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Understanding The Physical Properties of Neutron Stars and Black Holes Through Analysis of Gravitational Waves from Their Collisions

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ABSTRACT: Two celestial bodies, more than 100 times the mass of the sun, are hurtling towards each other, colliding to send ripples through the very fabric of reality. It is from this chaos that the grandest elements like gold and platinum form, or an even grander singularity is born, where our laws of physics cease to exist. And in short, this is how black holes, as well as neutron stars, collide. Due to recent advances in the field of gravitational wave technology and through observations by LIGO and Virgo, we have received immense new data, which makes it easier to analyze the collision of neutron stars and black holes using gravitational waves. Scientists often use machine learning data models to observe waveforms and determine physical parameters. This paper uses such detections to evaluate physical features about black holes and neutron stars, such as mass, angular momentum, tidal deformability, etc., by analyzing gravitational waves from their collisions. Understanding these features allows us to test theories like that of dense matter and even the limits of physics as we know it.

KEYWORDS: Physics, Astrophysics, Black Hole Collisions, Neutron Star Collisions, Gravitational Waves.

Introduction

When the universe's densest bodies—black holes and neutron stars—collide, they release more energy in mere seconds than our sun can in its entire lifetime. During this brief time, space and time ripples, new elements are born, and even larger black holes are formed as our universe is not just disturbed but reshaped.

These mergers or collisions can occur between binary black hole systems, binary neutron star systems, as well as black holes and neutron stars. These collisions send across gravitational waves— invisible ripples that travel through space—which help us detect physical components like mass, density, spins, tidal deformability, nuclear matter characteristics, etc., of these structures. This is one of the newest observations in astrophysics, with gravitational waves only being discovered in 2015,[1] although first predicted by Einstein in 19182 as a consequence of his general theory of relativity. GW150914 in 2015 was the first black hole collision detected by the Laser Interferometer Gravitational-Wave Observatory (LIGO).[3] This paper focuses on the physical properties of black holes and neutron stars that can be detected through analysis of gravitational waves from their collisions.

We need to understand the physical properties of these collisions to learn more about these events. Studying the properties like tidal deformability of neutron stars literally tells us about ultra-dense matter, while studying properties like spin distributions of black holes gives us a deeper understanding of how they were formed. Though there exist many papers about how gravitational waves have been used to detect specific properties of compact objects—talking about specific case studies or events—there is a lack of papers that specifically emphasize the physical nature of these collisions. This paper aims to do just that and address this lack by instead of focusing on observed data, showing how analyzing gravitational wave data can give us the physical properties like mass, spin, momentum, tidal deformability, etc., of binary black hole, binary neutron star, and black hole–neutron star collisions. It will review the common and unique physics of the events and refer to theories of general relativity,[2] dense matter, etc. Analyzing properties of black holes like mass ratios, spin magnitudes, etc., not only allows us to test the theory of general relativity but also tells us how black holes form and evolve.[3] Measuring radius, tidal deformability, etc., of neutron stars tells us about the equation of state, which is how matter behaves at nuclear and supranuclear densities. We also get information about the origin of heavy metals like gold and platinum through the process of nucleosynthesis. It is almost impossible for any experiment on Earth to recreate these processes, making studying these vital to not only astrophysics but also other basic sciences. Studying this helps us understand how matter is disrupted, and electromagnetic emissions like radiation and light are generated. It starts with a qualitative overview of general relativity (2.1). The next part (2.2) contains the breakdown of the different phases of a merger (inspiral, merger, and ringdown) and then focuses on physical properties derived from the gravitational wave data, like mass, spin, and tidal deformability (2.3). Important events like GW150914,3 GW170817,[4] and GW200115[5] are discussed along with their importance (2.4). It then talks about the astrophysical implications of these collisions, like equations of state, formation, and evolution of black holes (2.5). Finally,(2.6) it looks at future experiments and detectors that can help progress developments in this field and areas that should be focused on. The research used in this paper includes published data, such as results from detections, simulations, and

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prior analyses, to highlight the findings. This work is a review and does not present new gravitational-wave data analysis; it synthesizes existing observational results and theoretical models to highlight the physical interpretation of compact binary mergers.

Results and Discussion

2.1. The Theory of General Relativity:

The Theory of General Relativity by Albert Einstein was first published in 1916,[7] 11 years after his Special Theory of Relativity. A useful quote by John Archibald Wheeler can help sum it up—*Spacetime tells matter how to move; matter tells spacetime how to curve*. This can be explained using an analogy (Figure 1):

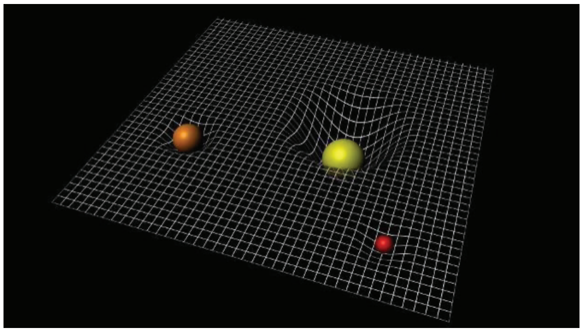

Figure 1:[6] Illustration of spacetime curvature caused by a massive object.

Imagine a stretched sheet of some rubber (spacetime) on which a ball (mass like a star) is kept. This obviously deforms the spacetime around it by "curving" it, and thus an object of a smaller mass (planet) when moving around it is not being "pulled" into it but following geodesics, which is the straightest possible path any object can take in a curved spacetime. The heavier the object, i.e., the more mass it has, the steeper the curves will be, and hence the geodesics will bend more sharply, causing smaller objects to be pulled into it.

