Observational Effects of Gravitational Wave Emissions Based on Differing Characteristics of Astrophysical Objects

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As observed in various astrophysical systems, gravitational waves propagate differently based on the properties of the systems. These observations concluded that the effects of gravitational waves on the bodies' environments vary based on the system's characteristics as well as the properties of the astrophysical environments the systems preside in. In this paper, the differing impacts that these astrophysical ripples have on the cosmic environments of two systems, namely binary black holes and binary neutron stars, were compared based on the varying attributes of the bodies, such as their mass, density, spin, electromagnetic fields, utilising previously collected observational data from optical instruments such as LIGO, Virgo, and eLISA. BBH mergers primarily affect their surroundings through gravitational waves, tending to have more significant observational effects, while BNS mergers can disrupt their environment, emitting electromagnetic signals like gamma-ray bursts and kilonovae, and have observable effects on surrounding matter, and can have a more substantial effect of its environment than BBHs in some cases. This evaluation will help enhance our understanding of the broader implications of these cosmic phenomena by allowing for the refinement of current wave propagation models and astrophysical theories of gravitational radiation and help guide future research on the interactions between gravitational waves and the universe.

Introduction

Gravitational waves are disturbances in the curvature of spacetime caused by the acceleration of celestial objects, such as binary star systems, neutron stars and black holes, propagated from their sources as waves. Analogous to the electromagnetic radiation experienced stemming from the rotation of charged objects, otherwise known as dipole radiation, gravitational waves are propagated from their sources as waves in spacetime. In his paper on the general theory of relativity, Albert Einstein anticipated that massive accelerating objects would disrupt spacetime, emitting radiation propagated from the source as gravitational waves. In this paper, Einstein created a set of nonlinear partial differential equations to describe the universe's gravitational interactions and spacetime geometrics to its mass and energy distribution, also known as Einstein's field equations (EFE). The EFE[1, 2] can be written as:

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \kappa T_{\mu\nu}$$

The Einstein tensor, denoted as $G_{\mu\nu}$, describes the curvature of spacetime caused by energy distribution. The metric tensor,$g_{\mu\nu}$, describes the geometry of spacetime in general relativity. The stress-energy tensor, $T_{\mu\nu}$, describes the distribution of energy, momentum, and stress within a given region of spacetime. Λ represents the cosmological constant, and κ is the Einstein gravitational constant. By rewriting Einstein's gravitational constant in terms of G, the Newtonian gravitational constant, and c , the speed of light in vacuum, we derive:

$$\kappa = \frac{8\pi G}{c^4}$$

Therefore, Einstein's field equation, in natural units, can be rewritten as:

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu}$$

The exclusion of c^4 in this equation is because c = 1 in the system of natural units.

Einstein's field equations can be rephrased by rewriting the Einstein metric in terms of Riemannian geometry, a branch of differential geometry that studies smooth, curved spaces called Riemannian manifolds and distances and angles in Riemannian metrics[3]. This equation is used to show the relationship between spacetime curvature and the stress-energy of the universe, where $R_{\mu\nu}$ is the Ricci curvature tensor and R is the scalar curvature[1]:

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu}$$

However, finding exact solutions to Einstein's field equations is difficult due to their highly nonlinear nature. The EFE can be solved by weak-field approximation, which linearises the metric around Minkowski space, a four-dimensional mathematical spacetime combining space and time, by rewriting the metric tensor as the sum between the Minkowski metric describing flat spacetime and a small perturbation[4]:

$$-\Box h_{\mu\nu} = 16\pi k T_{\mu\nu}$$

$\Box$ represents the d'Alembertian operator, which describes the propagation of gravitational waves through Minkowski spacetime, and $h_{\mu\nu}$ represents the perturbation of the metric tensor, which is used to explore the gravitational waves' interactions with surrounding matter. This linearised version of the EFE by weak-field approximation allows for the investigation of gravitational radiation by determining the behaviour of gravitational waves, including their propagation speed and polarisation states. However, since the Minkowski metric is used to describe flat spacetime in the weak-field approximation, this solution to the EFE operates under the assumption that there is minimal spacetime curvature and weak gravity.

