. Gravitational wave detections also offer opportunities to verify General Relativity, including the nature of spacetime, the propagation speed of gravity, and the behavior of gravity in the presence of massive objects. These observations probe the fundamental laws of physics in ways that electromagnetic methods cannot.

2. Detection Method

Among the gravitational wave frequency bands, there are four that are being explored experimentally:

- The high-frequency band ranging from 10^4 to 1 Hz frequency
- The low-frequency band ranging from 1 to 10^{-4} Hz frequency
- The very low-frequency band ranging from 10^{-7} to 10^{-9} Hz frequency
- The extremely low-frequency band ranging from 10^{-15} to 10^{-18} Hz frequency

High-frequency band, 1 to 10^4 Hz

The high-frequency band is the domain of earth-based gravitational wave detectors, laser interferometers, and resonant mass antennas. At frequencies below 1 Hz, Earth-based detectors face nearly overwhelming noise from fluctuating Newtonian gravity gradients and from Earth vibrations, which are extremely difficult to filter out. For one to detect waves below this frequency, a setup in space is needed [2]. Although ground-based gravitational detectors like LIGO have successfully detected numerous events, including the first black hole merger (GW150914), they are limited in detecting lower frequencies.

Low-frequency band, 10^{-4} to 1 Hz

The low-frequency band is detected in space. The most important methods for detection are Doppler tracking of spacecraft via microwave signals sent from Earth to the spacecraft and then transponded back to Earth, and optical tracking of spacecraft by each other, i.e., laser interferometry in space. Space-based interferometry is like ground-based interferometry but is implemented in space to detect lower-frequency gravitational waves that ground-based detectors are unable to detect [2]. Moreover, for space-based interferometry, there is an ongoing project named LISA (Laser Interferometer Space Antenna), a future mission led by ESA (European Space Agency) and NASA, scheduled for launch in the 2030s. LISA will consist of three spacecraft in a triangular formation.

Very low-frequency band, 10^{-7} to 10^{-9} Hz

To detect the very low-frequency band of gravitational waves, Joseph Taylor and other researchers devised a method to detect these waves using the timing of millisecond pulsars. When a gravitational wave passes over Earth, it perturbs the rate of flow of time and the ticking rates of our clocks relative to clocks outside the wave. Such perturbations show apparent fluctuations in the time of arrival of the pulsar’s pulses. If at a certain period no fluctuations are seen, we can be sure that neither Earth nor the pulsar is being affected by gravitational waves [2].

Extremely low-frequency band, 10^-15 to 10^-18 Hz

Extremely low-frequency (ELF) gravitational waves, typically in the range of 10^{-15} to 10^{-18} Hz, are generated by some of the most massive and dynamic astrophysical events in the universe, such as supermassive black hole mergers, cosmic strings, or the oscillations of neutron stars. These waves carry crucial information about their sources, providing insights into the fundamental nature of gravity and the structure of spacetime.

Other frequency bands and detection methods

Many other methods are being used to detect gravitational radiation, with different methods operating at various frequencies such as HF, LF, VLF, ELF, and others. However, none has shown anywhere near the achievement as has been demonstrated by the above-mentioned methods.

3. Working of gravitational wave detectors

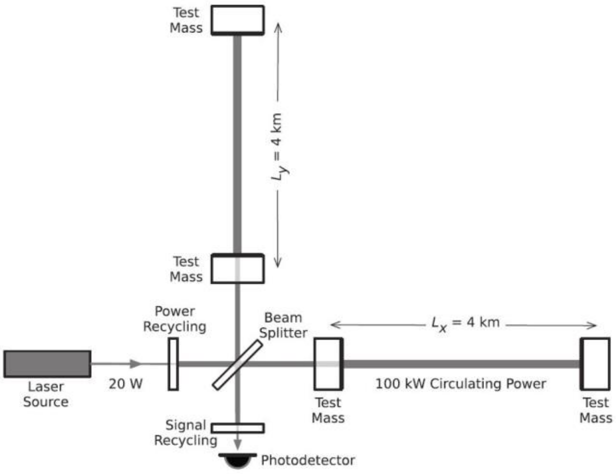

Figure-1 Schematic Diagram of a Laser Interferometer Gravitational Wave Detector [Credit: B. P. Abbott.et.al.2016]