Regarding this, Einstein's field equation states (Figure 2):

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

where $G\mu\nu$ is the curvature or Einstein tensor telling us how much spacetime is curved at a particular point in time, is the mass-energy or stress-energy tensor, G is Newton's gravitational constant (6.674×10^{-11} N·m^2/kg^2), and c is the speed of light (3 * 108 m/s).

General Relativity also talks about spacetime and mass-energy in the context of gravitational waves. When two masses orbit each other, spacetime gets deformed as discussed earlier. When the speed of these masses accelerates, they send ripples through space and time in all directions away from the source, i.e., themselves. These ripples are known as gravitational waves.[7]

These waves propagate away from their source at the speed of light and carry information about their origin. They are not distortions traveling through spacetime, but distortions of spacetime. Collisions of black holes and neutron stars provide strong gravitational waves, which are the key components that are detected and analyzed to obtain information about their physical nature by observatories like LIGO (Laser Interferometer Gravitational-Wave Observatory) and Virgo.[9] In fact, though Einstein's Theory of General Relativity (1916) predicted the existence of gravitational waves,[7] it was not detected until 14 September 2015 by LIGO when two massive black holes collided—GW150914.[10]

The theory of conservation of energy makes it impossible to produce gravitational waves by shifting the total mass up and down (monopole) or moving the center of mass back and forth (dipole). Instead, a quadrupole change is what generates gravitational waves, which is when the shape of the mass distribution is changed (stretched or squeezed) over time, like in orbiting binary systems. This wave distortion or strain depends on how fast the quadrupole changes, and the power carried depends on the acceleration of this change. This concept was originally discovered by Einstein in 1918,[11] confirmed indirectly through binary pulsar energy loss,[12] and finally observed by LIGO.[10]

According to weak-field observation, when a source is very far away, the curvature of spacetime is less distinct, so a flat Minkowski spacetime can be considered with a ripple. This can be shown through the following equation (Figure 3):

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

where $g\mu\nu$ is the spacetime metric, $\eta\mu\nu$ is the Minkowski metric from the theory of Special Relativity, and $h\mu\nu$ is the ripple that represents the gravitational wave. It helps provide an easier and simpler way to study gravitational waves without going into much detail about the math behind general relativity. This was derived by Einstein in his 1918 theory.

2.2. Phases of the Merger:

Merger:

A merger between stellar objects refers to the process by which these stellar bodies orbit each other at accelerating speeds and eventually collide due to the emission of gravitational waves by the bodies.[13] At this time, the spacetime curvature is greatest, and the gravitational wave signals have the most amplitude and frequency. These mergers between binary black hole systems, binary neutron star systems, and even black hole–neutron star systems will be studied. There are several phases to these mergers.

Inspiral Phase:

The first and longest phase of the merger is known as the inspiral phase. It is a very significant phase, as the gravitational wave signals from this phase are understood very well, helping scientists predict accurate information on the physical properties of these collisions.[14] In short, it is when the two bodies (neutron stars/black holes) are circling each other with increasing acceleration and are about to collide. This phase produces the gravitational wave "chirp" signal[15] which is a form of gravitational wave that continuously increases its frequency and amplitude over time. It occurs as the two objects orbit each other, they lose energy and angular momentum, radiating these waves. This produces a sort of feedback loop where the loss of energy and momentum causes the orbits to tighten more, accelerating the motion of the objects and generating more and more energetic gravitational waves, i.e., chirps with increasing amplitude and frequency. This freq of these waves is always double that of the orbit. For stellar mass binaries like binary neutron star systems, this usually occurs in seconds before the merger with detectable frequencies, while in supermassive black hole systems, it can last for minutes but be much less detectable. For neutron star binaries, finite-size tidal effects become important during the late inspiral and introduce additional phase shifts that depend on the tidal deformability parameter Λ, which encodes information about the neutron star equation of state.

Merger Phase:

The merger phase is the most violent and dynamic part of a binary collision, lasting from milliseconds to a few seconds.

As the two objects reach the innermost stable circular orbit (ISCO), after losing their orbital energy due to emission of gravitational waves, they collide and merge into a larger and more compact object.[16] It is a rapid occurrence where both objects move at a huge fraction of the speed of light. The curvature of spacetime is the most extreme here, and any gravitational interactions are non-linear.

For binary black hole mergers, this system includes the deformation of the black hole event horizons and their merging into a single, larger, common event horizon.[17] This also creates a new black hole that rapidly spins away. For binary neutron star mergers, the presence of matter makes the process much more complicated. Matter is heated to high temperatures and densities, which can form a hypermassive neutron star for a limited amount of time before collapsing into a black hole. The projection of matter can also occur, forming a kilonova.[18]

The merger part gives us the most powerful gravitational wave signals. It includes rapid increases in frequency and amplitude, leading to a single peak.[16] At this peak, the signal lasts only for a fraction of a second but radiates a huge amount of energy. This marks the point of peak luminosity, which can produce astonishing amounts of power—for the first-ever detection, GW150914, the peak gravitational wave luminosity exceeded the combined electromagnetic output of all the stars in the observable universe.[10]

The waveform of the merger is more complex than that of the inspiral phase, as it contains a superposition of various frequencies. Thus, modeling the gravitational waveform requires complex numerical relativity simulations, unlike the simpler PN model(a method of approximation used in General Relativity to find the motion and radiation of gravitational waves in binary systems), approximations in the inspiral phase.[14]

A unique feature of this part of the merger is the "kick" or the gravitational recoil that happens in binary black hole mergers when the gravitational waves emitted are anisotropic and carry away linear momentum. In accordance with the principle of conservation of momentum, the newly formed black hole moves in the opposite direction.[19] Thus, the asymmetry in the emission of the gravitational waves is due to the misalignment between the spins of the black holes individually and the orbital angular momentum of the system, leading to precession of the orbital plane.[20]