Einstein's prediction of gravitational waves was confirmed in 1974 by Russell Hulse and Joseph Taylor, who observed and studied the behaviour of a binary star system, PSR 1913 + 16, composed of a neutron star and a pulsar. Using observations of radio emissions, Taylor and Hulse discovered that the two objects revolved around each other at an increasingly rapid velocity over several years. They found that the system's orbital period decreased by the rate predicted by Einstein's theory of general relativity, which stated that the system's objects would inspiral and collide approximately 3×10^8 years. Einstein also stated that the decrease in the system's orbital period would result from gravitational radiation reducing the system's energy, thus proving the existence of gravitational waves[5]. In 2015, the LIGO and Virgo detectors made the first direct observation of gravitational waves, providing evidence for Einstein's predictions of general relativity. The detectors detected a binary black hole merger named GW150914, which occurred approximately 1.3 billion light-years from Earth. The merger of two black holes produced the gravitational wave signal. One had a mass of 36 solar masses, and the other had a mass of approximately 29 solar masses. The merger resulted in the forming of a single black hole with a mass of approximately 62 solar masses. The remaining mass was converted into energy and released as gravitational waves, as detected by the instruments[6].

In recent years, the sensitive detectors used in joint observation runs, including the LIGO, VIRGO, KAGRA and LISA observatories, have undergone significant developments that have increased the scope for detecting gravitational waves. These waves carry information about the dynamics of the objects that produced them. These can be analysed and help contribute to our understanding of the waves' origins and the dynamics of cosmic interactions[7].

However, they do not carry direct information about the observational effects they cause due to their propagation. By analysing the characteristics of the astrophysical systems, such as electromagnetic fields, accretion disks and stellar clusters, and the observable effects of the spacetime distortions caused by gravitational waves of surrounding systems, researchers can gain a deeper insight into the astrophysical interactions between systems of the universe and therefore the structure of the universe. This paper aims to distinguish between the observational effects of gravitational waves propagated from binary black holes and neutron stars based on their distinct astrophysical properties. The second and third sections introduce each astronomical body by detailing its formations, characteristics, and gravitational waveform; the fourth and fifth sections introduce the assessed environments, namely accretion disks and globular clusters; the sixth section examines the differences in observed observational effects, and the final section assesses potential limitations and opportunities for further investigation.

Methodology

To conduct this systematic review on the observational effects of gravitational wave emissions from binary black holes (BBHs) and binary neutron stars (BNSs) in different environments, a structured search following PRISMA guidelines was employed. A comprehensive search was performed across academic databases, including arXiv, Google Scholar, and key scientific journals. Relevant search terms, including "gravitational waves,""binary black holes,""binary neutron stars,""globular clusters,""accretion disks,"and "observational effects,"were utilised to allow only relevant and accurate sources to be analysed. Studies were assessed for eligibility and selected for analysis based on their relevance to the topic, peer-reviewed status, and number of references, as well as their focus on observational data or theoretical models that analyse BBHs and BNSs in globular clusters and accretion disks. A comparative analysis of the data points in the selected papers was conducted to identify differences in the observational effects of the two systems while also highlighting common themes and gaps in the existing literature. Limitations of this review include the potential bias towards more recent studies and the focus on specific environments, which may not encompass the full range of observation effects, although potential reporting bias was mitigated by selecting studies from diverse sources.

Binary Black Holes

A binary black hole (BBH), which consists of two black holes orbiting around each other that eventually collide, is one of the strongest known sources of gravitational waves. BBHs are formed from the collapse of two stars with sufficient mass, as per Einstein's theory of general relativity, in close proximity to one another or when two existing black holes come close enough to be gravitationally bound. As the black holes orbit each other, they emit gravitational waves, specifically compact binary inspiral gravitational waves produced by orbiting pairs of dense objects. This emission causes the orbit to decay, decreasing the orbital period and increasing the velocity of the orbit, in accordance with Einstein's theory of general relativity. This process continues until the black holes merge into a stable single hole once they are close enough, peaking gravitational wave emission[8]. This differs from Newtonian gravity, as in the classical theory of gravity formulated by Sir Isaac Newton, as this theory states that the orbit of two-point masses around one other is perpetually stable unless influenced by external influences, as there is no provision for the objects' energy loss. General relativity includes this energy loss by gravitational radiation, which allows for the decay of the binary's orbit and eventual merger.

