The Intertwine of Black Holes and Gravitational Waves

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Abstract. This paper is designed to offer a comprehensive review of the latest advancement in the field of black holes & gravitational waves research– think of it as a vassal to carrier the readers through the deep and often complex waters of those topic. By explain each concept with clearly and accessibility in mind, it makes sure that any readers, regardless of their prior level of expertise in the field of Astrophysics, can feel informed and up to date. This paper aims to explain the formation, evolution, and mechanism of black holes and gravitational waves, while summarizing the latest methods used to detect them. It accomplishes that by reviewing the important historical detections, along with current experiment that could yield promising data. Through these findings, we conclude that the merging of binary black holes creates the strongest signals of gravitational waves, which could be further verified with future detectors such as the space-based LISA and more advanced techniques like Pulsar Timing Arrays.

Keywords: Black hole, Gravitational wave, Singularity, Binary system, GW detectors

1. Introduction

In modern Astrophysics, black hole and gravitational waves stands as two of the most fascinating phenomena. Originally predicted in a solution to Einstein's field equations, Black hole is a region of spacetime so curved that no object, not even light, could escape. Over the decades, observational evidence —from X-ray binaries to the first high-resolution image of a supermassive black hole— has confirmed the existence of black hole. However, black hole isn’t the only thing predicted in Einstein’s theory of general relativity, as gravitational wave—small ripples in the fabric of spacetime created rapidly accelerating massive object. The detection of gravitational has proven to be a far greater challenge than that of black hole, as they remain elusive until 2015— when LIGO detect the first direct signal of gravitational wave generated by a two-merging black hole. This discover marked the beginning of a new era for modern astrophysics. [1]

On the path of understanding black holes and gravitational waves, many scientists and mathematicians had made notable contributions. While working on a solution to Einstein’s field equation in 1916, Karl Schwarzschild laid out the theoretical framework for a non-rotating black hole. More subsequential discoveries and the exponential growth in this field own much to pioneers such as John Wheeler, who popularized the term “black hole”, and Kip Thorne, who advanced theoretical understanding of gravitational wave. The joint effort by LIGO and Virgo that has led to the first direct detection of gravitational wave— an achievement that earned the 2017 Nobel Prize in Physics.

The structure of this paper is divided into three sections. The first part of the body paragraph aims to provide background information on black hole, their classifications, defining properties such as event horizon and singularity, and thermodynamic characteristic that tie them to fundamental physics. The second section will briefly go over the mechanisms of gravitational-wave, astro events that create them, and methods of detection used—from laser interferometry on Earth to pulsar-timing arrays. Finally, the last section reiterates the connection between BH and GW, and how such studies has improved the understanding of both the birth and the evolution of the universe. The paper concludes by summarizing key findings and identifying possible areas for future study.

2. Black Hole

2.1. Formation of black hole

As one of the most mysterious objects in the universe, black holes have captured the human imagination with their fascinating and physics-defying traits. They can only form in some of the most extreme events in the universe. Toward the end of a massive star's life, its hydrogen fuel becomes depleted, disrupting the delicate balance between the outward radiation pressure generated from nuclear fusion and the inward pull of gravity. Gravity would start crashing the star, which would skyrocket the temperature at the core of the star. Progressively heavier elements are then fused—first helium, then carbon, oxygen, and silicon—until the process finally reaches iron. Because fusing iron consumes more energy than it produces, gravity ultimately gains the upper hand, driving the star to collapse at speeds approaching 25% of the speed of light. If the star is sufficiently massive, its core collapses into a black hole. [2]

2.2. Black hole categories

Broadly speaking, there are typically three types of black holes: Stellar, intermediate-mass, and supermassive black hole. However, beyond these well-known categories, scientists have proposed the existence of a fourth type— Primordial black holes. Primordial black holes were formed shortly after the Big Bang when the universe was so dense that pockets slightly denser than neighboring pockets would collapse into a black hole. They are incredibly small— around the size of an atom but have a mass of a mountain. Many astrophysicists believe that they made up the mysterious dark matter.

As of now, there seem to be lack of concrete evidence that could validate the existence of Primordial black holes. However, some physicists argue that the Primordial black holes have evaporated due to Hawking Radiation, which causes black holes with smaller mass to evaporate significantly quicker than the heavier ones. [3]

Table 1. Categories of Black Holes.

	Mass ($M_{\odot}$)
Stellar mass	1 - 100
Intermediate mass	1,000 – 10,000
Super Massive	≥1,000,000

2.2.1. Stellar Black holes

The stellar black hole is the most common type, as it usually forms during a supernova or collisions of neutron stars. They can have masses of up to a hundred solar masses. In the Milky Way alone, cosmologists have identified and confirmed the existence of around 50 Steller-mass black holes, although many suspect there are up to 100 million.