This "kick" can cause recoil velocities of 5000 km/s, enough to expel a black hole from its original galaxy.[19] When it comes to the collision of two supermassive black holes, typically after the collision of their two galaxies, such "kicks" can cause the remnant to be removed from its galactic center and host galaxy, changing the evolution of both the black hole and the galaxy.[21] In neutron star mergers, a physical process called tidal disruption occurs. This is when a neutron star is completely torn apart by the tidal forces of its merger partner. This process then causes the ejection of matter, forming an accretion disk around the remnant after the collision. This process is extremely pertinent as, unlike in black hole mergers, these radiate electromagnetic material.[18] The material that gets ejected radiates across the electromagnetic spectrum, providing us with signals like a short burst of gamma rays or a kilonova. For example, in the GW170817 event where two binary neutron stars collided, the gravitational wave signal was followed by a short burst of gamma rays as well as a kilonova.[4]

Ringdown Phase:

The ringdown phase is the final phase of the merger. Though it is a brief stage of only fractions of a second to a few seconds, it is when the remnant of the collision or merger finally settles down into a stable stage.[16] After the dramatic merger phase, the remnant is newly formed, unstable, and distorted. During the ringdown phase, this remnant settles down into a stable equilibrium stage and releases a final burst of gravitational waves.

For a black hole, this final burst of gravitational waves includes exponentially damped oscillations called Quasinormal Modes. They are constantly damped due to continuous emission of gravitational radiation and are also known as the black hole's "fingerprint" because they provide a lot of information on the properties of the black hole.[22]

The remnants of neutron stars, however, are much more complex. The collision of neutron stars can lead to a new black hole and also hypermassive neutron stars that collapse after a short time. The gravitational wave signal contains information about this remnant finally settling down.[18] It is short-lived and chaotic, often releasing electromagnetic radiation.[4]

Thus, the three phases of the merger—inspiral, merger, and ringdown—are not completely different occurrences but all linked together to create a process that alters the shape of our universe. They have been crucial in receiving information regarding the physical properties of these collisions, which shall be discussed in detail later. They have also helped us discover many new truths and develop a deeper understanding of our universe. However, challenges remain.

For example, the impact of this "kick" or gravitational recoil in black hole mergers, especially when it comes to their galactic cores, is constantly being questioned.[19] However, with constant upgrades to the LIGO and Virgo observatories,[9] detectors, and key events like the GW170817 binary neutron star merger,[4] we are constantly receiving and decoding new information regarding these collisions. By combining these

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observations throughout the various spectrums, we will be able to paint a newer and more complete picture of this universe.

2.3. Physical Properties:

The detection, followed by the analysis of gravitational wave signals from these collisions, provides us with a lot of information on the physical properties of neutron stars and black holes themselves.

Quantities such as the chirp mass and the overall amplitude and frequency evolution of the signal are tightly constrained by the data itself; parameters including individual component masses, spin orientations, tidal deformability, and neutron-star radii require assumptions about general relativity, waveform models, and the equation of state of dense matter and theoretical modeling. This part of the paper defines how these physical properties are extracted for both the collisions commonly and specifically.

Mass and Mass Ratio:

Mass is the most important parameter we can extract from a gravitational signal from a merger. Since the individual masses cannot be directly determined from the signal, we instead extract a parameter called the chirp mass ($\mathscr{M}$), which is a specific combination of the masses of the two components that is mainly inferred from the gravitational waves in the inspiral phase.[23,24]

First, we need to understand the post-Newtonian (PN) expansion to understand the inference of chirp mass. The Post-Newtonian expansion is a simpler way to tell us about the orbital motion of the two bodies in terms of orbital velocity relative to the speed of light.[23] In simpler terms, it tells us about the increase in frequency of the gravitational wave over time, or gravitational wave chirp. In the lowest order, it can be defined with the following formula (Figure 4):

$$\frac{df}{dt} = \frac{96}{5}\pi^{8/3}\left(\frac{G\mathcal{M}}{c^3}\right)^{5/3} f^{11/3}.$$

Where f — **Gravitational-wave frequency**, equal to twice the orbital frequency of the binary in the inspiral phase; df/dt is the **Frequency evolution (chirp rate)**, describing how rapidly the gravitational- wave frequency increases as the binary loses energy through gravitational radiation. G is **Newton's gravitational constant**, governing the strength of gravity; c is the **Speed of light in vacuum**, setting the relativistic scale of the system; $\mathscr{M}$ is the chirp mass, and π is pi.

Since it is directly proportional to the frequency evolution, it is connected to the rate at which the frequency of the gravitational wave chirp increases. Since it is directly related to the waveform observed by scientists, we can infer the chirp mass with relative accuracy by measuring the derivative of frequency and time of the gravitational wave signal.[24,25] Chirp mass can also be defined using the formula (Figure 5):

$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}.$$

where m1 and m2 are the masses of the two components, however, we cannot always determine the individual masses from this equation, as different combinations or ratios of m_1 and m_2 give us the chirp mass. Thus, to get the individual masses and mass ratio, we must use PN formulas or corrections of a much higher order and complex nature.[23] These can include other physical components as well, like spin, higher-order velocity, etc. Since these other parameters cannot be as accurately measured from the waveform as the chirp mass, the degree of accuracy of the masses also decreases.

Another requirement to consider while measuring mass is the cosmological redshift(z). Since gravitational waves are stretched while they travel across the constantly expanding universe, the chirp mass is not the natural chirp mass but the chirp mass that has been influenced by the cosmological redshift.[25] Their relationship can be described by-observed $\mathscr{M}$ = Intrinsic $\mathscr{M}(1 + z)$

Thus, the gravitational waveform is not the only thing that must be considered while determining $\mathscr{M}$, as we also need to consider the redshift of the system. This can be done by multimessenger astronomy, where an electromagnetic complement can help us determine the cosmological redshift. For example, in the GW170817 event, the gravitational-wave signal and the electromagnetic signals from the kilonova due to the neutron star merger gave us an accurate redshift measurement.[26,27] On combining the Gravitational wave estimate of distance and electromagnetic wave estimate of distance, the deterioration between the mass and cosmological redshift was removed. Thus, both the combined electromagnetic wave signals and gravitational wave signals can give us extremely accurate information on the masses of the components of the systems.