To demonstrate the effect of the orbit's stage on the gravitational waves, Figure 1 illustrates the change in waveform of the emitted gravitational waveform of a non-spinning $30+30M\odot$ binary black hole system, where $M\odot$ represents solar masses during its various phases generated using the IMRPhenomX waveform model to explain how the acceleration of the binary results in stronger waves emitted and how the stable nature of the merger results in weaker waves emitted[9]. The top panel of Figure 1 illustrates the frequency-domain gravitational wave strain, which depicts the signal's amplitude plotted against frequency. The vertical lines denote key frequencies in the system's orbit, namely the fISCO, fMECO, and fRD. The innermost stable circular orbit (fISCO) is where the frequency of the waves is at its peak value, and these values can be used to study the behaviours of the binary system under extreme gravitational forces. The minimal energy circular orbit (fMECO) represents the orbit with the least possible energy and also helps researchers gain insights into the behaviours and dynamics of binaries. The ringdown frequency (fRD), where the wave reaches a characteristic oscillation frequency associated with the binary's natural vibrations, gives us information on the physical properties of the resulting object after the merger and during the stable ringdown phase. The bottom panel showcases the time-domain gravitational waveform, plotting the signal's amplitude against time with a smaller graph[10]. This graph provides a detailed view of the build-up, peak and decay of the waveform of the gravitational radiation by the depiction of amplitude in the binary's final inspiral cycles compared to its amplitude in its merger and ringdown phases. Additionally, the amplitude of the waves can indicate the physical characteristics of the binary objects, including the masses and orientations of the objects.

To summarise, the analysis of binary black hole dynamics and the evolution of their gravitational wave signals provides insights into these binaries' behaviours and physical features, as well as the universe's gravitational environment. With this foundation established, we now introduce binary neutron stars, another related cosmic event that provides an understanding of the nature of gravitational interactions between objects.

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Binary Neutron Stars

Another strong source of gravitational waves is binary neutron stars (BNS). Similar to the structure of binary black holes, BNS systems occur where two neutron stars, collapsed stellar cores formed from the supernova explosion of stars, orbit one another until they combine. Like BBHs, BNS systems undergo orbital decay due to the emission of gravitational waves, specifically compact binary inspiral gravitational waves like BBHs, decreasing the system's energy and accelerating the inspiral. Additionally, the gravitational forces generated by the orbit of the neutron stars accelerate charged particles to extremely high speeds and emit electromagnetic radiation alongside the gravitational waves[11]. Figure 2 depicts the waveform changes in a BNS by employing a time-domain representation of the gravitational wave to show how the amplitude changes as the binary forms a merger over time, thus depicting the strength of the waves and the amount of energy emissions from the binary[12]. h_+ denotes the positive polarisation state of the gravitational wave, which is the geometric form of the stretching and squeezing of spacetime induced by a gravitational wave as it travels. The figure thus shows how time affects both the orientation of the gravitational wave's oscillations and the amplitude of the waves, or the overall characteristics of the spacetime distortions, which can provide insights into the system's dynamics.

Spin Effect on Accretion Disks

The spin of the BBHs and BNSs affects the gravitational waves they emit. Spin angular momentum, or the angular momentum associated with the spins of the individual objects in a binary system, affects the gravitational waveform by modulating its amplitude, frequency, orientation, and phase evolution. When detectors observe and analyse the waves, the waveform can provide crucial information about the properties of the binary system, such as the masses, spins, and orbital parameters of the objects in the binaries.