2.2.2. Intermediate-mass Black holes

Interestingly, although astrophysicists have confirmed the existence of Steller-mass black holes and colossal Supermassive black holes, they have yet to find black holes with masses around tens of thousands of solar masses. Since they have not been able to find black holes at this intermediate stage a contradiction with the commonly accepted theory, that black holes gain their mass primarily though the merging and accretion of other astro objects, happens. If this theory were true then black holes would appear along the entire mass spectrum, not only at the extremes. Astrophysicists have only recently confirmed the existence of an intermediate-mass black hole. They have masses up to ~$1500 M_{\odot}$. [4]

2.2.3. Supermassive Black hole

It is generally accepted that there's a supermassive black hole in the centers of every galaxy. They have millions or even billions or solar masses. How they grow that massive is still a mystery to the scientists as there simply isn’t enough time since the Big Bang to allow black holes of such size, yet many have been detected.

“Massive black holes (MBHs) inhabit galactic centers, and power luminous quasars and active galactic nuclei, shaping their cosmic environment with the energy they produce. The origins of MBHs remain a mystery, and the recent detection by LIGO/Virgo of a black hole of almost 150 solar masses has revitalized the questions of whether there is a continuum between ‘stellar’ and ‘massive’ black holes, and what the seeds of MBHs are.” [5]

2.3. Event Horizon

Some of the supermassive black holes are so astronomically large it takes weeks for light to fall into their singularity after falling into the event horizon

Eventual horizon of a black hole marks points of no returner, as the escape velocity is equal to the speed of light. To find the radius of the event horizon, also known as Schwarzschild radius. Escape velocity equation from classical physics can be applied.

$$V_e = \sqrt{\frac{2GM}{r}} \tag{1}$$

Where G is gravitational constant, M is mass of the object, and R is distance from center of mass. Set escape velocity as the speed of light and the Schwarzschild radius would be obtained.

$$r_s = \frac{2GM}{c^2} \tag{2}$$

Inside the Schwarzschild radius, nothing could escape as the space falling into the black hole at a speed which exceeding the speed of light.

2.4. Singularity

Many scientists believed that at the center of a black hole lies singularity-- an infinitely small region with a huge amount of mass that result in an extreme curvature in spacetime.

As described earlier, many black boles are remnant of a massive star, which carries a massive amount of angular momentum. Due to the conservation of angular momentum, majority of black holes in the universe should be spinning— their singularity is ring-shaped.

However, there remains much uncertainty in this field. Many of the theory described above awaits valid data gathered from future experiment.

2.5. Thermodynamic characteristics of BH

Perhaps one of the most interesting properties of black hole is that it behaves like thermodynamic objects. Stephan Hawking famously demonstrated that black hole emits radiation near the event horizon— known as the Hawking radiation.

$$T_{Hawking} = \frac{\hbar c^3}{8\pi GMK_B} \tag{3}$$

Where $\hbar$: reduced Plank constant and K_B: Boltzmann’s constant.

Black hole, like other thermodynamic objects, could exchange energy (mass) and entropy with their surroundings. This remarkable discover has shown that black hole seems to intertwine with all three of the most fundamental theories in physics— thermodynamics, quantum field theory, and general relativity. [6]