Figure 1 provides a visual aid of the methodology proposed for this study. This study employed GMAT to simulate the orbital lifetime of rocket bodies and a Python interpolation model for lifetime prediction for user-interested configurations. The methodology comprises simulation setup, configuration of orbital parameters, and development of a Python-based 2D interpolation model to predict lifetimes at various orbital altitudes and inclinations.

Ground-Based Laser Interferometers Working

A ground-based laser interferometer works by detecting the tiny distortions in spacetime caused by passing gravitational waves. The system is based on the principle of interferometry, where laser beams are split and recombined to measure minute changes in distance. These interferometry techniques are designed to maximize the conversion of strain to optical signals, thereby minimizing the impact of photon shot noise **[1], [2]**. Gravitational wave astronomy uses multiple, widely separated detectors to differentiate gravitational waves from local instrumental and environmental noise, providing source exact coordinates and measuring wave polarization.

A laser interferometer gravitational wave detector consists of four masses that hang from vibrationally isolated supports, as shown in Fig-1, and the indicated optical system for monitoring the separation between the masses. Two masses are near each other at the corner of an L, and one mass is at the end of each of the L's long arms. The arm lengths are nearly equal: Lx = Ly = L = 4 km. When a high-frequency gravitational wave with a frequency of approximately 1 Hz passes through the detector, it pushes the masses back and forth relative to each other, thereby changing the arm length such that the measured difference is $\Delta L = L1 - L2$. This change is monitored by laser interferometry in such a way that the variation in the output of the photodiodes is directly proportional to ΔL **[1-2]**.

The laser interferometer can achieve measurement accuracies of $\Delta L = 10^{-16}$, i.e., 1/1000 the diameter of the nucleus. The key components of a ground-based laser interferometer and its working are as follows:

- **Laser:** Produces a stable light source for the interferometer.
- **Beam Splitter:** Divides the laser beam into two perpendicular arms.
- **Mirrors:** Reflect the laser beams back to the beam splitter.
- **Photodetector:** Measures the interference pattern of the recombined beams.
- **Seismic Isolation:** Suspends the mirrors to minimize environmental noise.
- **Vacuum System:** Removes air and particles that could interfere with the laser beam.

LIGO has two facilities in the U.S., one in Hanford, Washington, and the other in Livingston, Louisiana. Both works together to ensure that detected signals are genuine and not just local noise. When both observatories detect the same signal, it strongly indicates the detection of a gravitational wave. In addition, LIGO collaborates with Virgo (another interferometer in Italy) and KAGRA (in Japan) to triangulate the source of gravitational waves and improve the accuracy of detections.

Space-Based Laser Interferometer Working

eLISA (Evolved Laser Interferometer Space Antenna), now known as LISA (Laser Interferometer Space Antenna), is a future space mission by the European Space Agency (ESA) designed to detect gravitational waves—ripples in spacetime caused by massive astronomical events, such as the merger of black holes or the collision of neutron stars. Unlike ground-based observatories like LIGO, which are sensitive to higher-frequency gravitational waves, LISA will operate in space, allowing it to detect lower-frequency waves **[1]**.

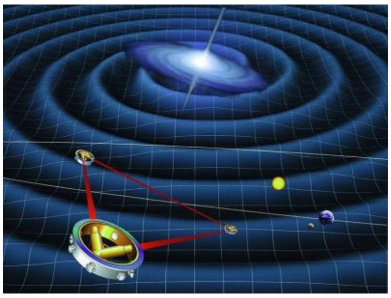

Figure-2 Schematic Diagram of Space Based Laser Interferometer [Source: Wikipedia]

The eLISA frequency band of 0.1 MHz to 100 MHz corresponds to 0.1 to 100 nTeV energy scales in the early universe, at which new physics is expected to become visible.

