Analysis Of Black Hole Merger from Gravitational Wave Generation and Observation

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Abstract. Currently, one of the main areas of interest for astronomical study is the monitoring of black hole merger events, thanks to the development of gravitational wave astronomy. Human beings now have the chance to go deeper into the cosmos thanks to this field's quick progress, particularly in terms of comprehending astrophysical processes under extremely strong gravitational fields. A detailed examination of the production and detection of gravitational waves during black hole mergers is the focus of this study. To gain a deeper knowledge of the phenomenon of black hole mergers in the universe, this study intends to investigate the dynamics and energy release mechanism of these events and confirm their existence using gravitational wave observatories like LIGO and Virgo. Black hole mergers have been shown to be a common occurrence in the universe through careful study and observation, and gravitational wave observations offer us a previously unattainable window into the most extreme astrophysical processes. These results establish a strong basis for further advancements in the study of black holes and gravitational wave astronomy.

Keywords: Black hole merger; gravitational wave; laser interferometer.

1. Introduction

The concept of black holes was first proposed by the renowned physicist Albert Einstein formulated this in 1916 because of his general theory of relativity. However, it wasn't until the 20th century that serious scientific investigation into black holes began. The measurement of light bending in the vicinity of the surface of the Sun by Eddington is the first experiment confirmation which was attained in 1919 that disseminated the theory widely [1]. However, it wasn't until the 20th century that serious scientific investigations into black holes began. Physicist John Wheeler coined the term 'black hole' in the 1960s to refer to regions in space with intense gravitational pull, preventing even light from escaping. This concept generated substantial interest among physicists and astronomers, prompting various observational and theoretical investigations. In 1971, Jacob Bekenstein proposed the ideal that black holes have an entropy, challenging the prevailing notion that they were completely devoid of any measurable properties which laid the foundation for the field of black holes thermodynamics. Large-scale tests of general relativity are mostly driven by observations from the cosmos. The issue of dark energy remains unsolved, even though the dark matter problem is more likely to be caused by some huge particles that interact weakly and are outside the scope of particle physics, rather than a violation of Newton's law of gravitation. Now, a modest positive ad hoc cosmological constant could account for the Universe's accelerating pace of expansion. But the real reason might be a large-scale collapse of general relativity or the emergence of a brand-new field with strange characteristics [1]. Testing general relativity at cosmological scales has been a particularly active area of research in the last two decades.

In recent years, black hole research has been revolutionized by technological advancements, particularly in the field of astronomy. The development of powerful telescopes and detectors, such as the Event Horizon Telescope (EHT), which is an international collaboration that combines multiple radio telescopes to create a network and has allowed scientists to observe black holes directly and capture images of their event horizons for the first time. In 2019, the EHT made a groundbreaking achievement by publishing the first direct image of the supermassive black holes at the core of the M87 galaxy. This discovery established the event horizon of the black hole and offered compelling visual proof for the sever gravity predictions of Einstein's general theory of relativity. Additionally, there have been notable observations related to black hole mergers. For instance, in 2019, Researchers in the field of astronomy have identified gravitational wave signals that are related with the merger of two enormous black holes. This event, known as GW190521, provided further insights into black hole fusion and contributed to the understanding of black hole evolution and important cosmic phenomena [2-4].

Overall, studying black hole merger can verify Einstein's general theory of relativity and by observing and simulating the extreme gravitational fields can be verified. Moreover, it is an important way to determine the physical properties of black holes likes, mass, spin, charge, the formation and evolution mechanism and further reveal the internal structure. By detect the gravitational wave which are space-time oscillations produced by matter or celestial bodies moving at an accelerated pace, dark matter and dark energy can be found in the universe, and proof the theory of black holes merger. However, at present, there are still many problems need to solve. For example, gravitational wave signal processing and analysis, likes noise processing, signal extraction, data processing, and model validation. Additionally, the dynamical behavior and merging process of multi-black hole systems and supermassive black hole merge are still not fully understood. This study will investigate the implications of the Einstein's theory for black holes and gravitational wave, taking into result detected by Laser Interferometer Gravitational-Wave Observatory and Virgo. The process of binary black holes merge in different phases and the formation of the gravitational wave. The principle of gravitational detection and the limitations of related detectors.

