Unveiling Gravitational Wave, Dark Matter, and Dark Energy in Astrophysics

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Abstract. Astrophysics is an important field of physics that has made a lot of achievements in the past hundred years. The research and discovery of gravitational waves is a very influential part of astrophysics, which has the effect of verifying the theory of relativity. This article discusses the relationship between gravitational waves and Einstein's general theory of relativity, which predicts the gravitational wave. This review delves into the genesis and nature of gravitational waves, elucidating their generation from cataclysmic cosmic events like binary black hole mergers and neutron star collisions. This review also emphasizes the meaning of research of gravitational wave in the physics and cosmology. It has played a key role in understanding the expansion of the universe and the behavior of black hole. Through a synthesis of historical, current methodologies and technology, and future aims, this review aims to provide an understanding of the gravitational waves, inspiring continued exploration in this captivating frontier of astrophysics.

Keywords: General theory; Black hole; Gravitation wave; Dark matter and energy.

1. Introduction

Historically, astrophysics is a very important part of physics. Since the time of Kepler and Newton, people have not stopped studying astrophysics. In the last century, people discovered the problem of Mercury's precession, and found the contradiction between Mercury's motion and Newtonian mechanics [1]. The limitations of Newtonian mechanics were discovered. Einstein proposed the theory of relativity, which can explain this problem very well. Astrophysics plays a huge role in the advancement of physics [2].

In astrophysics, gravitational waves and dark matter and dark energy are the most representative factors. In February 2016, the project team of Laser Interferometer Gravity-wave Observatory (LIGO) are preaching to the world that scientists find a gravitational wave signal without precedent [3]. It comes from the merging of two black holes, and these two black holes are divided in mass. Meanwhile, the dark matter is a central component of the universe model, which is currently the most successful theoretical framework for interpreting observational data about the universe [4]. The presence of dark matter helps explain the phenomenon of gravitational lensing, in which light from distant objects is bent as it passes through a strong gravitational field, such as that caused by dark matter [5]. When the mass of dark matter is concentrated in front of a star or galaxy, its powerful gravity can bend light from more distant stars or galaxies, like a lens. By studying this bending of light, scientists can infer the distribution and nature of dark matter.

The paper is organized as follow. In Section 2, the article talks about the Einstein's relativity theory that includes Lorentz transform and mass and energy equation. In section 3, it focuses on the method to find the gravitational wave and the approach to search the dark matter and dart energy. The last section is devoted to the conclusion.

2. Einstein's Relativity Theory

2.1. Special Relativity Theory

The Special Theory of Relativity, proposed by Albert Einstein in 1905, is one of the cornerstones of modern physics [6]. This theory mainly solves the contradiction between the principle of constant speed of light and Newton's laws of motion in classical physics. The core principle of special relativity

theory is twofold [7]. The first is the principle of constant speed of light, that is, the speed of light in a vacuum is constant for all inertial observers. The second is the principle of relativity, which states that all inertial observers are equivalent in describing physical phenomena and cannot determine by any experiment whether they are at rest or moving in a straight line at constant speed. Special relativity provides a new view of time and space, in which time and space are no longer independent, but interconnected into four-dimensional space-time. In this framework, the time and space coordinates of an object change as its relative motion changes. Special relativity also reveals the equivalence relationship between mass and energy, for which the mass-energy equation is $E = mc^2$.

While the mathematical basis of classical mechanics is the Galilean transformation, the basis of Special Relativity Theory is Lorentz transformation. Lorentz transformation is used to describe the transformation of time and space coordinates between different inertial reference frames. The following is a detailed explanation of the relationship between the two and the Lorentz transformation. The Lorentz transformation was originally proposed by Dutch physicist Lorentz before the advent of relativity in order to solve problems related to the principle of the constant speed of light in classical electrodynamics (Michelson-Marley experiment). Lorentz tried to make Maxwell's equations invariant in all inertial reference frames by adjusting the coordinates of time and space. This attempt provided an important mathematical basis for the later development of relativity.

There has strong connection between the Lorentz transformation and special relativity theory. Einstein discovered that by applying the Lorentz transformation, it is possible to ensure that the form of the laws of physics remained the same in all inertial reference frames, thus resolving the contradictions that existed in classical physics. Thus, the Lorentz transform became the mathematical formulation of special relativity, a bridge connecting different inertial reference frames. The Lorentz transformation inferred that a new method. Through it, the time and space coordinates in one inertial reference frame can be converted to another inertial reference frame. The specific mathematical expressions are

$$x' = \gamma(x - vt) \tag{1}$$

and

$$t' = \gamma\left(t - \frac{vx}{c^2}\right), \tag{2}$$

In which $\gamma = 1/\sqrt{1 - v^2/c^2}$ [8]. In addition, x' is the space coordinates and t' is the time in new reference. In this transformation, c is a constant representing velocity of light. Through the Lorentz transformation, special relativity successfully explained many phenomena related to high-speed motion, such as time dilation and length contraction, thus laying a solid foundation for the development of modern physics. At the same time, it provides an important framework that allows scientists to study the behavior of physical laws in different inertial reference frames.