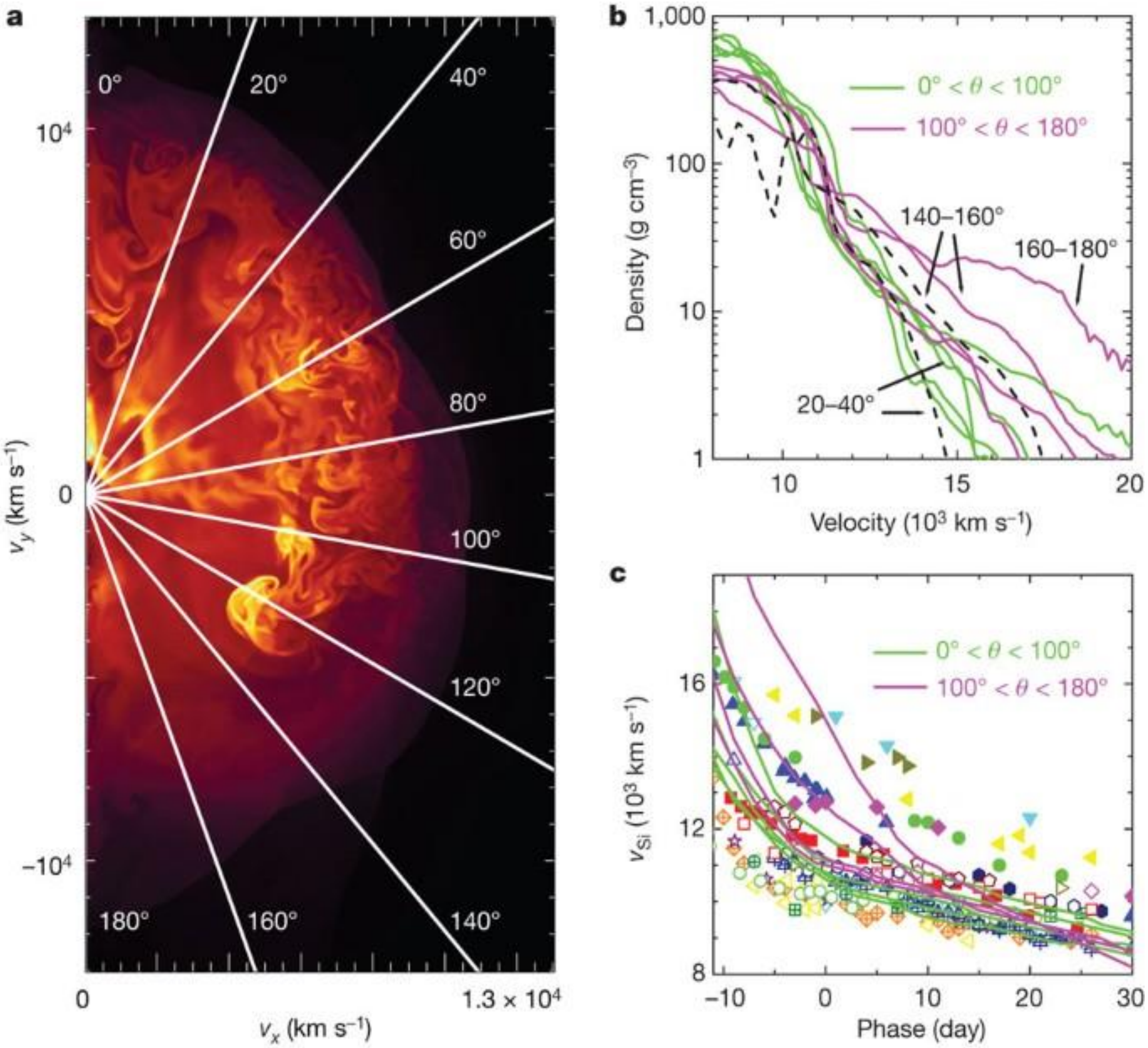

Fig 1. An asymmetric explosion as the origin of spectral evolution diversity in type ia supernovae [7].

3. The intricacy of Gravitational Waves

3.1. Overview

Gravitational waves are the ripples in the fabric of space time. Imaging throwing a small stone to a still pond, the way which ripples propagates outwards resemble how gravitational waves travel through spacetime. Only some of the most extreme astrophysical events could create detectable gravitational wave (GW). Although first predicted by Einstein's theory of General Relativity, the existence gravitational wave wasn't confirmed until 1974 when Russell Hulse and Joseph Taylor found a binary star system that was losing energy in the form of GW. In 2015, LIGO (Laser Interferometer Gravitational-Wave Observatory) made history by directly detecting GW for the first time. This is a game-changer. Until now, scientists have been able to gather information from distant galaxies only through electromagnetic wave (including visible light, radio wave, gamma ray, etc.) which is, according to the laws of physics, one of the two types of waves that carry information from distant universe. The other type consists of gravitational waves.

3.2. Formation of GW

One of the prime sources of GW are binary system. As mentioned in (Gravitational waves: Sources, detectors and searches), our most promising prospect for detecting GW lies in distant binary system as the two massive object (typically black holes or neutron stars) orbit around each other, they violently tear through the fabric of spacetime in a deadly ballet, leaving ripples that travel through space for millions of years. Although the source of the first GW event is a black hole merging event, more recently, GW from binary neutron star merging event had also been detected.

In addition to the Binary system, supernova exposition is another potential source of GW. As a massive star (> 8 solar mass) runs out of hydrogen fuel, it reached the end of its life in a supernova exposition. Due to the asymmetrical nature of such exposition (matters being ejected in an unevenly distribution), gravitational waves would be emitted.

However, GW emitted during a supernova is weaker than that of a binary system for a few reasons. Binary System typically have more mass. Mass motion of a binary system would generate stronger GW. Supernova exposition would result in a more diffuse GW.

