Proceedings of the 3rd International Conference on Computing Innovation and Applied Physics
DOI: 10.54254/2753-8818/13/20240790

Exploring black hole-neutron star binary merger by detecting gravitational waves

Jiahao Zhang

ACS International Singapore City 309937 Singapore

jiahao.zhang@acsinternational.edu.sg

Abstract. Unlike black hole binary merger, the merger between a neutron star and a black hole will produce an abundant number of gravitational waves and electromagnetic waves. Using this information, scientists can easily find many properties of the universe and test the general relativity and some other gravitational theories. The detection of the gravitational wave from source is essential to develop the current knowledge of the gravitational force. From last century, scientists were trying to detect the gravitational waves, and as the time passes, the method of detection has already developed from on land detector to space detector in order to take more precise readings. This paper provides some basic information of the neutron star and the black hole, together with the formation of the binary neutron star-black hole system. The relationship between the neutron star and black hole is explained in this paper. The knowledge of the current methods of detecting gravitational waves is also provided and the paper specifically elaborated the space laser interferometry.

Keywords: Gravitational Wave, Black Hole, Neutron Star, Space Laser Interferometry.

1. Introduction

The concept of black hole was brought along with the publishing of general relativity. In 1916, German astronomer Karl Schwarzschild found a vacuum solution for the Einstein Field Equation. This solution stated that if a static, symmetrical star had an actual radius that bellows a certain value, the surrounding will form a horizon which light cannot even escape from the horizon. This value is called Schwarzschild Radius. This kind of marvelous star is named “Black Hole” by John Archibald Wheeler, an American physicist.

Both neutron star and black hole are the most compacted celestial body in the universe, they are the product of collapse of massive stars [1]. These bodies have a strong gravitational field which might curve the spacetime around them. The merge of the two compacted celestial body will emit gravitational filed which is an important source where scientists could use to detect the merge process and test the theory of general relativity. Gravitational waves are ripples in the fabric of spacetime itself, generated by the acceleration of massive objects. Einstein’s theory describes gravity as the curvature of spacetime caused by mass and energy, and when massive bodies, such as black holes or neutron stars, accelerate or undergo violent events like mergers, they send out waves of gravitational energy that propagate at the speed of light. These waves ripple outward, carrying information about the masses, velocities, and geometries of the objects that produced them.

The first merge event was detected in 2015, which was a binary black hole merge. Then in 2017, the second event of a binary neutron star merge was detected. In 2020, two events of a binary neutron star-black hole merge were detected. Until then, the gravitational wave detector had collected all three merges of the most compacted stars. The two possible consequences of the merger of neutron star and black hole are emitting of gravitational waves and electromagnetic waves [2]. The first consequence will always happen no matter how large the two stars are. However, for electromagnetic waves, the mass of the neutron star must below a certain value or the mass of the black hole must be above a value. Thus, the method of detecting electromagnetic wave has a large limitation. Gravitational wave, just like its name, this quantity is caused by the gravitational force. In general relativity, gravitational force is described as a property that reflects the curvation of the spacetime. The massive bodies will curve the spacetime around them as they merge, the curvation can be detected as the emission of the gravitational wave.

The study of neutron star-black hole merger can be used to determine the boundary between the mass of the neutron star and the black hole. Also, it can be used to find the formation of the black hole horizon from the binary massive stars collapses and test the general relativity and the gravity theory [3].

2. Knowledge of The Merger Stars

2.1. About the relativity theory

The idea of general relativity is a concept that could not be escaped in the study of the gravitational wave. From 1915, the year that Einstein first introduced the idea, until now, thousands of experiments was conducted to test the feasibility of the theory. The scale of the experiment became wider and wider as the year passes. From the laboratory scale to solar system scale and then is the universe scale. The experiments that were conducted in the weak gravitational field and the strong gravitational field, the observations of the pulsars and the gravitational waves all obeys the general relativity [1].