2. Black Holes Merger

2.1. The Principle of Black Holes Merger

According to the general relativity, matter and energy can distort space-time, creating a gravitational field. When two supermassive black holes are in proximity, the gravitational interaction between them causes them to move closer to each other and the mass of black hole is greater, the gravitational field of it is stronger. The gravitational interaction can be described by the Einstein's function. Besides, the gravitational wave, which are gravitational fluctuation produced by the motion of massive celestial bodies, are predictions of Einstein's general theory of relativity, and these fluctuations propagate like ripples in space-time, will produce when two black holes are getting closer. The gravitational wave can take the energy and momentum of black hole system away that causes two black holes gradually close and merger finally. Kinetic energy conversion which means the kinetic energy of two black holes merging and converting to other forms, likes gravitational potential energy. In the special relativity, this energy conversion can use the Einstein's function to explain. For elaboration, according to the conservation of energy, the sum of the total energy of the merged black holes does not change. When two black holes approached and spiraled down, their kinetic energy will decrease, transforming to gravitational potential energy. Finally, a lot of energy which comes from the mass different between two black holes and the process that kinetic energy changes to gravitational potential energy is released.

2.2. Different Stages of Black Holes Merger

The reason why the binary black holes will merge instead of being entangled with each other all the time will be written here. During a supernova explosion, a black hole is created [5]. In a binary if mass is lost spontaneously from one component, conservation of momentum results in recoil; however, if the progenitor is a member of one of the components, mass loss during the supernova may cause the binary to be expelled [3]. As two black holes move closer to each other, the changing quadrupole moment of the system's mass causes the emission of gravitational waves. These waves lead to a reduction in the gravitational potential energy between the black holes. This leads to a decrease in orbital energy, causing the black holes to move closer to each other. As the two black holes move closer together, their orbit frequency increases due to the conservation of angular momentum. This leads to a higher amplitude of gravitational waves being radiated until the black holes eventually collide and merge. In such a geometric progression, soon the two ‘holes’ collided and merged instead of being entwined with each other all the time. However, if the mass of the celestial body is small and the distance is large, the gravitational wave caused by rotation is small that means there is not much energy that can be diffused to escape. In this way, the orbit can be maintained for a long time, approximating ‘stability’. But eventually they will also ‘attract’ each other and merge, if there is no outside interference or other factors.

Due to the conservation of angular momentum, the two black holes' orbital frequency and amplitude grow closer to one another as their distance from one another decreases. Eventually, the two black holes merge and collide [4]. The first stage is the rotation phase, in which the orbit of the close binary gradually changes from elliptical to circular due to gravitation are also gradually entering the measurement range of the detectors one has built on Earth. At this stage, the gravitational radiation continues to take away the orbital energy, the orbital shrinks, the gravitational wave waveform has the characteristics of a ‘chirp’ signal. In the second stage, called Merger, when the orbit of the binary star reaches thee innermost stable circle, the two stars will merger dynamically, and the gravitational radiation of the merging process will be violent and explosive [3]. The third stage is the decay phase. When two black holes merge into a high-speed rotating Kerr black hole, a theoretical model of a black hole that derived from Karl Schwarzschild in1916, the gravitational waves emitted by them have the characteristics of ‘after-winds’, and the amplitude gradually decays, similar to the situation where the bell gradually decreases after rattling until it disappears. It gives information about the mass of the merger, spin and so on. A typical process is shown in Fig. 1 [6].

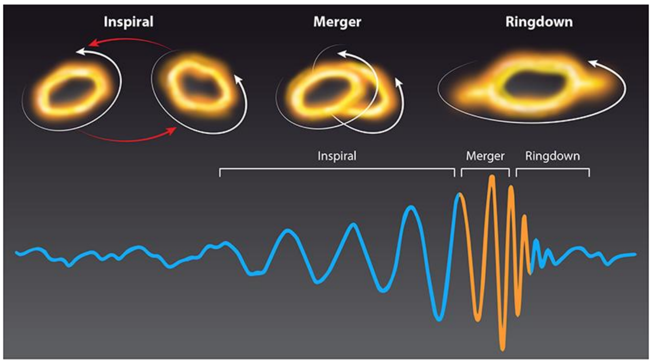

Fig. 1 The process of binary black hole merger [6].

