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Black Hole-neutron Star Mergers as Cosmic Laboratories for Modified Gravity Theories

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Abstract. Black hole–neutron star mergers provide a natural laboratory for probing gravity in regimes that other observations cannot reach. Their asymmetric composition and strong curvature make them sensitive tests that can support or challenge the standard theory. This work explains how gravitational waves and possible electromagnetic signals from these systems can be used together to search for small departures from expected behavior. This research outlines the main features of the mergers and how the disruption or direct swallowing of the neutron star shapes what this research measures. This research summarizes the current observations, which agree with general relativity, and describe how better data and modeling can sharpen limits or reveal new effects. This research notes simple ways to compare theory and data and the role of matter physics in avoiding confusion. This research also stresses the value of multi-messenger and multiband observations. Finally, this research points to next-generation detectors and improved simulations as key steps toward stronger tests of gravity.

Keywords: Black hole-neutron star mergers, modified gravity theory.

1. Introduction

Gravitational force is one of the fundamental forces of the universe, and all research of modern astronomy need to consider the impact of gravity, including the greatest problems of dark matter, dark energy and inflation. Through ground-based gravitational wave (GW) observations, three types of binaries are detectable, which include black hole-neutron star (BH-NS) mergers, playing a very important role in GW astrophysics [1].

Studying the BHNS mergers provide advancements in understanding of a variety of subjects. The evolution of BH-NS merger can be decomposed into three parts: in the first phase lasting a few million years, the two objects gradually rotate around each other and energy is lost through GW; in the second phase lasting 1 ms, the two objects merge and the neutron star is destroyed; the last phase varies depending on the final result of the neutron star [1].

The current standard model of cosmology has its base upon the general relativity (GR) theory. It is assumed that gravity is described by GR, but actual tests for it can only take place in the university. The modified gravity theory helps to explain some of the problems that GR is not able to provide the best solution. For example, modified gravity theory serves as an alternative to dark energy when explaining the accelerating expansion of the universe [2]. When this problem is seen

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from the opposite side, the modified gravity theory also challenges GR in its assumptions of dark energy and dark matter.

Given the difference in density of a black hole and a neutron star, the detection of such a binary system may contribute to extending or challenging general relativity. The paper mainly investigates the usage of BHNS mergers as laboratories for modified gravity theories.

2. Black hole-neutron star mergers: an overview

The merger phase eventually has 2 outcomes. When the black hole mass is small, the neutron star is deformed by the tidal field of the black hole, leading to mass ejection; when the black hole mass is large, the disruption does not happen and the neutron star gets absorbed by the black hole [3]. Tidal disruption occurs when the neutron star on the orbit around the black hole reaches a very close distance, teared apart by the black hole's tidal forces. Mass ejection therefore takes place, part of the neutron star no longer remains bound to the system but gets ejected away at high speeds [4].

The three stages of BH-NS mergers have unique wave forms. During the inspiral phase, the frequency and amplitude gradually increase. During the merger phase, there is a sudden increase in amplitude and frequency for a few peaks, then it shifts into the ringdown phase, where the wave amplitude decreases. The gravitational waveform of BH-NS mergers can therefore also be classified into three types. Depending on how tidally disrupted the neutron star is. In the first case, the neutron star is completely disrupted during inspiral phase, so the merger and ringdown wave forms are absent. In the second case, the neutron star is partially disrupted before being consumed by the black hole, all phases are present but the first two are emphasized. The last case is when tidal disruption does not occur, all phases are clearly shown [4].

The wave form of neutron star-neutron star mergers and black hole-black hole mergers is generally similar with the last case, presenting clearly the inspiral, merger and ringdown waveforms.

Many associated phenomena accompanies the merging of BH-HS system, they can not only help with understanding of it but also aid with the detection. When a BH–NS merger occurs, a fraction of neutron-star material is ejected. This matter rich in neutrons undergoes rapid neutron-capture nucleosynthesis, producing heavy elements like gold and platinum. The kilonova is a supernova like process powered by the radioactive decay of these substances [5]. In BH–NS mergers, if the neutron star undergoes tidal disruption and merge into the black hole, it launchs a relativistic jet, producing the short gamma-ray emmision, also known as short gamma ray bursts (sGRBs) [6]. Afterglow is the electromagnetic wave emission following sGRBs, composed of various wavelength.