Seems like the general relativity is the most successful gravitational theory. However even though the theory can explain most of the observations, there are still some difficulties which it cannot explain. In theory, it cannot explain the quantization of gravity and problem of the singularity of the spacetime. In observation, people have to use the idea of dark matter and the dark energy to explain the problems regarding the galactic rotation curve and accelerating expansion of the universe. These difficulties indicates that the general relativity is still not complete and leading the scientists to find more phenomenon that opposes the general relativity. The detection of the gravitational wave gives another option to study the physics behind the gravity, the high speed and strong field environment is recognized to be the ideal laboratory for testing the general relativity.

The merger of a neutron star and a black hole is an event of extraordinary significance. It serves as a crucible for extreme physics, allowing scientists to probe conditions that defy terrestrial experimentation [4]. As these celestial entities spiral inward, they accelerate to nearly the speed of light, generating gravitational forces capable of distorting and warping spacetime itself. This phenomenon, known as gravitational lensing, offers a window into the nature of gravity under conditions that are otherwise inaccessible. Moreover, the extreme gravitational fields generated during the merger can give rise to particle acceleration on a grand scale, potentially shedding light on the mechanisms driving high-energy cosmic phenomena. Equally compelling is the role of neutron star-black hole mergers in the cosmic chemical factory. These cataclysmic collisions release an incredible amount of energy, driving the ejection of matter at nearly the speed of light. This ejected material contains elements forged through nucleosynthesis in the intense heat and pressure of the merger. Some of these elements, such as gold, platinum, and uranium, are exceptionally rare and difficult to produce through other means [5]. Thus, these mergers provide a cosmic explanation for the origins of heavy elements that enrich the cosmos and contribute to the formation of planets, stars, and life itself.

2.2. About the neutron star

A neutron star is formed when a massive star runs out of fuel and explodes as supernova [2]. Every single star has its own gravity and the gravity always tend to compress the star (towards the core), but the internal pressure exerts an outward push to keep balanced. The internal pressure is produced by the nuclear fusion reaction at the star's core, however when the star's nuclear fuel runs out the internal pressure also removed. The gravity of the star compresses the star inwards and a shock wave get produced, the wave travels to the core and rebounds, blowing the star apart. As most of the star blown into the space, the core remains which has a mass approximately 1 to 3 solar masses. The gravity continues to compress the core until a critical point where the electrons get into the parent nuclei and merged with the protons to make neutrons [6].

One of the most important properties of a neutron star is that it is extremely condensed. As mentioned in 2.1, a neutron star can have a mass of 1-3 solar mass, but the volume can be as small as a sphere of a diameter of 20 kilometre. According to the research done by James M. Lattimer, the mean density of a neutron star is approximately 1015 g/cm-3 which means that four teaspoon contains the mass of the Moon (or a trillion kilograms in a sugar cube of neutron star according to NASA). The surface gravity of a neutron star can be as high as 1014 cm/s2 (100 billion time to the Earth's gravity) which make the surface of neutron star extremely smooth. Neutron stars will normally be detected as pulsars which emits radiations in a regular time interval. The beams of radiations can be powered by rapid rotation of the star or the magnetic field (in a magnetars) [5].

2.3. *About the black hole*

Albert Einstein first predicted the existence of black hole in 1916. And in 1971, the first black hole was identified. The formation of a black is very similar to the formation of a neutron star, the difference is that the core left after the supernova should have a mass more than 3 solar mass to be proven theoretically that no force can prevent the star from collapsing under the effect of gravity. Telescopes that search for light, x-rays, or other forms of electromagnetic radiation cannot see black holes. But one can infer the presence of black holes and learn more about them by watching how they affect nearby stuff. If a black hole passes through a cloud of interstellar matter, for example, it will accrete that matter, or pull it inward. As it approaches a black hole, a regular star might behave similarly. The star might sever in this circumstance as it is dragged toward the black hole. As it accelerates and warms up, the heated and accelerated attracting matter emits x-rays into space. Recent findings provide some enticing evidence that black holes have a significant impact on the neighborhoods around them, emitting powerful gamma ray bursts, devouring nearby stars, and spurring the growth of new stars in some areas while stalling it in others. According to their mass, black holes are typically divided into three groups: stellar-mass, supermassive, and intermediate-mass. Each group's mass ranges are approximations, and scientists are always revaluating where the boundaries should be drawn [3].