Spin of Components:

The spin of the two components involved in the collision heavily influences the shape of the gravitational waveform, helping us decode plenty of information.[28] Spin is a vector quantity, so the magnitude and direction in relation to the orbit impact the radiation emitted and thus the information we infer regarding the collision.

One of the most fundamental parameters to consider here is the effective spin- mass-weighted average of the two components of the spin. If the effective spin is positive, this means that spin is aligned with the orbital angular momentum, and the "hang-up" effect is observed. During this effect, the orbital angular momentum increases, slowing down the inspiral phase of the merger. The gravitational wave signals sent to the LIGO and Virgo detectors last much longer and are thus much easier to detect.[28] If the effective spin is negative, the spin is anti-aligned with the orbital angular momentum; the opposite effect can be observed. During this effect, the orbital angular momentum decreases, increasing the speed of the inspiral phase of the merger. This shortens the gravitational wave signals sent to the LIGO and Virgo detectors, making them harder to detect.[29]

However, by measuring the effective spin across many collisions, scientists can understand the evolution of these mergers and test predictions on different merger models.

Spins that are aligned or anti-aligned with the orbital angular momentum are known as aligned spins. There also exists a different type of spin caused by precessing spins, where the spins are tilted to some extent with respect to the orbital angular momentum.[30]

In this case, the theory of general relativity states that the orbital plane precesses around the total angular momentum.[28]

Precession is the movement of a spinning body around another such body due to a torque that changes the direction of the first body's axis, like how a spinning top will wobble under gravity due to precession. This can be detected in gravitational wave signals as there are modulations periodically in the amplitude and the phase of the waveform due to a change in the location of the precessing merger in relation to the Earth.[30] This not only gives us information that the spins are not aligned but also removes any degeneracies that exist while interpreting the waveform.

During isolated binary evolutions, the objects form a binary system earlier and end up evolving with each other. Thus, various processes, including tidal locking and stellar winds, align their spins with the orbital angular momentum. They show aligned spins with an effective spin nearly equal to zero or positive in nature.[31]

In dynamic binary evolutions, the objects are formed separately and brought together much later. This can be seen in dense stellar environments like clusters. The pairing of objects in this case is very random, and isotropic spin orientations are seen where there is no specific alignment.[32] There can be a mix of anti- aligned, misaligned, and slightly aligned spins of the mergers. The GW190521 event, which had strong evidence of precession, had a dynamic binary evolution,[33] but the GW170817 event of neutron star merger had relatively small spin effects and an isolated binary evolution.[26]

Radiated Energy and Angular Momentum:

Since the merger of black holes and neutron stars is one of the most energetic events, we already know that a small part of the masses of the components is transformed into gravitational-wave energy.[28] The amplitude and time span of the signal give us the radiated energy and angular momentum of the system, as those parameters tell us how much energy is converted to gravitational wave signals.[23] This radiated energy causes the collision by decreasing the distance between the objects and the overall energy of the system.

Black hole mergers particularly radiate a lot of gravitational wave energy, with the LIGO and Virgo detectors showing that these mergers have radiated energy equivalent to 1–3 solar masses in the fraction of a second.[26] This is literally more light energy than all the stars in the observable universe can emit at the same time. The efficiency of this radiation depends directly on the natural or intrinsic properties of the bodies, like mass, spin, etc. Binaries that have components with equal mass and aligned spins to the orbital angular momentum produce the biggest fraction for mass-gravitational wave energy conversion and have the longest inspiral phase.[28] The remnant thus contains the remaining mass and angular momentum of the system. These can also lead to strong gravitational kicks, already discussed earlier, which have a velocity of thousands of kilometers/second, ejecting black holes completely from their host galaxies.[30]

Final Remnants:

The collision finally leads to the formation of a remnant (a new, larger object that contains the remaining mass and angular momentum of the system).

For black holes, this remnant is usually another larger black hole as described in the Kerr Metric of the Theory of General Relativity.[28] The mass and spin of the remnants are not fixed at the beginning but established much later during merger and ringdown phases as large amounts of energy and angular momentum are radiated away from the system.[34]

As the gravitational wave signals conclude during the ringdown stage, spacetime vibrates around the remnant. This vibration can be expressed in the form of damped oscillations called quasinormal modes (QNMs).[34] Each mode has its own oscillation frequency and damping timeline depending on the remnant's spin and mass. Thus, through these quasinormal modes, the mass and spin of the remnant can directly be measured without the need for information on the previous inspiral phase.[34] This also helps us test the No-Hair theorem, which states that a stationary black hole can be understood just by its mass and its angular momentum.[34] One of the main tests for this is the Inspiral-Merger-Ringdown Consistency Test, which compares the remnant mass and spin predicted in the inspiral and merger phase to the remnant mass and spin of the ringdown phase.[34] If these estimates are constant, the No-Hair theorem from The Theory of General Relativity is true; any significant discrepancy would lead to a new physics beyond The Theory of General Relativity.