Each object in a binary system possesses its own intrinsic spin angular momentum. As the objects orbit each other in binary, their moments interact with the orbital angular momentum of the binary, leading to a phenomenon known as gravitational spin-orbit coupling. This coupling effect can be compared to the effect observed in magnetic dipoles, where the intrinsic angular momenta of electrons act as miniature magnetic dipoles and create external magnetic fields. However, these electrons are not in orbit, which is the case with binary systems, which exhibit a collective orbital motion due to their gravitational interactions. This interaction causes the orientation of the spins and the orbital

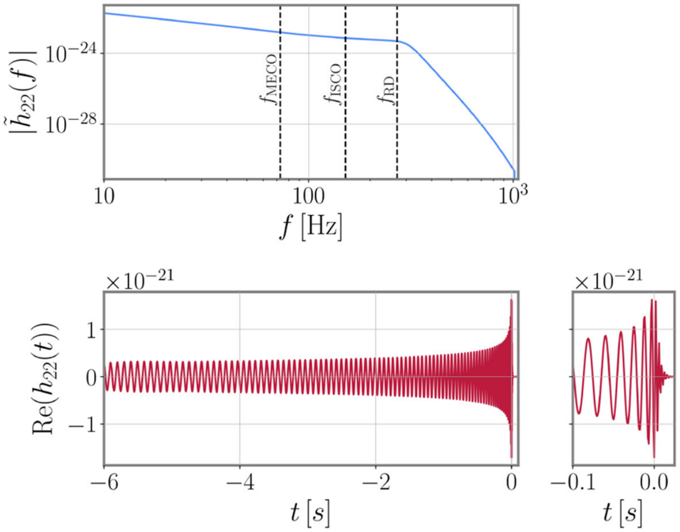

Figure 1: Frequency-domain & time-domain gravitational waveform in a Binary Black Hole's inspiral, merger and ringdown phases. $\left|\tilde{h}_{22}(f)\right|$ represents the absolute value of the Fourier transform of the h_{22} mode of the gravitational wave strain amplitude as a function of frequency. $Re(h_{22}(t))$ represents the real part of the h_{22} mode of the gravitational wave strain amplitude as a function of time, on the order of 10^{-21} in the units of strain. This image was taken from[10]

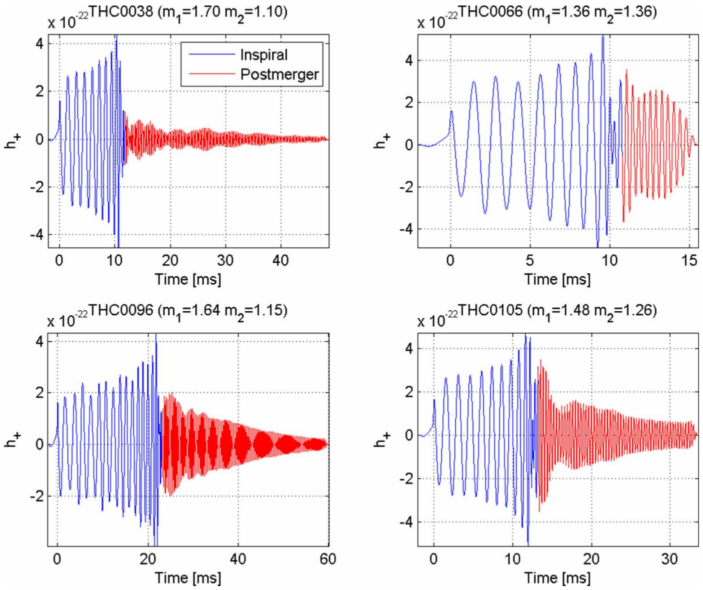

Figure 2: Time-domain gravitational waveform in various stages of a Binary Neutron Star. h+ represents the polarisation state relating to the wave's orientation on the order of 10^{-22} in the units of strain. The THC followed by the number denotes the unique identifier for the binary system analysed. The masses m1 and m2 represent the masses of the objects in terms of solar masses. This image was taken from[12]

plane of the system to change gradually over time, influencing the emitted gravitational wave signal[10].

If the spin angular momenta of the two objects are antiparallel to the orbital angular momentum of the binary motion, or if the alignment of the spin of the objects is in the opposite direction of the binary motion, the emitted gravitational waves have increasing amplitude and frequency as the spin angular momentum adds to the orbital angular momentum and slightly expand the orbit. Conversely, opposing spin angular momenta and orbital angular momenta in binary systems cause a reduction in the gravitational wave frequency, as the spin angular momentum partially cancels out the orbital angular momentum, slightly shrinking the orbit[10]. The magnitude of the effect of spin on the gravitational waveform can also be impacted by the masses of the binaries' objects, as objects with larger mass emit gravitational waves of larger amplitude and frequency.

