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TWO NEUTRON STAR-BLACK HOLE MERGERS OBSERVED BY THE LIGO-VIRGO COLLABORATION

Z. Vidadi[1*], N. Kochiashvili[2], N. Z. Ismailov[1]

[1] *Shamakhy Astrophysical Observatory named after N. Tusi, AZ5626 Shamakhy, Y. Mammadaliyev settlement, Azerbaijan*
[2] *E.Kharadze Georgian National Astrophysical Observatory; Mt. Kanobili, Abastumani, 0301, Adigeni, Georgia*

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ABSTRACT

Neutron star–black hole (NSBH) mergers are still very rare among gravitational-wave sources. However, together with binary neutron star (BNS) mergers, they play a crucial role in gravitational-wave astronomy, producing not only gravitational waves but also electromagnetic (EM) radiation, as well as neutrinos and high-energy particles (cosmic rays). In the Fourth Open Gravitational-wave Catalog (4-OGC), out of 94 recorded events, 90 are binary black holes (BBHs), 2 are NSBH mergers, and 2 are BNS mergers. Therefore, despite the limited number of NSBH and BNS mergers, their study remains a highly significant area of research.

In this article, we review existing observational data for the events GW200115 (S200115j) and GW200105 (S200105ae), which are confirmed NSBH mergers. Powerful networks have been developed globally to observe EM counterparts of gravitational waves, including the GRANDMA collaboration. The GRANDMA project, in which the Shamakhi Astrophysical Observatory named after N. Tusi participates, has been important for coordinating observations across multiple countries and implementing advanced tracking strategies via joint telescope monitoring.

No optical counterparts have been found, but the observational data obtained are useful for establishing constraints on the properties and observational capabilities of NSBHs.

Key words: stars: neutron stars, black holes, gravitational waves, kilonova.

1 INTRODUCTION

In 1916, Albert Einstein proposed the General Theory of Relativity and introduced the concept of gravitational waves, laying the theoretical foundation for gravitational-wave (GW) astronomy. For a century, the detection of gravitational waves remained impossible due to technological limitations. However, in 2015, the first GW signal (GW150914) detected by LIGO (Abbott et al. 2021) revived interest in this field. This event marked the first practical confirmation of GWs produced by the merger of two black holes, validating Einstein's predictions. Later, joint observations of Advanced LIGO and Virgo led to the discovery of the binary neutron star merger GW170817 (Bartos et al. 2017). These breakthroughs enabled GW astronomy to develop into an entirely new observational discipline.

The study of the late stages of stellar evolution has become one of the key areas of astrophysics involving GW messengers. The remnants of GW sources include neutron stars and black holes formed through several processes: neutron star–black hole (NSBH) mergers, binary neutron star (BNS) mergers, binary black hole (BBH) mergers, supernova explosions of massive stars, and direct collapse of massive stars. These events emit not only GWs but also electromagnetic (EM) radiation and neutrinos. Cosmic rays are also produced in NSBH and BNS mergers, but they cannot be detected due to their slow propagation—taking hundreds to thousands of years to reach Earth (Metzger 2019). The presence of multiple messengers allows multi-messenger astronomy to provide a more complete understanding of compact object mergers by combining GW, EM, and neutrino observations (Anand et al. 2021). Rapid development in this field is closely tied to advances in multi-messenger infrastructure.

Large-scale collaborations such as LIGO, Virgo, and KAGRA, together with EM telescopes and neutrino detectors, form a strong global infrastructure for observing transient events. Networks such as GRANDMA (Global Rapid Advanced Network Devoted to the Multi-messenger Addicts) and wide-field facilities like ZTF (Zwicky Transient Facility) play key roles in follow-up observations of GW alerts (Graham et al. 2021). The GRANDMA project, which includes the Shamakhi Astrophysical Observatory named after

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[*] Contact e-mail: zumrudvidadiqizi@gmail.com

N. Tusi, improves coordination between telescopes around the world and enhances follow-up strategies (Antier et al. 2020; Noysena et al. 2020). These efforts enable fast alert dissemination, rapid organization of real-time observations, and detailed study of remnants and their environments. Such follow-up observations aim to confirm or constrain the presence of kilonovae (Kasen et al. 2017) and relativistic jets, thus expanding our ability to detect these transients.

One of the main scientific targets is BNS mergers, which generate both gravitational waves and electromagnetic signals, including short gamma-ray bursts and kilonovae (Kasen et al. 2017). Another important field concerns the formation of black holes through failed supernovae, which emit GWs and neutrinos without a bright optical transient.

NSBH mergers have also become a crucial area of study in GW astrophysics. These mergers can produce a range of EM counterparts such as kilonovae, accretion-powered emission, and relativistic jets (Turpin et al. 2020). The outcome of an NSBH merger depends on multiple factors: total system mass, black-hole spin, and the equation of state of neutron star matter. These mergers typically lead to the formation of a more massive black hole, often surrounded by an accretion disc emitting EM radiation (Foucart 2018; Kawaguchi et al. 2020).

All confirmed BBH, BNS, and NSBH mergers are compiled in the Fourth Open Gravitational-wave Catalog (4-OGC) (Nitz et al. 2023). The 4-OGC catalog includes all observations from 2015 to 2020, covering the O1, O2, O3a, and O3b runs of Advanced LIGO and Virgo. This updated catalog includes seven previously unclassified BBH mergers from O3b. In total, 94 events have been reported: 90 BBHs, 2 NSBHs, and 2 BNS mergers. Thus, despite their rarity, NSBH mergers represent a highly important and rapidly developing direction in modern GW astrophysics.