3.3. Instrument used for measurement

In 2015, the first detection of GW by LIGO marked one of the most accurate measurements ever made— with precision down to 1/10000 the width of a proton. To put that into perspective, such precision is comparable to trying measure the variation of the width of a human hair along the distance from earth to the nearest star (Alpha Centauri), approximately 4.3 light years away. LIGO is one of the two main approach currently dominate the field: ground-based detectors such as LIGO, Virgo, Kagra & along with upcoming space detectors such as LISA and Pulsar Timing Arrays.

3.3.1. Ground-Based Gravitational Wave detector

The first is LIGO (Laser Interferometer Gravitational-Wave Observatory). There are two stations, one in Hanford, Washington, and the other in Livingston, Louisiana. Each station consists of two 4-km long vacuumed tube (by itself is the third largest vacuum chambers), with 1 MV laser. As GW passing by it alters the length of arm by a tiny amount, creating an interference pattern in the laser that would be detected by LIGO's sensor.

The second is Virgo. Located in Pisa, Italy, Virgo operates in a similar principle as LIGO but consists of two 3-km long arms. By working in conjunction, Virgo and LIGO can triangulate GW source more accurately, which in term improve the ability to locate.

The third is KAGRA. Located underground in the Kamioka mine in Japan, KAGRA is the first large scale underground GW detector. Differ from LIGO and VIRGO, it operates at cryogenic temperatures to reduce thermal noise— one of the primary sources of detector noise that potentially lead to inaccurate measurements. With the addition of KAGRA, the global detector strengthens its ability to locate source of GW waves in the sky and increase the rate of detection.

3.3.2. Space Based Detectors

The first is LISA. Planned to launch in the mid-2030s, the Laser Interferometer Space Antenna is a collaboration between NASA and ESA. It aims to detect low-frequency GW, some of which have wavelengths longer than the earth itself, making them impossible to detect for even the most advanced ground-based GW detectors. LISA consists of three spacecraft that fly in a triangular formation and separate by millions of miles. The laser beam between the spacecraft would inform them of their distance from one another. By measuring the change in distance caused by the passing GW, LISA would be able to identify their magnitude and location. [8] [9]

The second is Pulsar Timing Arrays. Pulsars are fast-spinning neutron stars that emits light beam on their polar regions, they carrier the angular momentum from the star prior to the supernova exposition. Pulsars are used as cosmic timekeepers by many astronomers as they have exceptionally regular pulse emissions. [10] By observation the arrival time of pulses from pulsars across the sky, astronomers can detect the alteration in their arrival time caused by passing GW. This method is great for detecting low-frequency GW, such as the ones emit by the merging of supermassive black holes in distant galaxies.

4. Conclusion

Overall, this paper has reviewed the latest advancement in black hole & gravitational waves in depth. Black holes were categorized into the following categories: Primordial, Steller mass, intermediate-mass, and supermassive black holes based on their mass. In addition, concept within important properties of a black hole, such as event horizon, singularity, and thermodynamic behaviors were being broken down into easily understandable pieces. The paper then dive into the intricate property of gravitational wave. Although generated by only the most violent events in the universe such as binary mergers and supernova, gravitational waves ironically require the upmost sensitive detectors for unmask their mysterious properties. Many detection methods were employed, including ground-based LIGO and Virgo, along with spaced based LISA and Pulsar Timing Arrays (PTAs), which are soon to be operational. Additionally, this article reiterates the connection between black holes and gravitational wave and how they intertwine with each other.

Our research confirmed that black hole mergers produce the strongest gravitational wave signal— a theory that will be further validated once space-based detectors LISA becomes operational. There are many key takeaways, one of which would be that different detectors could complement each other across a wide range of gravitational frequencies— from high frequency waves produced by binary stellar-mass black holes & neutron star system to low frequency wave originated from the merging of Supermassive black hole and hypothetical cosmic Strings.

Looking forward, future research would benefit greatly from the valuable date provided by the Space Based Detector. As mentioned earlier in this paper, Gravitational wave and electromagnetic wave are the only two types of waves capable of transmitting information from deep space. Together they could complement each other to provide valuable information— known as the multi-messenger approach. By integrating date from both EW and GW, physicists could potentially unlock deeper secrets of the cosmos.

In conclusion, the ongoing research in the field of black holes and gravitational wave is set to unlock the universe's deep secrets. Additional, ongoing technological advancements in GW detection and the adoption of multi-messenger astronomy would pave the way for a new generation of space exploration, along with the potential of answering some of the most pressing question in Astrophysics.

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