The remnants of neutron stars, however, are much more complex. The collision of neutron stars can lead to a new black hole or an HMNS (hyper-massive neutron star), which collapses after a short time.[37] The gravitational wave signal contains information about this remnant finally settling down. It is short-lived and chaotic, often releasing electromagnetic radiation.[38]

Demonstrative Example:

During the inspiral phase of a compact binary merger, the gravitational-wave signal is dominated by the gradual increase in the chirp mass defined above. The rate at which the gravitational-wave frequency increases is directly proportional to the chirp mass and frequency of the signal, so through measuring the frequency and its time derivative directly from the observed waveform, the chirp mass can be determined with high precision, largely independent of other parameters such as spin. For example, in the first gravitational-wave detection, GW150914, the observed chirp mass was approximately 30 $M_\odot$, indicating a binary system composed of two stellar-mass black holes significantly heavier than those previously observed through electromagnetic methods. While the chirp mass is tightly constrained, the individual component masses are less precisely determined because they enter the waveform at higher post-Newtonian orders and are partially degenerate with spin effects. In neutron star mergers, additional finite-

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size effects appear during the late inspiral. These tidal effects introduce small but measurable deviations from the point-particle waveform, allowing parameters such as tidal deformability to be constrained alongside the chirp mass. Thus, gravitational-wave observations enable both precise mass measurements and, in the case of neutron stars, direct probes of internal structure.

Properties specific to Neutron Stars:

Tidal Deformability (Λ) and Radii:

Tidal deformability is one of the main factors that separates neutron star mergers from black hole mergers.[35] In binary neutron star systems, each star deforms due to the tidal gravitational field of its merger partner.[35] This deformation, known as quadrupole deformation, is small compared to the overall size of the star but has a measurable impact on the gravitational-wave signal, introducing an additional phase shift. These tidal effects become especially important during the final few orbits before merger, when the orbital separation is smallest and gravitational tidal forces are strongest.[36] The degree of tidal deformation is described by the dimensionless tidal deformability parameter, Λ, which characterizes how susceptible a neutron star is to tidal distortion based on its mass and internal structure.[35] Neutron stars described by a stiffer equation of state have higher internal pressure, resulting in larger stellar radii and larger values of Λ, which produce stronger tidal signatures in the gravitational- wave waveform. In contrast, softer equations of state correspond to more compact neutron stars with smaller radii and smaller Λ, leading to weaker tidal effects.[36] In this way, the tidal deformability parameter Λ provides direct information about the properties of ultra-dense nuclear matter.[36] landmark detection of the GW170817 event provided the first observational constraints on tidal deformability.[27] Analysis of the inspiral phase placed an upper limit on Λ, ruling out extremely stiff theoretical models that predicted neutron stars with very large radii and strong tidal distortions.[36]

Since constraints on the equation of state determine the relationship between neutron star mass and radius, measurements of Λ can also be used to infer neutron-star radii.[35] For the GW170817 event, gravitational-wave observations indicated that a neutron star with a mass of approximately 1.4 $M_\odot$ has a radius in the narrow range of about 11.8–13.7 km.[27,36] These findings not only constrain neutron-star radii and equations of state but also provide insight into whether exotic forms of matter, such as deconfined quarks, may exist in neutron-star cores, as well as the maximum mass these stars can support before collapsing into a black hole.[37] Tidal deformability is unique to neutron stars because it arises from their finite size and internal structure. Black holes, by contrast, have no material surface or deformable interior and are fully described by vacuum solutions to Einstein's equations, meaning no tidal deformability effects occur in black hole mergers.[35]

The Final Remnant and Signal

The remnant of a binary neutron star merger depends on the mass of the total system and the nuclear equation of state.[37] It is not common or universal to all mergers. Various possible things could happen- Black Hole- If the mass exceeds the constraint or limit determined by the Equation of State, around $\gtrsim$ 2.8–3.0 $M_\odot$, the remnant immediately collapses to form a black hole with almost no stage in the middle and a very short ringdown gravitational wave signal.[38]

Hypermassive Neutron Star- If the mass is slightly lower compared to the above case, around 2.6–2. $M_\odot$, a hot neutron star is formed, which rotates in different directions. Its mass exceeds the limit on a uniformly rotating star, so though it can be stabilized temporarily by rapid rotation and thermal support, it almost immediately(within milliseconds to seconds) collapses to form a black hole due to cooling down and reduction of angular momentum.[37]

Supramassive Neutron Star: If the mass is slightly lower compared to the above case, around 2.3–2.6 $M_\odot$, a rotating neutron star is formed. Since its mass is above that of the maximum non-rotating limit but less than the differential rotation limit, it survives for longer (it can survive for a few hours). Eventually, it collapses to form a black hole due to the reduction of angular momentum.[38] Stable Neutron Star: If the mass is relatively much lower, typically $\lesssim$ 2.2 $M_\odot$, a new stable neutron star is formed that has a long lifetime before it collapses.[37] When the remnant forms a Hypermassive Neutron Star or Supramassive Neutron Star, a shorter but higher-frequency (2–4 kHz range) gravitational-wave signal is generated.[38] However, unlike the inspiral signal, which is dependent on tidal deformability, the post-merger signal is dependent on the supranuclear-density of the EoS.[37] These post-merger signals are relatively much weaker, so there are certain limits on their detections as seen during the absence of a clear post-merger signal in GW170817.[27] This is trying to be overcome by observatories like Einstein Telescope and Cosmic Explorer, which are currently under development and are sensitive to kHz.[38]

To conclude and summarize, the following table tells us about the physical properties of these compact mergers (Table 1):

Physical Properties Summary:

Table 1:

Property	Waveform	Phase
Chirp Mass	Frequency (df/dt)	Inspiral
Mass Ratio/ Individual Mass	Higher order PN terms	Inspiral/Merger
Aligned Spin	Duration	All
Misaligned Spin	Precession	All
Final Mass	QNM frequency	Merger/ Ringdown
Final Spin	QNM decay time	Ringdown
Radiated Energy	Amplitude/ Duration	Merger/ Ringdown
Tidal Deformability	Phase Shift	Inspiral

