CONSTRUCTIONS ON THE ELECTROMAGNETIC COUNTERPART OF THE NEUTRON STAR BLACK HOLE MERGER GW200115

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Draft version February 18, 2022

ABSTRACT

We report the results of our follow-up campaign for the neutron star - black hole (NSBH) merger GW200115 detected during the O3 run of the Advanced LIGO and Advanced Virgo detectors. We obtained wide-field observations with the Deca-Degree Optical Transient Imager (DDOTI) covering ~20% of the total probability area down to a limiting magnitude of \( w = 20.5 \) AB at ~23 h after the merger. Our search for counterparts returns a single candidate (AT2020aoe), likely not associate to the merger. In total, only 25 sources of interest were identified by the community and later discarded as unrelated to the GW event. We compare our upper limits with the emission predicted by state-of-the-art kilonova simulations and disfavor high mass ejecta (>0.1 \( M_\odot \)), indicating that the spin of the system is not particularly high. By combining our optical limits with gamma-ray constraints from Swift and Fermi, we disfavor the presence of a standard short duration burst for viewing angles \( \lesssim 15 \) deg from the jet axis. Our conclusions are however limited by the large localization region of this GW event, and accurate prompt positions remain crucial to improving the efficiency of follow-up efforts.

Subject headings: gravitational waves – stars: black holes – stars: neutron – binaries: close

1. INTRODUCTION

Compact binary mergers composed of two neutron stars (NSs) or a NS and a stellar mass black hole (BH) have long been suspected of being the possible progenitors of at least a class of gamma-ray bursts (GRBs; Eichler et al. 1989; Kluzniak & Lee 1998; Janka et al. 1999; Rosswog, Speith, & Wynn 2004; Faber et al. 2006) and of being relevant to the production of r-process elements (Lattimer & Schramm 1974). Depending on the BH mass, its spin and the NS compactness, the close encounter of the two compact objects could lead to the tidal disruption of the NS (e.g. Foucart, Hinderer, & Nissanke 2018, for a recent exploration of the parameter space). When this happens, a hot (\( T \sim 10 \) MeV) and massive (up to \( \sim 0.3 \) \( M_\odot \)) accretion disc is formed around the BH, likely providing the energy source for a GRB (Popham, Woosley, & Fryer 1999; Narayan, Piran, & Kumar 2001; Lee, Ramirez-Ruiz, & Page 2005). A large amount of neutron-rich matter is also ejected in the form of tidal tails and disc outflows, and its radioactive decay could power a bright kilonova emission (Li & Paczynski 1998; Roberts et al. 2011; Kutykou et al. 2015; Fernández, Foucart, & Lippuner 2020). Therefore, the expectation is that NSBH mergers should be characterized by electromagnetic (EM) counterparts similar to binary NS mergers such as GW170817 (e.g. Abbott et al. 2017). However, the presence of a primary BH with a significantly higher mass and a definite event horizon, rather than a NS, unavoidably changes the merger dynamics and is likely to leave distinguishable imprints in the EM radiation, such as the color and luminosity of the kilonova or a long-lasting hard X-ray emission (Norris & Bonnell 2006; Troja et al. 2008; Barbieri et al. 2020; Dichiara et al. 2021). An outstanding issue is whether in a NSBH event the dynamics will allow for full disruption of the NS and the formation of an accretion disk that will both release gravitational binding energy into a relativistic outflow to power the GRB and eject neutron-rich matter leading to a kilonova, or if the NS will be accreted whole leading to little or no counterpart EM emission.

Although NSBH binaries and their mergers were a longstanding prediction of stellar evolution models (Yungelson & Portegies Zwart 1998; Pfahl, Podsiadlowski, & Rappaport 2005), proof of their existence remained elusive until recently. The advent of gravitational wave (GW) astronomy provided us with a new avenue to discover binaries of compact objects: over 40 binary black holes (BBHs) mergers, and two NS mergers were identified through GW searches (Abbott et al. 2021a, 2019). In addition, several NSBH candidates were found during the third run of Advanced LIGO and Virgo observations.