2.3. The Role of Black Holes Merger in the Evolution of the Universe

When the black holes merging, the gravitational waves it releases travel to all corners of the universe, which can be detected and affected the process by which the structure of the cosmos was created. The formula of energy released by gravitational waves is

$$E = \frac{G}{5c^5}\left[m_1 \cdot m_2 \cdot (\frac{v}{c})^2\right]^2 \tag{1}$$

Here, G is the gravitational constant, c is the velocity of light, m_1 and m_2 are mass of the black holes, v is the velocity of black holes merger.

3. Gravitational Wave Generation

3.1. The Basic Information of Gravitational Wave

The theory of general relativity states that compact concentrations of energy, like black holes and neutron stars, should strongly warp spacetime. At the same time, the uneven and asymmetrical distribution of mass and energy in the process of motion, interaction or evolution of celestial bodies is also one of the important factors. For example, when two supermassive black holes close to each other, due to the asymmetry of black hole motion (e.g., non-concentric orbital motion). Whenever such a concentration of energy changes shape, it should produce a dynamically changing spacetime warpage that travels through the universe at the speed of light. This propagating warpage is known as a gravitational wave. It is generated by the movement of masses, and similar to electromagnetic waves, they travel at the speed of light. The waves have polarization and are caused to compress and stretch spacetime in a plane perpendicular to their direction of propagation [7]. When gravitational waves (GWs) are present in spacetime, they physically appear as time dependent strains, or more specifically, $h=\delta L/L$, where L is the distance between two reference locations in space and δL is the induced displacement over the baseline [8]. As per general relativity prediction, the induced strain is quadrupolar and perpendicular to the GW propagation axis. This means that, for a single polarization, a wave travelling along the z-axis will cause the x-axis to expand and then compress while the y-axis will shrink and then stretch. With orthogonal polarization, elongation and compression will happen along axes that are rotated 45° in relation to the x- and y-axes.

When it comes to learning about the most intense astrophysical processes in the universe, GWs provide unparalleled insights, and provide vital insights into the dynamics of huge objects that are travelling at relativistic speeds [8]. GWs are signals that may travel through the entire universe and are not obstructed by matter, unlike electromagnetic waves. Through gravitational wave observations, extreme celestial bodies such as black holes and neutron stars in the universe, as well as events in the early universe, can be studied.

3.2. The Causes of Gravitational Waves Form in the Black Hole Merger

The initial stage of a black hole merger involves two black holes orbiting each other. This might happen in a binary system, which is the close-knit pair of black holes. The black holes' orbits get closer together over time because of gravitational radiation emission, which eventually causes a collision. The gravitational interaction intensifies as the black holes get closer. The two black holes spiral inward toward one another during this phase, which is referred to as the inspiral. They release gravitational waves as they orbit at ever-faster speeds. The energy and angular momentum that these waves remove accelerates the black holes' approach to one another. Also, the evolution of black holes slows down when they are within a parsec (3.26 light-years) of one another due to the surrounding dark matter and stars. This phenomenon is referred to as the 'last parsec problem'. In comparison to the earlier stages, this one could take a long time. What's more, at some point, the black holes resolve their last parsec issue and go on to the merger's last phase. It is at this coalescence that gravitational waves are most powerfully released. A single, more enormous black hole is created when the black holes collide. Gravitational waves burst out as result of the asymmetry in the mass distribution and dynamics of this last plummet.