Cosmologists believe a fourth type of black hole, known as a primordial black hole, may also be present in the universe but be undiscovered. For the stellar type, the core of a star that is more than eight times as massive as the Sun collapses, bounces back, and erupts as a supernova. For the supermassive type, the core of a star that is more than eight times as massive as the Sun collapses, bounces back, and erupts as a supernova. For the intermediate type, the core of a star that is more than eight times as massive as the Sun collapses, bounces back, and erupts as a supernova [4].

3. Relationship between the neutron stars and black holes

One of the most captivating aspects of black hole-neutron star mergers is their role in the synthesis of heavy elements. Neutron stars are known to be cosmic crucibles for nucleosynthesis, creating elements through rapid neutron capture processes during their violent births. When a neutron star merges with a black hole, the intense tidal forces and heat generated during the event create conditions conducive to the production of even heavier elements, including gold, platinum, and uranium. These elements, which are integral to the formation of planets, stars, and life, find their origins in these cataclysmic collisions [7]. Recent studies have leveraged advanced simulations to model the intricate dynamics of matter ejected during the merger. By combining nuclear physics, hydrodynamics, and radiative transfer calculations, scientists have made significant strides in predicting the composition of the ejected material and the resulting nucleosynthetic yields. These predictions have provided valuable insights into the abundance patterns of heavy elements observed in the universe, aligning the theoretical expectations with observational data.

The extreme conditions generated during black hole-neutron star mergers offer a unique laboratory for probing the frontiers of fundamental physics. As the two objects approach each other, their gravitational interaction causes ripples in spacetime – gravitational waves – which carry the signature of the objects' masses, spins, and orbital parameters. By analyzing these signals, scientists can test the predictions of Einstein's general theory of relativity, as well as alternative theories of gravity. Moreover, these mergers create conditions where matter reaches densities and temperatures that are otherwise unattainable on Earth. This opens avenues for studying the behavior of matter under extreme gravitational fields and exploring the properties of fundamental particles in novel regimes. The accretion disks and jets formed during these mergers can host processes that accelerate particles to energies far beyond those achievable in terrestrial particle accelerators, leading to insights into the mechanisms behind high-energy cosmic phenomena such as gamma-ray bursts [7].

In addition, the detection of the gravitational wave can be used to test the general relativity. The recent tests are residual examination, inspiral-merger-ringdown, the chromatic dispersion of the gravitational wave, polarization of the gravitational wave and the echo. The merger of the neutron star and black hole can also be used to explore the expansion of the universe as it emits both gravitational waves and electromagnetic waves. The merger of compacted stars can be used to determine the Hubble constant, the gravitational wave is used to determine the distance and the electromagnetic wave is used to determine the speed of the merger system. This method was successfully done in the binary neutron star merger GW170817 [5], but due to the difficulty of determining the dip angle of the orbital, there is a 14 present uncertainty. However, the scientists believes that the black hole-neutron star merge will provide a more accurate measurement of the distance and thus get a more precise and accurate Hubble constant.

Black holes and neutron stars are very dense objects with intense gravitational forces. Their gravitational attraction grows stronger as they draw near to one another. As a result, the spacetime in their immediate vicinity is warped, leading to ripples that eventually spread outside as gravitational waves. In 2015, scientists first observed the black hole-black hole merge (GW150914), after two years at 2017, the first neutron star-neutron star merge was also detected (GW170817). In 2020, LIGO from the US detected the first neutron star-black hole merge (GW200105) and just after ten days at the 15th, the second NS-BH merge was detected by LIGO and Virgo. In event GW200105, the merge happened approximately 900 million lightyears away from the Earth and the mass of the NS and BH are 1.0 and 8.9 solar mass respectively. Whereas the mass of NS and BH in event GW200115 are 1.5 and 5.7 solar mass and is 1 billion lightyear away from the Earth.