The first two candidate NSBH mergers were GW190426 and GW190814 (Abbott et al. 2020). The former has a low statistical significance and cannot be confidently associated with an astrophysical event, the latter has a secondary mass
of \( \approx 2.5 \, M_\odot \) which does not allow for an unambiguous classification as either NS or BH. None of these GW signals was associated to an EM counterpart (Andreoni et al. 2020; Ackley et al. 2020; Dobie et al. 2020; Page et al. 2020; Thakur et al. 2020; de Wet et al. 2021; Watson et al. 2020; Becerra et al. 2021; Oates et al. 2021). In January 2020, two more NSBH candidates were discovered with the advanced LIGO and Virgo interferometers: GW200105, detected with high significance only by LIGO Livingston and therefore poorly localized to a 90% credible region of 7200 deg\(^2\), and GW200115, seen by all three GW detectors and localized within a 90% credible region of 600 deg\(^2\) (Abbott et al. 2021b). Their component masses are approximately 8.9 \( M_\odot \) and 1.9 \( M_\odot \) for GW200105, and 5.7 \( M_\odot \) and 1.5 \( M_\odot \) for GW200115, which confidently place them in the NSBH range. In all these cases, the BH spin is estimated to be low or anti-aligned to the orbital angular momentum, which reduces the chance of a NS tidal disruption, hence of a bright EM counterpart. Furthermore, due to their high mass ratio, GW190814 and GW200105 are often considered as either plunging events, in which the NS was entirely swallowed by the BH, or low-mass BBHs.

In this paper, we focus on GW200115 which, due to its relatively contained localization and low mass ratio, is thus far the best candidate to constrain the EM counterparts of a NSBH merger. Different satellites, including Swift, Fermi, AGILE, MAXI and CALET, covered part of the probability region of this GW event but no counterparts were detected at high energies. Six candidates were discovered during the optical follow-up campaign of this GW event (Anand et al. 2021). It is interesting to note that the number of optical candidates reported for GW200115 is much lower than the ones found in the case of GW190814, for which 85 candidates were reported within the 19 deg\(^2\) localization region (see Thakur et al. 2020). Most of the candidate counterparts were identified by Swift: nine XRT sources, classified as possible "sources of interest" (Rank 2; Page et al. 2020), and ten faint UVOT sources (Oates et al. 2021). The majority of these were later associated to AGN activity.

In §2 we present the data analysis results of our observing campaign of GW200115 with the Deca Degree Optical Transient Imager (DDOTI; Watson et al. 2016), the wide-field optical imager located at the Observatorio Astronómico Nacional (OAN) on the Sierra de San Pedro Mártir in Mexico. In §3 we outline different constraints from our observations. Finally, in §4 summarize our results and discuss their implications.
Follow-up observations of GW200115

3. Constraints to the Electromagnetic Counterparts

3.1. GRB Prompt Emission

At the time of the merger, ~12% of the GW probability region was within the field of view of the Swift Burst Alert Telescope (BAT; Figure 1) with partial coding <60%. We use the BAT data to constrain any possible prompt gamma-ray emission from GW200115. The prompt phase of short GRBs is characterized by three main features: a) a precursor, visible in <15% of the events (e.g. Troja, Rosswog, & Gehrels 2010), b) a main peak of short duration and hard spectrum and c) a temporally extended emission with soft spectrum (Norris & Bonnell 2006). The latter component is visible in <20% of the events, although might be present in a larger fraction of events and be undetected due to instrumental effects (Dichiara et al. 2021).

Precursors might precede the merger by a few seconds. Their origin is not well understood but is commonly interpreted within the framework of binary NS interactions (e.g. Tsang et al. 2012), and may not be present in NSBH mergers.