2.2. General Relativity Theory

The starting point of general relativity is the equivalence principle, which states that in any small region, the effects of gravity are essentially indistinguishable from the effects of acceleration. In other words, an observer in a free-falling frame of reference cannot detect the presence of gravity by any experiment [9]. The geometric description of the general relativity is that it explains gravity as the curvature of space-time. In this theoretical framework, gravity is no longer seen as a transfer of forces, but as a geometric property of space-time. The Einstein field equation is at the heart of general relativity, which describes the relationship between the curvature of space-time and the distribution of matter. This equation is a very complex tensor equation, which includes the geometric properties of space-time and the energy-momentum tensor of matter.

The general relativity predicts that the path of light through a gravitational field will bend. This prediction was verified by observations of a solar eclipse in 1919, thus providing important support for the correctness of general relativity. The general relativity also predicts that gravity will affect the

passage of time, that is, time will pass more slowly where gravity is stronger. This prediction has been verified in a number of experiments, such as precise atomic clock experiments. The general relativity also predicts that under certain extreme conditions, the curvature of spacetime can become so strong that it forms a region from which not even light can escape, forming the so-called black hole. In addition, the general relativity also provides the basis for modern cosmology, which can be used to describe the evolution and structure of the universe. The cosmological solution to Einstein's equations has provided important insights into the expansion of the universe and the Big Bang theory.

3. Applications

3.1. Gravitational waves

The gravitational wave is often termed gravitational radiation. The aforementioned ripples manifest as perturbations within the space-time continuum, initially postulated by Albert Einstein's theory of general relativity [10]. According to this theory, gravity is the consequence of matter and energy distorting the fabric of space-time. These gravitational waves are generated by the movement of massive celestial bodies, such as spiraling and merging black holes or neutron stars. Gravitational waves are ripples in the fabric of spacetime caused by some of the most violent and energetic processes in the universe. Albert Einstein predicted their existence in 1916 on the basis of his Theory of General Relativity. According to Einstein's theory, when massive objects like black holes or neutron stars orbit each other or merge, they can produce a burst of gravitational waves that propagate through spacetime at the speed of light.

The significance of gravitational waves extends to cosmology as well, offering a method to probe the early universe. They are of particular interest because they provide a new way to observe the cosmos, allowing scientists to detect and understand phenomena that are otherwise invisible through electromagnetic observation.

The significance of gravitational waves extends to cosmology as well, offering a method to probe the early universe. They are of particular interest because they provide a new way to observe the cosmos, allowing scientists to detect and understand phenomena that are otherwise invisible through electromagnetic observation. The signal detected in this event originated from a binary black hole system, located approximately 410 megaparsecs away from Earth, where two black holes merged into one, releasing a significant amount of energy in the form of gravitational waves. Gravitational waves carry information about their origins and about the nature of gravity that cannot be obtained through other astronomical observations. This is because these waves are not easily scattered or absorbed by matter, so they travel through the universe largely unimpeded. The detection of gravitational waves provides a new way to observe the cosmos, offering insights into phenomena like the collision and merging of black holes, neutron star dynamics, and potentially even the very early moments of the Big Bang.

The LIGO is an ambitious scientific project that has profoundly impacted people’s understanding of the universe. It consists of the world's largest precision optical instruments and leverages one of the world's largest vacuum systems to detect gravitational waves, subtle ripples in the fabric of spacetime caused by cataclysmic astrophysical events [11]. The LIGO represents a pinnacle of scientific achievement in the field of astrophysics, designed to detect and study gravitational waves. Initial LIGO (iLIGO), completed in 1999, laid the foundational work for advanced gravitational wave detection despite not observing any events. Subsequent enhancements culminated in Advanced LIGO (aLIGO), which, since its first observing run in 2015, has made seminal discoveries including the direct detection of gravitational waves from black hole mergers and neutron star collisions, ushering in the era of multi-messenger astronomy. Technological innovations born from LIGO's requirements have propelled advances across various scientific fields and led to numerous spin-off technologies. LIGO's expansion into an international collaboration with the forthcoming addition of a detector in India, alongside partnerships with Virgo and KAGRA, is poised to extend its observational reach and scientific contributions. The observatory's future upgrades aim to increase its sensitivity, promising

deeper insights into the properties of gravitational waves, the validity of general relativity, and the extreme conditions of celestial phenomena. LIGO's journey, marked by meticulous improvements and collaboration, continues to challenge people's understanding of the cosmos and enrich the broader scientific and technical community.