However, in some cases, the effects of spin and mass on the amplitude and frequency of gravitational waves can overlap, making it challenging to separate and distinguish their contributions to the effects[13]. This is particularly problematic in scenarios where only limited data is available. For instance, certain combinations of spin and mass parameters might result in nearly identical gravitational waveforms, such as is the case with a waveform from a system with non-spinning and more massive black holes that might resemble the waveform of a system with lighter and rapidly spinning black holes, leading to ambiguity in interpretation. This degeneration can be reduced to an extent by utilising techniques such as Bayesian Inference and Markov Chain Monte Carlo (MCMC) methods to explore parameter spaces and quantify uncertainties, helping to differentiate spin and mass contributions by fitting models to high-quality waveform data from multiple gravitational wave events.[14]. Additionally, combining gravitational wave data with other astrophysical observations can help distinguish between mass and spin effects. For example, precise measurements of the higher-order harmonics of the gravitational waveform, as well as an analysis of the precession effects, can be used to identify spin-induced changes in the waveform. Simultaneous observations of electromagnetic data, such as light curves or spectra from the accretion disks, can help infer the masses and spins of the objects and, hence, determine the cause of the changes in the gravitational waveform.[15]. However, the degeneracy remains, which makes the interpretation of amplitude and frequency measurements challenging.

Accretion disks are rotating discs of matter formed around a central body accumulated due to gravitational forces. Figure 3 illustrates the disks formed around each binary object in a binary black hole system by the accumulation of matter from the circumbinary disk (CBD) surrounding the whole binary. The differing waveforms caused by the spins of the objects in the systems have varying effects on the system's accretion disks by disrupting surrounding gas and dust clouds. Similarly, in binary neutron star systems, the interaction between the neutron stars and their environment results in the formation of accretion disks from the accumulation of matter from the surrounding environment, such as from stellar winds and tidal interactions, with distinct characteristics influenced by the unique properties of neutron stars[16],[17].

For example, gravitational waves with higher amplitude and frequency extract more energy from the binary, drawing the system's objects in a closer orbit than a wave with lesser amplitude and frequency. Thus, these waves can disrupt the surrounding gas and dust clouds more significantly than those with lesser energy. This disruption can affect the behaviour of the accretion disks, leading to changes in their density, temperature, and overall structure or the accretion rate onto the objects of the system. These effects can be indirectly measured in a multitude of ways. Changes in the density of the surrounding gas clouds, caused by tidal forces that compress parts of the accretion disk, can be inferred from spectroscopic data such as from variations in the emission or absorption lines of ionised gas measured from the Hubble Space Telescope (HST).[19]. Temperature changes in the gas and dust clouds caused by gravitational wave-induced shock heating can be inferred from photometric measurements and observations in the infrared and X-ray spectra, such as the infrared thermal emission from dust and X-ray emission from hot gas[20].

Changes in the structure and dynamics of accretion disks, observed through high-resolution imaging from instruments like the Chandra X-ray Observatory, vary depending on the binary system due to their differing influences. In a BBH system within an accretion disk, the presence of the binary black holes causes gravitational perturbations that lead to dynamic effects in the surrounding matter. The inspiral and merger of the black holes exert gravitational and tidal torques on the disk, which can redistribute angular momentum to deplete the inner region of the disk, hence modifying the radial density profile of the disk and disrupting its structure and material distribution. As the BBHs decouple and merge, the accretion rate temporarily decreases as the hollow is not yet filled, resulting in a temporary decrease in the inflow of matter onto the black holes and the luminosity output, then increases as the low-density region is refilled with gas from the outer disk, leading to shock heating of the surrounding gas as well as a significant increase in electromagnetic luminosity[21]. General relativistic magnetohydrodynamic (GRMHD) simulations, such as those performed by Farris et al. (2012), provide critical insights into the gravitational wave-induced disruptions in accretion disks surrounding merging binary black holes in its pre and post-decoupling phases, particularly in the context of disk depletion and electromagnetic radiation enhancement post-merger. However, the various discussed impacts of GWs of BBH mergers within accretion disks, as well as other impacts such as accretion variability, shock formation, and changes in