2.4. Key Events:

The field of gravitational wave astronomy evolved from Einstein's Theory to reality by the first LIGO detection in 2015.[39] Since then, the LIGO and VIRGO observatories have recorded black hole mergers, neutron star-neutron star mergers, and even black hole-neutron star mergers, which gave insight and information on the physical properties of these objects.[40] The following key events- GW150914, have not only validated already existing theories but challenged them, introducing new concepts like multi-messenger astronomy.[39–43]

These detections have only been made possible by many observatories like the LIGO Laser Interferometer Gravitational-wave Observatory and Virgo observatory, which can detect minute changes between two mirrors spread across vast distances of several kilometers.[44] The LIGO in Hanford, Washington, and Livingston, Louisiana, has two 4 km L-shaped interferometers where split laser beams measure distortions as small as 10^{-19} m.[44] The Virgo near Pisa, Italy, with 3km arms, works similarly. They began joint observations in 2017, which improved sky localization, helping with follow-up observations.

GW150914- The first detection of gravitational waves by LIGO on 14th September, 2015, when two black holes of 29 and 36 M⊙ merged into a 62 M⊙ remnant, radiating 3 M⊙c^2 in 0.2s.[39] Before this, we only knew of black holes as massive as 20 M⊙, but this showed us that black holes of 29 and 36 M⊙ can exist and merge, releasing ~3 M⊙ of energy in a fraction of a second—more than all the stars in the observable universe at that moment. It confirmed Einstein's Theory of General Relativity, matched the Kerr metric, and proved that interferometers like LIGO can detect waves invisible to telescopes, revolutionizing the field of gravitational wave astronomy.[39]

GW170817- The first neutron star merger on August 17, 2017, by LIGO and Virgo, where both gravitational waves and electromagnetic waves were detected, giving rise to the concept of multi- messenger astronomy.[41,42] In this event, a 100-second signal was followed by gamma rays, kilonova, X-rays, and radio waves, which confirmed the r-process nucleosynthesis in neutron star mergers, constrained neutron star radii (~10–13 km), and showed the effects of tidal deformability.[41,42]

GW190521- The detection of 85 and 66 M⊙ black holes merging to form a 142 M⊙ remnant on May 21, 2019, by LIGO and Virgo, which was the first detected intermediate-mass black hole43 and violated the "mass gap" from stellar evolution theory and confirmed theories of hierarchical mergers where black holes can combine to form larger ones.[43]

GW200105 & GW200115- The detection of neutron star and black hole collisions by the LIGO and VIRGO collaborations on January 5, 2020, and January 15, 2020, respectively.[40] GW200105 had a 9 M⊙ black hole and 1.9 M⊙ neutron star forming an 8.9 M⊙ black hole remnant, while GW200115 had a 6 M⊙ black hole and 1.5 M⊙ neutron star forming a 6.4 M⊙ black hole remnant. This confirmed neutron star–black hole mergers as well as dark mergers due to almost no electromagnetic radiation detected, and expanded our knowledge on these mergers.[40]

The above-mentioned 5 key events revolutionized this field in astrophysics forever by detecting gravitational waves, three merger types (BH–BH, NS–NS, NS–BH), and introducing the concept of multi-messenger astronomy.[39–43] They constrained the equation of state of ultra-dense matter and confirmed the r-process of nucleosynthesis as well as intermediate-mass black holes.39–43 New upcoming detectors and improved sensitivity of the current detectors shall help us detect more gravitational waves and possibly discover a new type of signal.[44]

2.5. Astrophysical Implications:

Detection of Gravitational-Waves and Multi-Messenger Astronomy:

The field of gravitational wave astronomy has become a new way to explore the universe, as these waves have not only confirmed black hole-black hole collisions, neutron star-neutron star collisions, and black hole- neutron star collisions, but also allowed us to test existing theories and gain information on the physical properties of these stellar objects and their mergers.[26,27] Certain events like GW170817 combined this gravitational wave emission with electromagnetic emission, which gave rise to the concept of Multi-Messenger Astronomy and helped us get a better understanding of physical parameters like chirp mass, distance, and the location of the collision.[28,29]

The Equation of State and Tidal Deformability:

Neutron stars are made of ultra-dense nuclear matter, so their structure depends on the nuclear equation of state (EoS), which describes how matter behaves under different conditions.[30] One of the main observable properties related to the EoS is tidal deformability, which tells us the degree of distortion of a star due to its partner's gravitational field.[31] Although this quadrupole deformation may be small, it causes a measurable phase shift in the inspiral gravitational-wave signal, especially in the final orbits before the merger, where the gravitational tidal forces are strongest.[32]

A stiffer EoS produces neutron stars with larger radii and stronger pressure support, resulting in stronger tidal effects, whereas a softer EoS produces smaller, more compact stars with weaker tidal deformation signatures.[30] This information also tells us about the size and stability of neutron stars.

Observations from GW170817 show that a 1.4 M⊙ "canonical" neutron star has a radius of around 11.9 ±1.4 km, ruling out extremely stiff EoSs that predict oversized stars as well as overly soft EoSs that are inconsistent with the existence of 2 M⊙ pulsars.[28,33]

Because neutron stars reach densities several times greater than that of an atomic nucleus, conditions unachievable on Earth, they act as natural laboratories for nuclear physics.[34] Constraints from GW170817 placed limits on the pressure of matter at approximately twice nuclear saturation density, helping refine theoretical models and rule out unrealistic EoSs.[28,35] The EoS also determines whether the merger remnant collapses immediately into a black hole or forms a long-lived neutron star, as well as the amount of matter ejected, linking it to nucleosynthesis and short gamma-ray bursts.[28,36] A remnant with a softer EoS has less pressure support and is more likely to collapse promptly into a black hole, whereas a stiffer EoS allows higher maximum masses and can produce a hypermassive or supramassive neutron star that survives for milliseconds to seconds before collapse, or in some cases remains stable. A stiffer EoS can also lead to greater matter ejection through tidal interactions, which is important for r-process nucleosynthesis.[28]