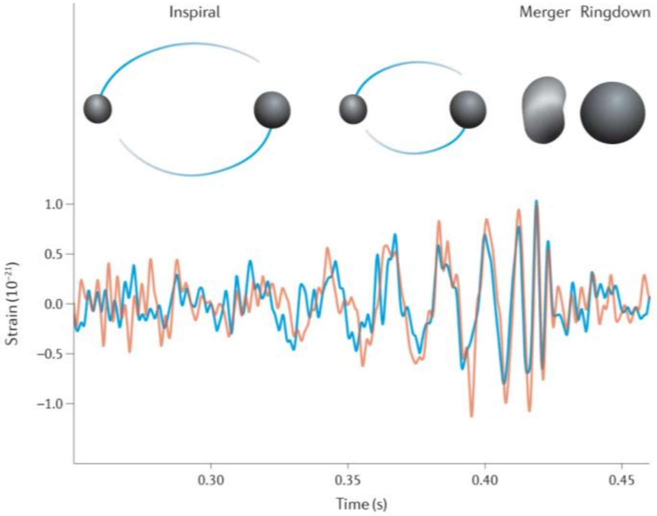

Fig. 2 The changes of gravitational wave when black holes merger [8].

4. The Basic Working Principle of Detector

4.1. Working Principle of Laser Interferometer

Over the last five years, there has been a significant revolution in the field of astronomy.In 2015, the binary black hole merger known as GW150914 (seen from Fig. 2) released GWs that were detected by the Advanced Laser Interferometer Gravitational-Wave Observatory (LIGO) instrument [8]. This is a significant achievement that showcasing the ability to detect GWs, and the different insights were provided into these exotic object and Universe. Another important event is the detection of GW170817 that finished by the Advanced LIGO and Advanced Virgo detectors on August 17th, 2017.This event involved a binary neutron star system merge and the observation of the entire spectrum about electromagnetic radiation emitted across it.

For the purpose of measuring the distances between the masses, a laser interferometer gravitational wave detector, also known as an "interferometer" for short, is comprised of four masses that are suspended from vibration-isolated and the identified optical system. The basis of GW detectors is the measurement of changes in the amount of time it takes for light to travel between distinct reference sites, or "test masses," as a result of a passing GW. The test masses are arranged so that they are scattered over extremely long baselines and are all in almost perfect free fall, which makes them resemble local inertial frames. A detector tracks and measures the light travel times between test mass pairs, modulating the light travel timings in response to variations in spacetime curvature brought on by passing gravitational waves. A gravitational wave, with frequencies much higher than the pendulum frequency of the masses, which is around 1 Hz, modifies the arm-length difference, which is denoted by the equation $\Delta L = L_1 - L_2$. The masses move back and forth in respect to one other as if they were not linked to their suspension wires as a result of this wave acting as a cause. To monitor changes in a manner that creates fluctuations in the photodiode's (the interferometer's) output that are directly proportional to $\Delta L(t)$, another technique known as laser interferometry finds application. The lengths of the two cavities are altered as a result of the gravitational wave's impact on the detector, which causes the masses to be moved (as illustrated in Fig. 3). This causes the resonant frequencies of the two cavities to be somewhat displaced in relation to the laser frequency. This causes a change in the phase of the light that is contained within the cavity, as well as an effect on the phase of the light that is emitted from the cavity and travels towards the beam splitter [8-11].