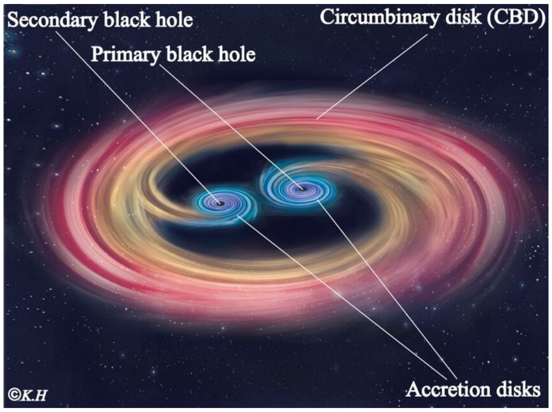

Figure 3: Artistic depiction of a BBH surrounded by a circumbinary disk (CBD) from which accretion disks form around each black hole from transferring the CBD's gas. This image was taken from reference[18]

the disk's density profile, tend to be indirect due to the lack of direct matter interactions.

In a BNS, the presence of neutron-rich matter leads to more direct interactions between the GWs and the accretion disk. As the two neutron stars spiral inwards, the GWs combined with tidal forces cause the neutron stars to deform, ejecting a portion of the material when the two objects merge while another portion forms an accretion torus around the newly formed compact object. In this torus, non-axisymmetric magnetorotational instability (MRI) and Kelvin-Helmholtz instability (KHI) drive turbulence-like motion, which enhances mass accretion by redistributing angular momentum and releases large amounts of thermal energy that can power strong winds and outflows, altering the overall geometry of the surrounding disk.[22]. High-resolution magnetohydrodynamics simulations, such as those by Kiuchi et al. (2015), provide detailed insights into the effects of black hole-neutron star mergers on accretion disks, including the impacts of the formation of an accretion torus and the formation of transient emission, although it should be noted that the discussed effects of BNSs on accretion disks are more energetic and long-lasting as compared to black hole-neutron star mergers. Additionally, the interaction of GWs with the disk can also lead to transient heating of the disk material and increased luminosity, contributing to observable electromagnetic signals like kilonovae and SGRBs and the production of heavy elements via r-process nucleosynthesis. The ejecta from the merger can also lead to kilonovae, while the formation of a black hole or hypermassive neutron star from the BNS merger results in additional electromagnetic afterglows in X-rays and gamma rays.

However, many effects of gravitational waves, including the mentioned effects, are detected indirectly, so accurate models and simulations are needed to interpret the observed data and separate the effects of the waves from other astrophysical processes, and the resolving power and sensitivity of current imaging instruments may make it challenging to detect subtle changes in effects like temperature, density, and structure that require highly sensitive instruments against background noise.

Additionally, due to the increased orbital speed of the compact objects in the binary system, there can be stronger gravitational interactions with the material of the accretion disk. This can also affect the rate at which material accretes onto the objects as the stronger gravitational forces can pull more material from the disk onto the compact objects, increasing the accretion rate and leading to increases in the luminosity of the system due to the release of energy in the form of electromagnetic radiation as well as instabilities of the disk[23]. This is one of the more observable effects of the influence of gravitational waves, especially in systems with high accretion rates or significant variability. Changes in luminosity, and hence the accretion rate, can be detected using modern telescopes and observatories such as the Chandra X-ray Observatory or the Hubble Space Telescope, which are equipped to detect X-ray or optical wavelengths with high precision.[24]. However, the observability of these effects depends on the sensitivity of the observational instruments used, the duration of the change, and the system's characteristics, such as its distance from Earth, baseline luminosity, and the presence of other complicating factors like dust or any intervening material.