In China, there is also a very famous radio telescope called "FAST". The Five-hundred-meter Aperture Spherical Telescope (FAST), also known as Tianyan, is the world's largest filled-aperture radio telescope, located in Guizhou, southwest China. Its novel design features an active surface with 4,500 metal panels forming a parabolic shape to capture radio waves across wavelengths of 10 cm to 4.3 m. FAST began construction in 2011, saw first light in 2016, and became fully operational in January 2020. It is designed for scientific endeavors such as pulsar detection and has discovered over 500 pulsars since its inception, helping to advance people's understanding of the universe. The FAST radio telescope has significantly aided gravitational wave research by detecting key evidence for the existence of nanohertz gravitational waves through pulsar timing observations. FAST's high sensitivity enabled the Chinese Pulsar Timing Array team to observe 57 millisecond pulsars over 41 months, leading to the detection of quadrupole correlation signatures that align with nanohertz gravitational wave predictions. These observations are crucial for studying massive celestial bodies like supermassive black hole binaries, which are primary sources of gravitational waves in the nanohertz band. Such research helps in understanding the fundamental physical laws of spacetime and the universe's structure. Detection of nanohertz gravitational waves is challenging due to their low frequency, with periods potentially spanning several years. Pulsar timing arrays are the most effective tool for this detection, and FAST's capabilities are comparable to other international groups despite its shorter data collection timeframe. The ongoing efforts of various regional collaborations are essential for improving detection sensitivity, which increases with longer observational time spans. This technology will help human continue to explore the universe in the future.

3.2. Dark Matter and Dark energy

The dark matter is a term used to describe substances that do not directly emit or reflect light in the universe. It is an important component of the total amount of matter in the universe, but unlike atoms, molecules, and other "ordinary" matter known to people (called baryonic matter), dark matter does not interact with electromagnetic forces and therefore cannot be directly observed in conventional ways, such as with optical telescopes. Non-luminous and non-absorbent dark matter neither emits nor absorbs light and is therefore invisible across the electromagnetic spectrum. This is the main reason why it is called "dark" matter [12]. Dark matter seems to interact only gravitationally with ordinary matter. This property was deduced by scientists by observing the behavior of large-scale structures in the universe such as the rotation of galaxies and galaxy clusters. Since dark matter does not emit, absorb, or scatter light in any way, it does not engage in electromagnetic interactions, making it physically distinct from ordinary matter.

The main sources of mass and gravity in the universe is most of the mass in the universe is made up of dark matter. According to current cosmological models, dark matter makes up about 27 percent of the total mass of the universe, while ordinary matter (such as stars, planets, and interstellar gas) makes up only about 5 percent. This means that the gravitational structure of the universe is largely driven by dark matter. The large-scale structure of the universe, such as superclusters and the cobweb structure of the universe, is largely shaped by the distribution and gravitational effects of dark matter. Dark matter plays an important role in interpreting observational data on the cosmic background radiation (cosmic microwave background radiation). The tiny inhomogeneity of the cosmic background radiation reveals the distribution of matter in the early universe, with dark matter playing a key role.

With only visible matter, people would expect the edges of galaxies to rotate more slowly than the center. However, observations show that the rotational velocity of galaxies is almost constant over a wide range of time, suggesting the presence of additional unseen mass (i.e., dark matter). This is radiation emitted in the early Universe, and by accurately measuring the tiny temperature variations

of this radiation, scientists can learn about the distribution of matter, including dark matter, in the early Universe. Although dark matter cannot be directly observed, scientists are trying to detect dark matter particles directly. For example, special detectors in underground laboratories are being used to look for the tiny signals produced when dark matter particles interact with ordinary matter. In the Large Hadron Collider (LHC), for example, scientists try to produce dark matter particles through high-energy particle collisions in order to study their properties.

The study of dark matter and dark energy is helping to advance fundamental theories of physics, especially the understanding of the origin, structure and future of the universe. This may lead to new physical models and theories. In the course of efforts to detect and study dark matter and dark energy, new technologies and instruments may be developed that can be applied to other areas of science, such as particle physics and astrophysics. A better understanding of dark energy could have profound implications for people's fundamental understanding of energy, force and gravity, which could theoretically facilitate the development of new energy technologies. The study of dark matter and dark energy may inspire entirely new scientific hypotheses that may lead us toward new scientific discoveries and technological innovations. However, it should be emphasized that the current understanding of dark matter and dark energy is still very limited, and their direct applications may require a long time of exploration and research. Currently, they serve more as important factors in promoting basic scientific research.

4. Conclusion

To conclude, this paper firstly presents the theoretical basis for the prediction of gravitational waves, namely the Einstein's general relativity and special relativity. This article discusses the mathematical basis of general relativity and special relativity, and shows the significance of the discovery of relativity. Some basic phenomena derived from the theory of relativity are discussed as well. Afterwards, the paper presents two representative examples of the theory of relativity, one is the gravitational waves while the other is dark matter and dark energy. The first direct detection of gravitational waves was made by the LIGO and Virgo collaborations, The statement validates a crucial hypothesis derived from Einstein's theory and inaugurates the realm of gravitational wave astronomy. Since then, various gravitational wave events have been observed, helping scientists to understand the distribution of black holes and neutron stars in the universe, test the limits of general relativity, and study objects and events that are otherwise invisible in traditional electromagnetic observations. On the other hand, the dark matter and dark energy are two very important concepts in cosmological research, but they currently have relatively limited application prospects, mainly because their nature and properties remain major unsolved mysteries in the scientific community. Nevertheless, people can explore their potential applications from both theoretical and scientific research perspectives. To summarize, the astrophysics is a promising research area in modern physics.

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