The major methods of detecting these merging events are by detecting the electromagnetic radiation or the gravitational wave. If the merging black hole's mass is lesser than 6 solar mass AND the mass of the neutron star is less than 1.5 solar mass, the neutron star will be teared into pieces by the tidal force of the black hole and form an accretion disk. During this process there will be a gamma-ray burst and the respective optical afterglow. Some of the neutron particles will conduct nuclear reactions and produce massive amount of heat. This heat might be radiated as infra-red radiations and a kilonova phenomenon will happen, which can be detected by the electromagnetic wave telescope. Otherwise, there will be no electromagnetic radiation as the neutron star merges with the black hole as a whole and thus the electromagnetic radiation detection will not be suitable [8].

When two massive stars collapses and become neutron star and black hole, they might form a binary neutron star-black hole system. This formation of the binary system has mainly three reasons. The first reason is that most of the stars in the universe are in binary system. The stars with the large masses collapse then became neutron stars and black holes and stay in their system. The stars in the star cluster exchange their companions and finally form a system with a neutron star and a black hole. In some star clusters, the compact stars may frequently integrate with each other and lead to an smaller orbit and the neutron star and black hole finally merge.

During the process of orbiting, the black hole and neutron star will radiate gravitational waves. These waves mainly from the kinetic and potential energy(or energy for the orbiting motion), the loss of energy will result the closer distance between the two stars and finally merge together. At the merging process, the orbiting speed of the stars will approach the speed of light, the gravitational field around will be extremely large and a huge amount of gravitational wave is radiated. However due to the long distance between the merging stars and the Earth, the energy transferred to the signal reviver is only a tiny proportion of the energy in total [9].

The current method of detecting the gravitational wave is using space laser interferometry. This method will use the distance between the tested masses as sensor and transfer the signal of the gravitational wave to the signal of the change in distance between the masses. Then use the laser interferometer to read the signal of changing distance.

In order to make the reading more accurate, no-drag spaceflight is introduced. To keep the tested masses not be affect by external disturbances such as the solar wind and radiation from the universe, a spacecraft will be containing the mass. However as the spacecraft got affect by the disturbance, it will produce a relative displacement with the tested mass. To reduce the displacement, a displacement sensor is used to detect the signal and send to the control system and make the small propeller push the space craft to make the relative displacement remains zero. A laser ray will be shot from a telescope and be received by another telescope on the other spacecraft. The ray will be imported to the local laser interferometer and get reflected by the tested mass. Then it will interfere with the laser ray from the local laser emitter. By measuring the relative displacement of the interference signal, $\delta\phi$, the change in distance between the two masses can be calculated using the equation:

$$\delta\phi = 4\pi\delta L\lambda \tag{1}$$

Due to the relative displacement between the spacecrafts, Doppler shift occurs which must be deducted from the final signal result. The Doppler shift can be calculated using:

$$\Delta f = -V_r c f_o \tag{2}$$

Where V_r is the speed difference of the spacecraft, c is the speed of light and f⍰o⍰ is the frequency of the laser.

There are also some studies about the neutron star-neutron star merge, which indicates that when two neutron stars merge, a massive, high temperature and high spinning speed neutron star will be formed. The non-axisymmetric deformation and the vibration of the star can emit a wealth of gravitational waves. After modulation, the scientists found that the peak frequency has a strong relationship between the reduction ability of the twin-stars' tidal deformation ability. Also, the state of matter should be considered in the type of interation condition where the stars are experiencing, especially the strong force interation. The strong force interation can deform the state of matter, as shown in Figure 1, the state of matter is different when considering strong force interation [10].