R-Process Nucleosynthesis:

Neutron star mergers tell us of the origin of heavy elements like gold, platinum, and even uranium through the rapid neutron-capture process (the r-process).[37] Nucleosynthesis is the process by which atomic nuclei are formed through existing particles like protons, neutrons, etc.[38] In GW170817, neutron-rich debris ejected at ~10% the speed of light underwent nucleosynthesis, with radioactive decay powering the kilonova afterglow.[28,39] The kilonova color change from red to blue indicated many ejecta components which produced lighter nuclei ($Z < 140$) and heavier nuclei, including lanthanides and actinides.[28,39] Spectroscopic observation confirmed strontium, the first element traced to cosmic nucleosynthesis.[40] Though this confirms that neutron star-neutron star collisions are dominant sources of r-process nucleosynthesis, questions remain whether other cosmic phenomena like collapsars also contribute.[41]

Stellar Formation:

Binary black hole mergers form through isolated binary evolution and dynamical assembly in dense stellar clusters.[42]

The isolated binary evolution of two stellar objects evolves together and eventually collapses to form a black hole, though uncertainties exist, like "common envelope," where the outer envelope of one object should expand and engulf its companion, mass transfer, and supernova kicks that can unbind binaries.[42,43] The dynamic channel in denser environments like globular clusters and nuclear star clusters brings black holes together, often leading to hierarchical mergers where remnants can merge again, possibly producing intermediate-mass black holes.[44] However, parameters like merger rate evolution with redshift, eccentricity, and most importantly, spin alignment are required to gain more information.[45]

Mass Gap:

Stellar evolution theory predicts a mass gap of ~50–120 $M_\odot$ where black holes cannot form due to the pair-instability supernova where the core of massive stars is hot enough to form electron–positron pairs, reducing internal radiation pressure that counteracts the impact of gravity, triggering the runaway contraction and explosive burning that destroys the star, leaving no remnant which explains the predicted black hole “mass gap” of 50–120 $M_\odot$.[46,47] This theory was disputed by the GW190521 event, where the masses of the colliding black holes were 66 $M_\odot$ and 85 $M_\odot$ approx, and forced scientists to reconsider.[48] Alternate theories like dense stellar environments, where repeated mergers push remnants into the gap, and alternative stellar pathways, where low metallicity and rotation alter mass loss and allow direct collapse into heavier black holes, have been proposed.[49] Detecting black holes in this mass gap has broader implications for stellar evolution. Population III stars could have formed black holes and distinguished between isolated stellar evolution and dynamical assembly ways.[50]

Neutron Star-Black Hole Collisions:

The fate of a neutron star-black hole merger can be determined depending on whether the neutron star crosses the black hole’s event horizon before it is deformed by tidal forces.[51] If disruption happens before the ISCO is reached by the powering kilonovae, gamma-ray bursts, and r-process nucleosynthesis.[52] Otherwise, the neutron star directly moves into the black hole with limited matter ejected. This causes a “dark merger" that can only be detected by gravitational waves.[51]

This depends on physical properties like mass ratio, spin of black holes, and compactness of neutron stars.[53] High spins and lower mass ratios shift the innermost stable orbit inward, giving tidal forces time to disrupt the neutron star and produce ejecta and light.[54] High mass ratio and low spin cause plunging of the neutron into the black hole with no electromagnetic signals. GW200105 and GW200115 confirmed these “dark mergers” with minimal electromagnetic radiation.[55] Thus, the absence of detection of light from a merger reveals information like the mass, spin, as well as constraints on the EoS of ultra-dense matter.[51] Thus, gravitational astronomy has helped us revolutionize our understanding of astrophysics, constrain the EoS of dense matter, uncover nucleosynthesis sites, and reshape stellar evolution theory.[26–55]

2.6. Future:

After the first detection of gravitational waves in 2015, a new window was opened to observe the universe. The current observatories, like LIGO and Virgo, have made revolutionary discoveries that not only confirmed the Theory of General

Relativity, but also provided unprecedented insights into the properties and collisions of black holes and neutron stars.[56,57]

As science progresses, this initial phase of discovery is now transitioning into an era of more precise detections and quantitative measurements in gravitational-wave astronomy.[58]

Next-Generation Observatories:

The new era will be ushered in by third-generation ground-based detectors already in advanced planning and early construction stages. These instruments are designed with a sensitivity an order of magnitude greater than Advanced LIGO.[59]

This enhancement has profound consequences:

- Range: Because the amplitude of gravitational waves decreases inversely with distance, a tenfold sensitivity increase corresponds to a tenfold extension in range.[60]
- Volume: Since observable volume scales with the cube of distance, detection volume grows by a factor of a thousand.[61]
- Events: The detection rates could increase from dozens per year to millions.[62] This massive dataset will shift the focus from individual case studies to statistical population analyses of compact binaries.[63]

Key scientific goals like mapping the mass and spin distributions of compact binaries,[64] inferring merger rates as a function of redshift,[65] and studying binary formation channels and evolutionary pathways.[66]

The two main third-generation observatories are:

- Cosmic Explorer (CE): Two L-shaped surface interferometers with 40 km and 20 km arms are planned. The 40 km instrument will provide broadband sensitivity, while the 20 km interferometer will excel at detecting high-frequency signals from the ringdown phase.[67]

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- Einstein Telescope (ET): A subterranean triangular design, with three 10 km arms forming three V-shaped Michelson interferometers. Its "xylophone" configuration consists of interferometers optimized separately for low and high frequencies, providing sensitivity across the full spectrum.[68] ET's low-frequency capability extends inspiral phase tracking and enables detection of intermediate-mass black hole binaries.[69]