Multi-messenger astrophysics have a close link with BH-NS mergers. It is linked to multiwavelength astronomy but provides more insights by using the information from photons, neutrinos, and gravitational waves [7].

3. Modified gravity theory and their predictions

Scalar–tensor theories are a class of modified gravity theories where gravity is mediated not only by the usual tensor field of general relativity but also by an additional scalar field. It is among the most studied alternative theories of gravity. There are many scalar-tensor equations owing to the two free functions given by the Lagrangian density equation. The Horndowski equation is the most general four-dimensional scalar-tensor theory with second-order field equations. The f(R) theory is the fourth-order theory, adding additional scalar curvatures to space [8].

The vector-tensor theories extend GR by introducing a dynamical vector field in addition to the metric tensor. Gravity is then defined by both tensor and vector degrees of freedom. The tensor-

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tensor theories extend GR by adding an additional metric tensor instead of more scalars and vectors [8].

The “chameleon” mechanism is a theoretical framework in modified gravity where the strength of gravity is dependent on local matter density. So in high density regions like Earth, the field is strong and the force is hidden (screened), in lower density regions the field is weak so gravity is modified [9]. The Vainshtein mechanism states that near massive objects, nonlinear derivative interactions of the scalar field suppress its coupling to matter, so on small scales, GR is recovered while on large scales, scalar modifications become active [10].

From these theories of modified gravity, the dynamics of the BH-NS merger system may change due to new degrees of freedom. Extra scalar or vector fields may carry away energy and angular momentum, altering the inspiral rate [11]. Screening mechanisms like chameleon may suppress deviations in dense environments, though it may become ineffective in extreme settings. This affects whether the neutron star is swallowed whole or disrupted outside the horizon, influencing ejecta production and sGRBs [12].

The propagation of gravitational waves over cosmological distances can reveal modifications of gravity. In massive gravity or bimetric theories, gravitons may have nonzero mass, causing frequency-dependent propagation speeds [13]. This produces an arrival-time deviation across frequencies, detectable in precise waveform reconstructions. Extra polarizations (scalar or vector modes) may dilute energy from the tensor modes, reducing observed strain amplitude [12]. Alternatively, some modes may decay differently due to couplings with background fields [1].

Electromagnetic counterpart will also undergo changes when considering the modified gravity theories. Changes in merger dynamics will modify the ejecta mass and composition. This impacts the brightness, color, and timescale of kilonova [5]. The accretion disk, what debris of neutron star after disruption form, can change in angular momentum, which in turn leads to change in ability to create jets [14]. Since afterglows depend on jet energetics and geometry, deviations in mass ejection and jet launching can lead to distinct light-curve shapes [14].

4. Observational constraints from BH-NS mergers

LIGO/Virgo/KAGRA is an advanced gravitational wave detecting network. However, observational data from them show no evidence of modified gravitational wave propagation, with results aligning with the predictions of GR, indicating currently there are still constraints. It is expected that future data will sharpen these tests, potentially revealing subtle deviations or further reinforcing GR’s robustness [15].

Together, Einstein Telescope (ET) and Cosmic Explorer (CE) form a powerful third-generation detector network, expanding both the number and precision of observed events. A simulation of binary neutron star and BH–NS events with electromagnetic counterparts observed by ET and two CE detectors demonstrate that this network can effectively constrain modified gravity models [16]. The CE–ET network dramatically enhances pre-merger detection and localization as well: a full network of CE-ET system can localize sources to ~1 deg², enabling coordinated electromagnetic observations, crucial for detection of jet and kilonova physics [17].

Multi-messenger astronomy combines gravitational waves and electromagnetic waves. In the context of modified gravity theories, this approach allows constraints to be placed both on the generation and propagation of GWs. In BH–NS mergers, electromagnetic signatures such as kilonova light curves or sGRBs and afterglows can test whether tidal disruption and mass ejection processes follow GR predictions. Modified dynamics can alter the amount of ejected matter, disk formation, and thus the electromagnetic brightness [18]. Dispersion or damping of GWs due to extra

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fields would affect GW waveforms, while electromagnetic signals remain unaffected, providing a clean cross-check. Next-generation detectors combined with sensitive electromagnetic observatories could narrow the range dramatically [19].

Currently, two BH-NS merger events are observed (GW200105, GW200115). They are likely BH-NS mergers because of the mass distribution consistent with prediction. However, there is no evidence for tidal disruptions or electromagnetic counterparts, allowing still the chance of it being binary black hole mergers [20].