LISA, like LIGO, uses laser interferometry to detect gravitational waves. However, instead of being on the ground, LISA consists of three spacecraft in a triangular formation that will orbit the Sun. The three drag-free spacecraft form a triangular constellation with arm lengths of one million km, and laser interferometry occurs between the "free-falling" test masses. The interferometer measures the variation in light travel along the arms due to the tidal deformation of spacetime by gravitational waves. In comparison to Earth-based gravitational wave observatories like LIGO and VIRGO, eLISA addresses a much richer frequency range, which is inaccessible on Earth due to arm length limitations and terrestrial gravity noise.

The LISA mission consists of three spacecraft: one central "mother" spacecraft located at the vertex of the formation, and two "daughter" spacecraft positioned at the ends of the arms, creating a Michelson interferometer setup (diagram). Each spacecraft follows its own independent orbit around the Sun (heliocentric), without the need for active station-keeping. Together, the three spacecraft form a nearly equilateral triangle that lies in a plane inclined at an angle of 60 degrees to the ecliptic. This triangular configuration trails the Earth along its orbit, maintaining a position between 10 and 30 degrees behind the planet (diagram). Due to celestial mechanics, the triangular formation rotates almost rigidly around its center as it orbits the Sun, with slight variations in the length of the arms and the angles between them, which remain stable within a few percent.

The payload consists of four identical components: two are located on the mother spacecraft, and the other two are placed on each of the daughter spacecraft. Each component contains a Gravitational Reference Sensor (GRS), which houses a free-floating test mass. This test mass serves as the endpoint for measuring optical distance and acts as a reference for tracking motion in space (geodesic reference)

A 20 cm telescope is used to send light from a 2-watt laser, which operates at a wavelength of 1064 nm, down the arm of the spacecraft. This telescope also receives a small portion of the laser light that is sent from the distant spacecraft. The measurement of these light waves is done using a laser interferometer on an optical bench placed between the telescope and the GRS. This setup allows the precise measurement of distance changes between the spacecraft **[1]**.

4. Astrophysical sources of gravitational waves

There are many astrophysical sources of gravitational waves that help us identify and explore the universe. These sources are listed below **[5], [4], [8]**:

Binary Black Hole Mergers

Binary black hole systems consist of two black holes orbiting each other. As they lose energy through the emission of gravitational waves, the black holes spiral closer together and eventually merge. These events produce strong gravitational wave signals, which have been detected by observatories like LIGO and Virgo **[4-5]**.

Neutron Star Mergers

Neutron stars are the remnants of massive stars that exploded in supernovae. When two neutron stars are in a binary system, they emit gravitational waves as they spiral together and eventually collide. These events not only produce gravitational waves but also electromagnetic radiation, allowing for multi-messenger astronomy **[4-5]**.

Black Hole-Neutron Star Mergers

These systems involve a black hole and a neutron star in orbit around each other. As with other compact binaries, gravitational waves are emitted as they spiral together and merge. The dynamics of these systems are different from binary black holes or binary neutron stars due to the tidal effects that the neutron star experiences as it gets close to the black hole **[4-5]**.

Supernovae

When a massive star undergoes a supernova explosion at the end of its life cycle, it can release gravitational waves. The core collapse of the star can create asymmetries that generate gravitational waves. These signals are generally weaker than those generated from compact object mergers.

Spinning Neutron Stars

Isolated neutron stars, especially those with asymmetries, can emit continuous gravitational waves as they spin. This is particularly true for pulsars, which are rotating neutron stars with strong magnetic fields.

Stochastic Gravitational Wave Background

This refers to the combined gravitational wave signals from numerous unresolved sources throughout the universe, creating a background noise of gravitational waves. These sources could include early universe phenomena such as phase transitions or cosmic strings, unresolved mergers of compact objects, or astrophysical events that occurred over cosmic time [5].