Understanding Supranuclear Matter:

Binary neutron star inspirals generate gravitational waves encoding the cold nuclear Equation of State (EOS), while post-merger ringdown phases probe the hot nuclear EOS.[70] Current detectors primarily access inspiral signals, but next-generation sensitivity will allow detection of faint, high-frequency post-merger waves.[71]

Key insights from these detections include constraints on temperature-dependent EOS in ultra- dense matter,[72] probing phase transitions in neutron star matter,[73] and establishing connections between gravitational-wave signals and heavy-ion collision experiments on Earth.[74]

Challenges include noise contamination of faint, short-lived post-merger signals. Advanced signal processing and novel instrument configurations are required to overcome glitches and non-Gaussian noise.[75]

Black Hole Spectroscopy:

A cornerstone of General Relativity is the No-Hair Theorem, which posits that black holes are fully characterized by mass and spin.[76] Gravitational-wave spectroscopy of ringdown emissions provides the means to rigorously test this theorem. Older detectors could only observe the dominant quasinormal mode (QNM).[77] Next-generation detectors will resolve multiple subdominant QNMs and even nonlinear quadratic QNMs.[78] Independent recovery of black hole parameters from multiple modes allows consistency checks of the No-Hair Theorem.[79]

Multi-Messenger and Multi-Disciplinary Future:

Third- generation detectors are also expected to significantly advance multi-messenger astronomy, coordinating gravitational-wave detection with electromagnetic and neutrino observatories.[80] Such synergies will enable precise localization of neutron star collisions and deeper insights into r-process nucleosynthesis.[81]

The nuclear EOS faces discrepancies between astronomical observations and terrestrial nuclear physics experiments. Future detectors will help bridge this divide as gravitational-wave constraints on neutron star structure will inform and refine nuclear theory and EOS modeling,[82] these models can be tested against experimental data from facilities like Jefferson Lab and FRIB400,[83] and machine learning approaches will iteratively improve EOS predictions through a feedback loop between theory, astrophysical measurements, and laboratory data.[84] This integration of astrophysical measurements, nuclear physics experiments, and computational modeling is poised to revolutionize our understanding of matter under extreme conditions, advancing gravitational-wave science into a quantitatively predictive discipline.[85]

■ Conclusion

To conclude, gravitational wave astronomy has completely changed the way we study the universe by transforming a mere theory in Einstein's Theory of General Relativity into reality by the 2015 LIGO detection.[86] This new beginning in observational astronomy has helped us detect the collisions of black holes and neutron stars and thus infer physical information from them.[87] Thus, this paper aimed to describe the physical properties of neutron stars and black holes that can be detected through the analysis of gravitational waves from their collisions.

The foundations of this are rooted in the Theory of General Relativity, which describes gravity as the curvature of spacetime rather than a conventional force.[88] The detection of gravitational waves confirmed this with a high degree of accuracy and showed that the three phases of a merger- inspiral, merger, and ringdown align with the theory.[89]

Each phase carries its own signals, which carry unique information on not only the merger but also the physical properties of the objects involved in the merger.[90] The inspiral phase tells us about physical parameters like mass and spin with high precision, the merger phase releases huge amounts of energy in the form of gravitational wave emission, and the ringdown phase gives us information on the remnant formed and its stability, providing the most stringent tests of Einstein's theory.[91]

A huge amount of information on the physical properties, such as mass and spin of colliding objects and their remnants, can also be inferred through gravitational waves from the collisions.[92] Since gravitational waves are directly produced from compact objects, we can get accurate information on parameters like masses, spins, radii, and even internal structure, unlike in electromagnetic astronomy, which depended on light interacting with matter.[93] Some events like GW170817 tell us about tidal deformability and the equation of state of nuclear matter, giving us information on physics at densities unattainable on Earth.[94] There have been many key detections that have shaped this field which include GW150914- first detection of gravitational waves from a black hole-black hole collision,[95] GW170817- first detection of neutron star-neutron star collision which introduced the concept of multi messenger astronomy,[96] GW190521- detection of black holes in the "mass gap" which challenged the stellar evolution theory,[97] GW200105 and GW200115- detections of black hole-neutron star collisions.[98]

This also has far-reaching astrophysical implications.[99] Binary neutron star mergers give us a way to connect gravitational physics with nuclear physics and chemistry, giving us a deeper insight into the r-process of nucleosynthesis, nuclear Equation of State, etc.[100] Binary black hole mergers tell us about stellar evolution, binary formation channels, and dynamical processes in dense clusters.[101] Neutron star–black hole collisions shed light on the concept of "dark mergers" without any electromagnetic radiation produced.[102]

The future of gravitational wave astronomy is also very promising.[103] It includes both updates to current detectors and development of third-generation observatories such as the Einstein Telescope and Cosmic Explorer, which will help improve sensitivity to fainter and more distant gravitational wave signals, possibly helping us detect millions of mergers per year.[104] This also helps in the development of multi- messenger astronomy, which will give us better measurements of properties of compact objects, their evolution, and destruction.[105]

Thus, gravitational-wave astronomy is changing the way we see the universe, but it is only in its beginning stages.[106] There are many persisting questions, like the true equation of state of matter in neutron stars, and how much nuclear matter is ejected into the universe during nucleosynthesis. Though current models have provided plenty of information on this field, many uncertainties, like the ones mentioned, remain. However, since future detectors will be able to detect fainter and a broader range of frequencies, the mysteries can be resolved, and a gap between theory, observation, and experimentation can be closed. Around a decade ago, the signals were a mere theory, but now they are frequently detected, observed, and decoded to gain information and test the laws of physics.[107] As the detection technology advances, we are at the threshold of discoveries that change our understanding of matter, gravity, and tell us the story of how the cosmos has been made.

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