The method for extracting deviations from GR in BH-NS merger is by using parametrized deviations in GR predictions and then using Bayesian inference on observed data. The parameterized post-Einsteinian framework captures the deviations from GR waveforms in both amplitude and phase. Then, Bayesian inference is used to quantify how detectable the such deviations would be [21].

Many challenges are present when modified gravity effects are evaluated in astrophysical observations. One great source is similar astrophysical effects. Modified gravity theories predict measurable deviations in GW waveforms, while many astrophysical processes can produce similar waveforms. An example is that strong gravitational lensing in GR can introduce a frequency-independent phase shift. When higher-order GW modes (beyond the dominant quadrupole) are present, these shifts become alike with modified dispersion relation induced deviations, making it difficult to tell them apart using waveform data alone [22].

5. BH-NS mergers as cosmic laboratories

Many advantages exist for BH-NS system when using them as the cosmic laboratory of modified gravity theories. Since most of these theories require adding curvatures to the Einstein-Hilbert actions with some constants, the deviations considering the shortest curvature length scales is very higher, so small compact objects is the best choice to prove or serve as evidence for modified gravity theories [23]. “For a binary system, the dipole radiation power is proportional to the charge difference squared.” The BH-NS system with the two objects having significantly different charges is much more fitting for the job, unlike binary black holes and binary neutron stars [24].

Complementary investigation with binary black hole mergers or binary neutron star mergers can offer deeper insights. Owing to the difference in dipole radiation power, the observation of BH-NS system provides different insights to other systems.

The gravitational wave emitted by the decaying orbit of binary neutron stars can be used to calculate Hubble constant to an accuracy of 3% [25]. A similar system of BH-NS should be able to complete this task as well. At the same time, data from multi messenger gravitational wave can be used to calculate the cosmological expansions, helping in determining the equation of state of the dark matter [26].

One important challenge is in modelling the BH-NS mergers.

Another challenge is the difficulty in simulations. The high complication of the system makes high-precision simulations hard to be done, though thanks to the advance in computational technology currently researchers are able to follow from the merger phase to the point of ejecta rays happen [27].

6. Future prospects and open questions

Advances in detector sensitivity and network coverage allows a qualitatively new regime for using black hole–neutron star (BH–NS) mergers as precision tests of gravity. Third-generation ground

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detectors (Cosmic Explorer, Einstein Telescope) that extends the observer volume will improve signal-to-noise across the different phases [28]. The role of space-based observatories such as LISA is expected to provide more observations, like the evaluation of data from more confirmed BH-NS mergers.

On the theory side, to refine modified gravity, a plausible way is to embed modified gravity signal into gravitational template or the other way round. Through this way, better analysis of data can be done to acquire the estimate of deviation and the detection of bias.

Realistic astrophysics is equally important. Numerical relativity simulations that include magnetization, neutrino transport, and tidal disruption criteria predict cutoff frequencies, disk masses, and ejecta that feed both gravitational wave and electromagnetic counterparts.

Can deviations from GR be conclusively detected in BH–NS mergers? To date, population-level tests across GWTC-3 find no statistically significant departures in generation, propagation, or polarization, with increasingly tight bounds from combined events [29]. Future observations with increase in precision and sample size may be able to improve the current status.

What will the implication for fundamental science be? Detection of such modified gravity theory evidence will constrain extra degrees of freedom and screening, reshaping cosmological inference [30].

7. Conclusion

BH–NS binaries sit in an asymmetric, high-curvature regime where GR do not have the effects, dipole radiation, extra polarizations, modified dispersion, screening mechanisms, can leave clean fingerprints in the waveforms. Tidal disruption, ejecta, and remnant-disk formation also links to gravity. BH-NS mergers are promising tools to study modified gravity theory. Their mixed nature lets us look for small deviations from general relativity in both the gravitational waves and any light human may see. So far, observations agree with general relativity, but they also set limits that guide future work. Better detectors and wider networks, together with careful theory and realistic simulations, will make these tests sharper and reduce confusion with astrophysical effects. Multi-messenger observations will add key pieces by linking what astronomers hear in waves to what astronomers see in light. With more events and better models, BH–NS mergers can either confirm general relativity with higher precision or reveal the accuracy of modified gravity theory.

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