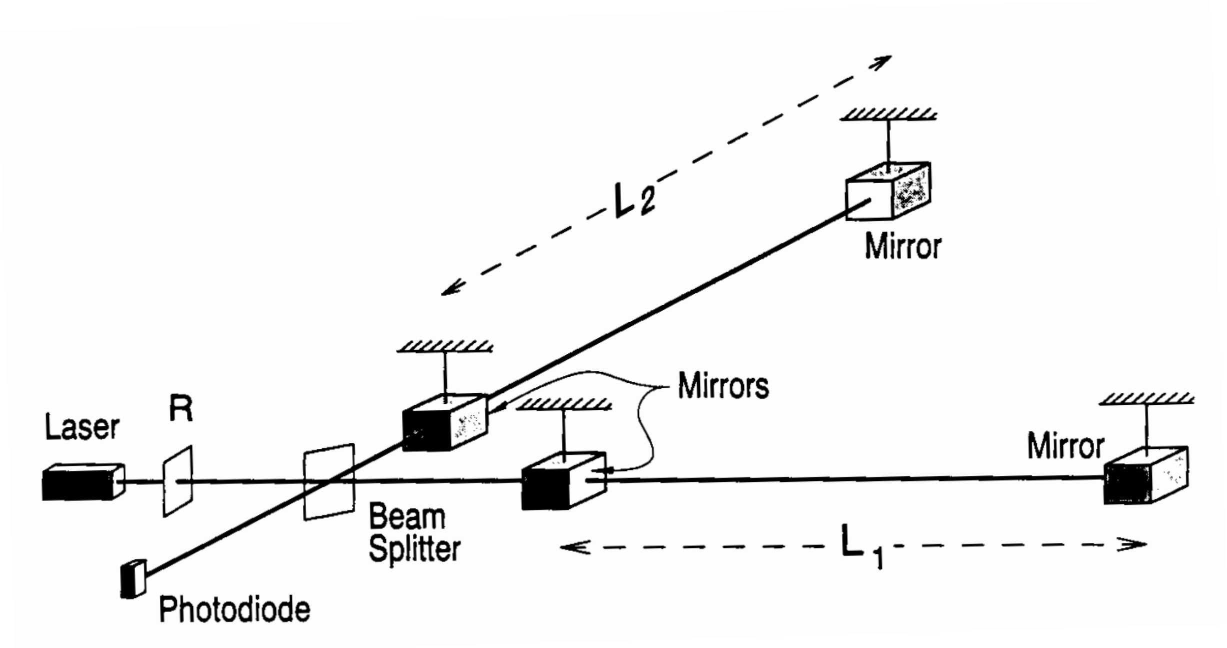

Fig. 3 Probing principle of a laser interferometer gravitational wave detector [10].

4.2. LIGO and VIRGO

Laser Interferometer Gravitational-Wave Observatory (LIGO) is a larger-scale scientific experiment dedicated to the direct detection of gravitational wave signals from the depths of the universe that originate from extreme astronomical events, which consist of two detectors, one in Hanford, Washington, and one in Livingston, Louisiana. All of the detectors are Michelson interferometers, and each one is made up of two optical cavities that are four kilometers long and are arranged in a L form. Due to the architecture of the interferometer, laser beams that are flowing in both arms will arrive at a photo detector exactly 180 degrees out of phase. This will result in the lack of gravitational waves, which will result in the production of no signal. When a gravitational wave moves at a right angle to the detector plane, it disrupts the ideal destructive interference that would otherwise occur. One arm will expand and the other will contract during the first half-cycle of the wave; these changes are then reversed during the second half-cycle. The optical power can reach the photodetector as a result of these length changes altering the phase difference between the laser beams. LIGO can eliminate false signals, such as those caused by a nearby seismic wave, by using two interferometers instead of one [9, 10]. Besides, the remarkable sensitivity of LIGO allows it to identify changes in arm length. The main source of detector noise for LIGO is thermal motion, photon shot noise, and seismic waves. These disruptions can readily obscure the faint signal that gravitational waves are supposed to produce [8].

Virgo is situated roughly 25 kilometers north of Pisa, Italy, and construction on it started in 2003. In order to increase the precision of gravitational wave event localization, the facility was chosen to form an angle with LIGO's two detection stations, one in Louisiana and one in Washington State. Virgo is supported by the National Science Foundation of France and the European Science Foundation. The structure of it is similar to LIGO.

As part of a global network for gravitational wave detection, the Virgo and LIGO observatories cooperate. Gravitational wave events can be more precisely pinpointed because to the data from several sites available in this network. For instant, on September 14, 2015, LIGO made the first detection of GW150914, a gravitational-wave event resulting from the merging of two enormous black holes. As it supports the hypothesis and establishes the existence of gravitational waves, this discovery is regarded as a significant milestone in the history of science [12]. GW170817, a gravitational wave signal produced by the merging of two neutron stars, was identified as the gravitational wave event that LIGO and Virgo jointly observed in 2017. Not only did this occurrence validate the existence of neutron star mergers, but it also marked the first observation of their attendant phenomena, such as heavy element synthesis and γ-ray bursts.