Primordial Gravitational Waves

These are gravitational waves that were produced during the very early universe, potentially from processes like cosmic inflation. If detected, these waves would offer a direct window into the conditions of the universe in its first moments after the Big Bang.

Intermediate Mass Black Hole Mergers

Intermediate mass black holes (IMBHs), which are more massive than stellar-mass black holes but smaller than supermassive black holes, may also merge and emit gravitational waves. These events are expected to occur in dense environments such as globular clusters.

5. Major discovers and its significance

GW150914: First Detection of Gravitational Waves

On September 14, 2015, the LIGO detectors observed gravitational waves from the merger of two black holes. This event, named GW150914, was the first direct detection of gravitational waves. This detection confirmed a major prediction of Einstein’s General Theory of Relativity, which had remained unproven for nearly 100 years. It marked the beginning of a new era in astronomy, allowing us to observe events that were previously invisible through electromagnetic observations.

GW170817: Neutron Star Merger

On August 17, 2017, LIGO and Virgo detected gravitational waves from the merger of two neutron stars, named GW170817. This was the first event to be observed both in gravitational waves and electromagnetic radiation. The detection of light from this event allowed for independent measurements of the Hubble constant, offering a new method to measure the expansion rate of the universe.

First Black Hole-Neutron Star Merger: GW200105 and GW200115

In January 2020, LIGO and Virgo detected gravitational waves from two separate events involving the merger of a black hole and a neutron star. These events were named GW200105 and GW200115. This provided the first direct observational evidence of black hole-neutron star mergers, a class of systems that had been theorized but never observed. These detections help us understand the formation and evolution of compact binary systems and the interaction between black holes and neutron stars, particularly the tidal effects during such mergers.

GW190521: The Most Massive Black Hole Merger

Detected on May 21, 2019, GW190521 involved the merger of two black holes, forming a final black hole with a mass of about 142 solar masses. This was the first detection of an intermediate-mass black hole. The detection provided the first strong evidence for the existence of intermediate-mass black holes (IMBHs), which are thought to be the "missing link" between stellar-mass and supermassive black holes.

6. Future of gravitational wave research

The future of gravitational wave research will be shaped by big improvements in technology and ambitious scientific goals. This field, which is still young, is set to become an important part of astronomy, helping us explore the universe with greater sensitivity and across more frequencies than ever before **[6-7]**.

Expansion of Detector Networks and Global Collaboration

The gravitational wave research community plans to enhance its detection capabilities through the development of third-generation ground-based detectors and the construction of space-based observatories. The notable projects include:

- **Einstein Telescope (ET):** A third-generation observatory designed for underground operation to reduce noise and improve low-frequency sensitivity. This will enable detection of signals below 10 Hz, which are currently inaccessible.
- **Cosmic Explorer:** A potential high-sensitivity U.S.-based observatory that could push detection limits further than current LIGO and Virgo capabilities.

Advancements in Space-Based Detectors

Space-based missions promise to open new observational windows in the gravitational wave spectrum:

- **LISA (Laser Interferometer Space Antenna):** Funded by ESA and NASA, LISA is projected to observe waves in the millihertz range. This allows for the study of massive black hole mergers, extreme mass-ratio in spirals, and signals from the early universe.

- **Intermediate and Future Missions:** Missions like DECIGO (proposed by Japan) and the Big Bang Observer (BBO) seek to capture waves at decihertz frequencies and study primordial gravitational waves, potentially revealing insights into the Big Bang and cosmic inflation.

Diverse Frequency Ranges and New Technologies

Covering a broad range of gravitational wave frequencies is essential for a complete understanding of astrophysical phenomena:

- **Low-Frequency Detection:** Observatories like LISA will target sources such as supermassive black holes and binaries that emit at lower frequencies.

- **High-Frequency Developments:** Research continues resonant mass and electromagnetic systems to detect higher-frequency signals.