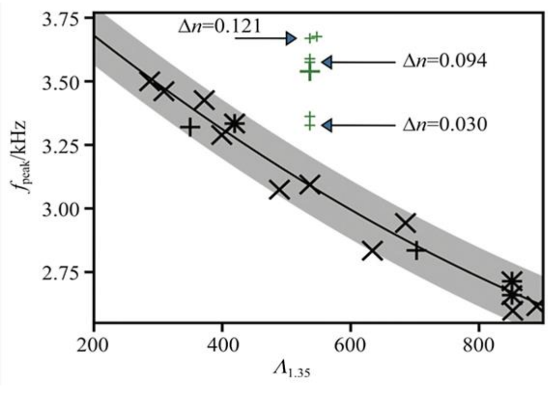

Figure 1. The black mark represents the state of matter that used pure hadron model. The green marks represent the state of matter with concerns about strong force deformation [10].

After the merge, because of the increase in mass, the center density of the star increases as well. The center region of the star might form a high-density region which allows the strong force deformation to happen, the quarks might appear in this region. However, after the deformation, the star returns to a more stable (i.e. lower energy level) state thus the neutron star will be easier to be deformed. Under the integration of gravity, the neutron star might have a decrease in the radius, the frequency where the star vibrate might become larger. This study can be also used in the neutron star-black hole merge as one of the stars has even larger mass. The center region of the merged star might become so dense that the strong force could cause a nuclear reaction.

4. Conclusion

From 2015 the first-time human detected the merger of a binary black hole system until 2020 the first time detect the neutron star-black hole binary merger. The scientists were developing the method of the detection to make sure that the results obtained is as accurate as possible. After the on-ground vibration detector, the most current space laser interferometry has its own advantages and disadvantages. It is more accurate as the noise from the space is far lesser than that on the ground as the Earth also vibrates and orbits. However, the method still needs to be modified and developed as most of these detectors are made to detect the low frequency gravitational waves, it can detect the gravitational waves emitted from the massive black hole ad neutron star mergers but with lower mass it is hard to detect. Also, the data transmission and analysis are a problem for space laser interferometry method as transmitting data from space to Earth and processing it for gravitational wave detections can be complex and resource-intensive. It requires efficient data compression and transmission techniques, as well as sophisticated data analysis pipelines. Lastly the challenge of this method is that launching and maintaining a space-based observatory is extremely expensive and complex. Building and launching the necessary spacecraft, ensuring they are properly aligned and maintained over time, and dealing with potential technical failures can pose significant challenges.

References

[1] Lattimer, James M. (2015). Introduction to Neutron Stars. AIP Publishing 1645(1), 61-78.
[2] Liu, J., Wang, G., Hu, Y., Zhang, T., Luo, Z., Wang, Q., Shao, L. (2016). GW150914 and Gravitational-wave Astronomy. Chinese Science Bulletin, 61, 1502-1524.
[3] Sedda, Manuel Arca. (2020). Dissecting the Properties of Neutron Star–black Hole Mergers Originating in Dense Star Clusters. Communications Physics, 3, 43.
[4] Lu, Youjun, & Guo, Xiao. (2022). The first detection of neutron star-black hole binary mergers. Science China Press, 67(22): 2610-2615
[5] Zhou, Enping, (2019). Numerical relativity and binary neutron star merges. Physics, 48(9): 573-580.
[6] Xu, Renxin. (2018). The ideal tool to measure the expansion of the universe-neutron star-black hole binary merger. Physics, 47(9), 591
[7] Vincentelli, F. M., Neilsen, J., Tetarenko, A.J. et al. (2023). A shared accretion instability for black holes and neutron stars. Nature, 615, 45–49.
[8] Charles, D. Dermer, Armen, Atoyan. (2006). Collapse of Neutron Stars to Black Holes in Binary Systems: A Model for Short Gamma-Ray Bursts. The Astrophysical Journal, 624: L13-L16.
[9] Luo, ZR, Bai, S, Bian, X, Chen, GR, Dong, P, Dong, YH, Gao, W, Gong, XF, He, JW, Li, HY, et al. (2013). Space laser interferometry gravitational wave detection. Advances in Mechanics, 43(4), 415-447.
[10] Emrah Kalemic, Sara Elisa Motta. (2023). Bright Black Holes and Neutron Stars Beat Alike. Nature, 615: 38-39.