5. The Current State of Black Hole Fusion Observations

In the present, there are still certain restrictions and difficulties, even though EHT published the first picture of a black hole's shadow in the center of the M87 galaxy in 2019, marking the first direct sight of a black hole's event horizon in human history. Here are some of the principal obstacles that black hole fusion observations now face. To begin with, the gravitational waves that are currently being observed coming from such black holes are restricted to detecting the merging of stellar-mass black holes, allowing for the examination of the inspiral and ringdown signals [13]. The primary drawback is that the spin effects are ignored by the template waveforms. Examples of this can be found that massively spin black holes discovered in X-ray binaries, but nothing is known about the statistical distribution of black hole spins in binaries. The predicted gravitational-wave signal from a binary system that contains components that spin round will vary compared to a system without spinning components. The amplitude and phase of the gravitational wave may be affected, and the observed time could also be different. The effectiveness of the detection will be negatively impacted if the spinning components of binaries are ignored in the search templates. With that being said, at the time that this search was being conducted, there were no analytical spiral merger-ringdown waveforms that were accessible for systems that had generic spins. Another drawback of the search is that it is more difficult to discern between real signals and background events because the signals themselves are more "glitch-like" due to their shorter length and bandwidth as compared to searches for systems with lower masses. To increase the sensitivity of searches for these systems, new methods for ranking candidate events are being developed [2]. In addition, there are currently three limitations on the interferometer's sensitivity. The quality and stability of the optical components, which are the core of the interferometer, and the surface quality, reflectivity, and transmittance of the specular surface, the stability of the laser beam, and the optical path length of the interferometer can directly affect them. And the performance of the laser light source. The frequency stability and power stability of a laser light source can affect the stability of the phase, while the stability of the power affects the signal-to-noise ratio. Various types of noise, such as thermal noise, Newtonian noise, and quantum noise, can lead to vibrations in the interferometer, ultimately decreasing its sensitivity. Thermal noise results from random displacement, Newtonian noise is caused by earth and atmospheric density perturbations affecting the mirrors, and quantum noise arises from vacuum fluctuations and quantum radiation pressure noise impacting mirror displacements [9].

To provide top-notch scientific content, the range of detectors will be further extended by a new generation of gravitational-wave detectors, including the Astronomer's LIGO-III, Virgo+, and upcoming gravitational-wave space probes [14]. The KAGRA detector has just become part of the LIGO and Virgo collaboration, forming the LIGO-Virgo-KAGRA network, which could offer more detailed data for testing gravitational waves. Upcoming ground-based detectors aim to increase sensitivity by up to ten times compared to the current network.The main modification will involve raising the baseline arm length, L, in two 3G detector designs. ET in Europe and CE in the USA, are now being explored simultaneously. As of right now, ET is planned as an underground facility in Europe equipped with three ten-kilometer-arm-length triangular interferometers.

6. Conclusion

Overall, this study has explored the complex fields of gravitational wave generation and observation as well as black hole mergers. In order to predict the presence of gravitational waves and the general theory of relativity developed by Einstein served as the theoretical basis that was first examined in the analysis. Then, attention turned to the astrophysical phenomena of black hole mergers, delving into their dynamics, energy release, and post-merger black hole development. The vital role that gravitational wave astronomy plays in the study of the universe is one of the main conclusions of this research. Gravitational waves have been directly observed, providing a new window on the universe that has made it possible for us to see phenomena that were previously invisible to conventional telescopes. Einstein's predictions have been verified by the revolutionary discoveries made by LIGO, Virgo, and other observatories. These discoveries have also shed light on the characteristics of black holes and their mergers. Gravitational wave astronomy seems to have a bright future ahead of it. It is expected that ongoing and planned improvements to current detectors, along with the construction of space-based observatories, would greatly improve the ability to see. This will make it possible to detect a wider range of black hole mergers, including as those involving neutron stars, lower-mass black holes, and possibly unusual objects. To sum up, the work in this paper adds to the increasing amount of information about gravitational wave astronomy and black hole mergers. The science is developing quickly, and additional secrets of the universe should be revealed by further technological and collaborative advances, demonstrating the profoundly positive effects of gravitational wave astronomy on the comprehension of the universe.

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