Advancements in Theoretical Physics and Numerical Simulations

The field of gravitational wave science is closely linked with advancements in theoretical physics and numerical simulations, magnetic systems to detect higher-frequency signals:

- **Numerical Relativity:** Continued progress in solving Einstein’s equations enables more accurate modelling of complex systems like black hole mergers.

- **Machine Learning and AI:** These tools are being employed for signal extraction and data analysis, enhancing the ability to detect subtle and faint signals buried in noise.

Multi-Messenger Astronomy and Fundamental Physics

Future detectors will support multi-messenger astronomy, where gravitational wave data are combined with electromagnetic and neutrino observations. This approach enables:

- **Cosmological Insights:** Using binary mergers as "standard sirens" to measure the Hubble constant, contributing to understanding the universe's expansion and addressing discrepancies between current measurement techniques.

- **Testing General Relativity:** Improved data will allow scientists to test the limits of general relativity in strong-field regimes, exploring deviations that could signal new physics, such as extra dimensions or quantum gravity effects.

Gravitational wave research continues to influence and benefit from other scientific fields, including precision measurement and space technology. Cross-disciplinary efforts are expected to yield mutual advancements in fields like metrology, computational science, and materials engineering.

Underground Observatories and Advanced Technologies

Underground facilities could be designed with optimized isolation techniques to further reduce ground motion effects. Underground helps minimize seismic and environmental noise, particularly at low frequencies (<10 Hz).

Advanced Mirror Coatings

Current mirrors face thermal noise limitations. Research into next-generation mirror coatings, such as crystalline coatings or highly uniform materials with lower mechanical loss, could significantly reduce this noise source.

Cryogenic Technologies:

- **Cooling Test Masses:** Lowering the temperature of the test masses and suspension systems to cryogenic levels (for example, using materials like sapphire) reduces thermal noise. This is key for improving low-frequency sensitivity.
- **Superconducting Materials:** Exploring the use of superconducting materials for both test masses and suspension wires could further decrease noise from thermal and vibrational sources.

Enhanced Interferometer Arm Lengths

Longer Baseline Detectors

Constructing larger ground-based facilities, potentially with arm lengths of 10 km or more. Longer arms improve sensitivity by amplifying the signal detected by the interferometer. Maybe in the future, when we can become a multi-planetary species, this method can be used in a wide manner. The moon can also be used as a base for the installation of large interferometers with long arm lengths.

Machine Learning and AI in use

Real-Time Signal Extraction

With AI and machine learning becoming popular and their application in various fields leading to Nobel Prizes, we could implement advanced machine learning algorithms to identify and extract gravitational wave signals in real-time from noisy data. This would improve detection rates and reduce false positives.

Hybrid Detection Networks

Strengthen collaborations with telescopes and neutrino observatories to form a robust multi-messenger astronomy framework. This will enhance source localization and provide richer data sets for astrophysical analysis.

7. Conclusion

The field of gravitational wave research has witnessed remarkable progress since the first direct detection in 2015, opening an entirely new way of observing the universe. The advancements in current ground-based detectors like LIGO and Virgo have already expanded our knowledge of astrophysical events, such as black hole and neutron star mergers. However, the future of gravitational wave astronomy promises even greater discoveries as technology and collaboration continue to evolve. Future generations of detectors, such as the Einstein Telescope and Cosmic Explorer, will push the boundaries of sensitivity and frequency range, enabling the detection of gravitational waves from more distant and varied sources. Space-based observatories like LISA will complement ground-based detectors by probing low-frequency gravitational waves, revealing phenomena like mergers of supermassive black holes and the gravitational wave background from the early universe. In summary, the future of gravitational wave research is bright, filled with opportunities to answer profound questions about the universe's origin, the nature of black holes, and the fabric of spacetime itself. Continued investment in innovative technologies, international collaboration, and theoretical research will ensure that this rapidly growing field continues to push the frontiers of science, promising not only groundbreaking discoveries but also an enriched understanding of our universe.

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9. Conflict of Interest

The author declares no competing conflict of interest.

10. Funding

No funding was received to support this study.