Globular Clusters

Another environment affected by gravitational waves is globular clusters (GCs), which are compact and bright clusters of stars that are gravitationally bound, increasing in concentration toward their centres. There are some theoretical frameworks around the formation of GCs. One suggests that they form under special conditions in low-mass dark matter haloes or regions with small concentrations of dark matter, either during or before reionisation, while another suggests GC formation is a natural consequence of the active star formation process seen at high redshift. In this epoch, the light of astronomical objects shifted to longer wavelengths due to the expansion of the universe[25]. Most GCs formed before most stellar formation in galaxies, typically in single episodes of star formation instead of continuous episodes, as the environment was usually unsuitable for star formation after the initial formation period changed the physical conditions of the environment.

There has been difficulty defining GCs, as the previous classical definition was found to be ambiguous and applicable to many scenarios, even if the identified objects were not GCs. A revised version describes GCs as stellar systems with observed anti-correlations among light elements[27]. GCs are often confused for other astronomical objects due to their similar characteristics, such as dwarf spheroidal galaxies due to similar domains in parameter space and open clusters due to their conglomerations of stars[28]. However, GCs are most affected by gravitational waves as their small and highly dense nature results in frequent dynamical interactions between the multitude of stars, binaries, and compact objects present that can influence the structure and dynamics of the globular cluster.

GCs can create exotic stellar systems through dynamical interactions, which are the gravitational interactions and energy exchanges between astrophysical objects in a dense stellar environment, such as X-ray binaries, pulsars and the merging of BBH systems. While theoretical support exists for the formation and existence of BBHs and BNSs in GCs, direct observational evidence is limited[29, 30]. However, some studies have suggested potential candidates for BBHs or BNSs in globular clusters based on indirect evidence, such as X-ray emissions and short gamma-ray bursts[31]. The nature of the gravitational wave sources can be determined by analysing the X-ray signatures and the spectral and temporal features of the detected X-rays and SGRBs. This, combined with the temporal coincidence with a gravitational wave signal, which can be further analysed by evaluating the waveform signature, chirp signal, and complex post-merger signals, can indicate the presence of a BBH or BNS as opposed to another astrophysical object. Additional studies have been conducted on how mergers can form in stellar clusters and GCs using models based on Newtonian and Post-Newtonian N-body dynamics, providing predictions about the frequency of the gravitational waves and eccentricity distributions of these binaries' mergers, which can help identify mergers that likely originated from globular clusters when compared with observed GW data.[32].

Comparison of the two bodies

As discussed previously, gravitational waves affect the accretion disks of both BBHs and BNSs. They can disrupt the accreted matter and, consequently, the disk's structure, influencing the acceleration of the objects in the binary and causing stronger gravitational interactions with the matter. However, the gravitational emissions of the two binaries have varying effects on the systems' accretion disks due to their differing characteristics. For example, BBHs can have components with masses ranging from about 3 $M_\odot$ to over 30 $M_\odot$, depending on the type of black hole, although there is no known maximum mass of a black hole[6], and are typically more massive and compact than BNSs, which have an average component mass of 1.17 to 2.0 $M_\odot$.[33]. Thus, BBHs have stronger gravitational interactions and cause more significant deformations of spacetime than BNSs, which intensifies the effect on the waveform of the emitted gravitational waves, resulting in waves of greater amplitude and frequency. In rare cases where the mass of a small BBH overlaps with that of a large BNS, such as when both systems have component masses around 2.5 to 3 $M_\odot$, it is difficult to distinguish the objects based on mass or the gravitational wave signal during the inspiral phase, as they may be similar. However, BBH mergers tend to have a more pronounced final merger and ringdown phase due to the absence of matter, while BNS mergers involve matter interactions, leading to additional features in the waveform, such as longer inspiral phases or post-merger effects related to ejecta. To definitively distinguish the type of system, additional data like post-merger signals, such as X-ray or radio emissions, or electromagnetic counterparts, such as kilonovae or short gamma-ray bursts, is needed. For example, in a case where a small BBH and a large BNS have similar masses, the BBH will lack electromagnetic counterparts due to the absence of matter, and the BNS will produce such signals due to the presence of ejecta, hence allowing for the distinction of the system for their observational effects. However, all available data should be carefully analysed as there is a possibility that electromagnetic counterparts are undetectable due to observational limitations or the orientation of the system, which may affect the evaluation of the data and type of system.