2 PROPERTIES OF GW 200115 AND GW 200105 EVENTS

In this paper, we examine the events GW200115 and GW200105, which are confirmed to be NSBH mergers based on their mass and spin characteristics (LIGO Scientific Collaboration & Virgo Collaboration 2020a). Unlike binary neutron star mergers, NSBH mergers are less likely to produce an observable kilonova because the neutron star may be completely consumed by the black hole without forming a significant accretion disk (Foucart 2018). However, if the neutron star is disrupted before being fully swallowed, a kilonova might still be detected.

The detection of GW200115 and GW200105 has prompted extensive follow-up observations to search for electromagnetic counterparts. Collaborations like GRANDMA have played a significant role in coordinating optical follow-ups of these GW events (Graham et al. 2021; Kawaguchi et al. 2020; Noysena et al. 2020). By analyzing data from various telescopes around the world, researchers are looking for kilonova signatures or afterglows associated with these mergers. The study of the remnants of mergers like GW200115 and GW200105 is crucial for understanding the late stages of stellar evolution. These events, detected by the LIGO and Virgo collaborations (LIGO Scientific Collaboration & Virgo Collaboration 2022), are thought to result from NSBH mergers. By combining GW data with EM and neutrino observations, scientists can gain a more complete understanding of these powerful cosmic events (Bartos et al. 2017).

Optical follow-up observations were also conducted by various networks and telescopes, including the Zwicky Transient Facility (ZTF), which covered a significant fraction of the localization regions. However, no EM counterparts were detected. Despite this, the observations provided constraints on the ejecta mass, mass ratios, and spin properties of black holes (Foucart 2018; Kawaguchi et al. 2020; Metzger 2019). Observations in the i- and z-bands are considered particularly important for detecting NSBH kilonovae, due to their sensitivity to these events.

S200105ae was detected on 5 January 2020 at 16:24:26.057 UTC. Although observed by both LIGO detectors, it was recorded only by the Livingston detector, as Hanford was temporarily offline. Initial analyses indicated it was an NSBH merger (LIGO Scientific Collaboration & Virgo Collaboration 2020b). S200105ae was initially classified as a 97% probability terrestrial signal, but its significance was later reassessed as high. Its chirp-like structure in the spectrograms indicated a real astrophysical event. Finally, it was classified as an NSBH merger with $> 98\%$ probability that one component had a mass $< 3\ \mathrm{M}_\odot$, making it a neutron star. The initial analysis estimated that the probability of remnant material being left after the merger was $< 1\%$. Its 90% confidence localization covered 7373 deg^2, and its median distance was 283 ± 74 Mpc. Optical follow-up observations by ZTF covered 48% of the localization region. Over three nights, 3300 deg^2 were observed. GRANDMA performed tiled observations with the FRAM-Auger, FRAM-CTA-N, TAROT-Calern (TCA), and TAROT-Chili (TCH) telescopes, covering ∼8.5% of the GW skymap (Noysena et al. 2020). Observations were sensitive enough to detect kilonovae brighter than −17.5 mag fading slower than 0.5 mag/day, but no counterpart was detected. Observations were compared with kilonova model simulations, suggesting that ejecta masses $M_{\mathrm{ej,dyn}} \leqslant 0.02\ \mathrm{M}_\odot$ and $M_{\mathrm{ej,pm}} \leqslant 0.04\ \mathrm{M}_\odot$ would have been detectable at 283 Mpc in a polar direction (Perkins et al. 2024; LIGO Scientific Collaboration & Virgo Collaboration 2020c).

3 CONCLUSION AND DISCUSSION

It has been determined that NSBH mergers generally produce more massive ejecta compared to binary neutron star mergers. Consequently, this results in a slower evolution of kilonova brightness after reaching its peak. In future observations, it is crucial to aim for consistent and deep coverage across all wavelengths, particularly in the i- and z-bands, as these bands are more suitable for detecting NSBH kilonovae. Although no optical counterpart was detected during the study of S200105ae, this event remains an important case for understanding NSBH mergers (LIGO Scientific Collaboration & Virgo Collaboration 2020a,b,c; Foucart 2018; Kawaguchi et al. 2020; Noysena et al. 2020).

Due to the large distance of the S200115j event and limited sky coverage, constraints on kilonova properties have been weaker. Deeper observations in the i- and z-bands could improve the study of optical counterparts of NSBH kilonovae. The high probability of remnant material remaining after the merger makes S200115j an important candidate for understanding NSBH mergers and their electromagnetic signatures (LIGO Scientific Collaboration & Virgo Collaboration 2020a,b,c; Foucart 2018; Kawaguchi et al. 2020; Noysena et al. 2020).

Observing the remnants of gravitational-wave sources is crucial for understanding the complex interactions following compact object mergers. Although observations of GW200115 and GW200105 have not revealed confirmed electromagnetic counterparts, ongoing and future studies, including contributions from the GRANDMA collaboration, will enhance our ability to detect and study such phenomena. The next generation of gravitational-wave observatories, such as the Einstein Telescope and Cosmic Explorer, will provide deeper insights into the late stages of stellar evolution, through observations of compact object mergers and other gravitational-wave sources (Punturo et al. 2010).

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