These stronger gravitational interactions result in BBHs affecting the structure and characteristics of the accretion disk more and having a higher accretion rate than BNSs, which may induce more instabilities, such as spiral density waves or shocks, within the disk, altering its structure and behaviour. Stronger gravitational interactions also cause the BBHs orbit's decay rate to be higher than that of BNSs, provoking a more efficient emission of gravitational waves in relation to how effectively the system converts its orbital energy into gravitational wave radiation. This causes them to lose orbital energy and angular momentum faster, increasing

Figure 4: Image of the Omega Centauri globular cluster taken from reference[26]

the gravitational interaction between objects and, therefore, the strength of the emitted waves, which causes a more substantial effect on the accretion disk.

BNSs produce ejecta, which is material ejected outward from the system and is considered more in amount than BBHs. This ejecta, which is typically released during the merger of the binary system, consists of neutron-rich material and radioactive isotopes, which can enrich the accretion disk's composition by influencing its chemical makeup and promoting the synthetization of heavy metals by rapid neutron capture (r-process) nucleosynthesis[34]. Additionally, BNSs tend to have stronger jets, which are collimated beams of matter ejected from astronomical objects, than BBHs due to the presence of neutron-rich material and, thus, its more significant r-process nucleosynthesis. This ejected material in the jets can cause powerful relativistic jets or beams of ionised matter ejected from objects at almost the speed of light, which leads to phenomena such as short gamma-ray bursts (GRBs) and kilonovae, which can alter the chemical composition of the accretion disk with the injection of heavy elements as well as the structure due the ionised matter[35,36]. The jets also carry mass from the accretion disk, which results in changes in the mass distribution within the disk and its structure.

Furthermore, the gravitational waves of the two binaries have varying effects on globular clusters. BBHs, releasing more gravitational energy than BNSs, can significantly impact the surrounding GC environment by disrupting nearby stellar systems by exerting tidal forces on objects caused by their gravitational interactions. Tidal forces are gravitational effects that stretch a body along the line towards and away from the centre of mass of another body. This triggers star formation by injecting energy into and disrupting surrounding gas and dust clouds, ionising gases in the environment due to the release of gravitational waves and possibly electromagnetic emissions from accretion processes[37]. BNS mergers release substantial energy but are less so than BBH mergers as they involve less massive objects, thus having a lesser environmental impact. However, they can still have a significant effect due to the greater electromagnetic emission from its composition of neutrons.

As BNSs have greater nucleosynthesis than BBHs, they influence the GC environment substantially by ejecting neutron-rich material and heavy elements produced in the merger, including r-process elements, enriching the surrounding gas and influencing subsequent star formation[38,39]. Although BBHs do not produce ejecta, they may still contribute to the chemical enrichment of the environment through other processes, such as stellar winds and supernova explosions[40].

Conclusion

This paper has discussed and compared gravitational waves as well as the observational effect of these waves emitted from binary black holes and neutron stars. Although the two bodies share some observed observational effects, the extents of the effects vary due to the differing properties of their emitted gravitational waves. This research provides a detailed analysis of the observational effects of two particular astrophysical objects. Generally, it can be concluded that BBHs have a more significant observational effect in most cases due to their larger mass, greater density, and higher orbital velocity. However, BNSs can have a more substantial effect in some cases due to their electromagnetic emissions and mass ejection.

For a deeper understanding of the differing effects on environments from gravitational wave properties, one must examine and compare the other astrophysical bodies equally worthy of investigation, including white dwarf binaries, compact binary systems, supernovae, pulsars and colliding galaxies. Furthermore, studying the observational effects of gravitational waves has implications for future research in astrophysics and cosmology. For example, gravitational waves convey information about their environmental interactions, which may be utilised to develop further our current knowledge of astronomical phenomena such as galaxy formation, cosmic dynamics, and universe structure, as well as to test and refine current astrophysical models and cosmological frameworks to improve our understanding of astrophysical processes. The detection of gravitational waves can also help advance research in other domains, such as material science and mechanical engineering. The technology used to develop the detectors has the potential to contribute to advances in high-precision measuring instruments and sensor technology that are resistant to severe environments and can be used for various applications in research areas such as aerospace technology, navigational systems, and medical imaging systems.

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