The main short-duration GRB is produced by a highly-relativistic jet launched by the merger remnant and is therefore expected to occur right after the merger event. Due to the beamed geometry of the outflow, it is visible only to observers close to the jet’s axis. No transient was detected by BAT within 4 s of the GW trigger down to a 3 σ upper limit of \( \approx 9 \times 10^{-8} \text{ erg cm}^{-2} \text{s}^{-1} \), corresponding to an isotropic equivalent luminosity of \( \approx 10^{45} \text{ erg s}^{-1} \) at a distance of 300 Mpc. This is below the typical luminosity of cosmological short GRBs \( (\approx 10^{51} \text{ erg s}^{-1}; \text{Lien et al. 2016}) \) and strongly disfavors the presence of an on-axis explosion, whereas off-axis jets cannot be ruled out. The GW localization was only partially covered by the BAT, but fell within the field of view of the Fermi Gamma-Ray Burst Monitor (GBM) that covered \( \approx 96\% \) of the probability region including also the field observed by DDOTI. Also in this case, the GBM did not detect any short duration signal around the time of the GW trigger down to a 3 σ flux limit of \( \approx 3 \times 10^{-7} \text{ erg cm}^{-2} \text{s}^{-1} \) (Goldstein et al. 2020). Assuming the luminosity distance derived from the study of the gravitational wave signal (300 Mpc) this corresponds to an isotropic equivalent luminosity limit of \( 4 \times 10^{48} \text{ erg s}^{-1} \), which rules out the presence of a typical short GRB (the only short burst with a luminosity lower than this value is GRB 170817A).

The short GRB peak is sometimes followed by a prolonged tail of emission. A typical example is GRB 050724A (Barthelmy et al. 2005), a short burst followed by a tail of spectrally soft emission with a luminosity of \( 4 \times 10^{48} \text{ erg s}^{-1} \) and duration of \( \approx 100 \text{ s} \). In some models, this extended emission is linked to NSBH mergers and the fallback accretion of NS matter on the central BH (e.g. Rosswog 2007). The outflow powering this emission is not necessarily characterized by the same degree of collimation of the initial GRB jet and, if wider, could be seen by an off-axis observer. Therefore, we searched for long-duration transients in the BAT rate light curves during the time interval 5-100 s after the GW trigger. Assuming a typical power-law spectrum with photon index \( \Gamma = 1.8 \) (Lien et al. 2016) we derive a 3 σ upper limit of \( \approx 7 \times 10^{-6} \text{ erg cm}^{-2} \) on the fluence of the extended emission. At such sensitivity, a soft tail similar to or brighter than GRB 050724A would be detectable up to \( z \lesssim 0.35 \).

3.2. GRB Afterglow

If a successful GRB jet is launched by the merger remnant, its interaction with the surrounding medium will produce a broadband synchrotron radiation known as afterglow. The properties of the afterglow are determined by the energy of the explosion \( E_K \), the density of the environment \( n \), and the shock microphysics, described through the parameters \( \epsilon_B, \epsilon_e \), and \( p \), which represent the fraction of energy that goes into the...
magnetic field, the fraction of energy that goes into the electrons, and the spectral index of the electron energy distribution $N(E) \propto E^{-\gamma}$, respectively. An additional key parameter is the observer’s viewing angle $\theta_v$, which can be aligned to the jet-axis (on-axis) or not (off-axis). In the former case, the observed afterglow emission reaches its peak luminosity soon after the GRB and rapidly fades away. In the latter case, the afterglow peak is delayed by several days or even months, and its peak luminosity quickly drops when moving away from the axis (e.g. Ryan et al. 2020).

We use DDOTI upper limits to constrain a possible afterglow emission following GW200115. A comparison to the observed light curves of short GRBs, shifted to a common distance of 300 Mpc (cf. Fig. 8 of Thakur et al. 2020), shows that our limits could rule out 50% of the observed events, as also found for GW190814 (Thakur et al. 2020; Watson et al. 2020).

We also simulated a large set of optical afterglow light curves, representative of the sGRB population, using AFTERGLOWPY (Ryan et al. 2020). We used the distance posterior distributions of Abbott et al. (2021b), a log-normal distribution for $\epsilon_e$ centered at -1 with width $\sigma = 0.3$ (Beniamini & van der Horst 2017), and a log-uniform distribution for $\epsilon_B$ ranging between $-4$ and $-1$ (Santana, Barniol Duran, & Kumar 2014). The spectral index $\beta$ was set to 2.3. We then created a grid of $100 \times 100$ elements to take into account different values for the total kinetic energy and the density of the external medium ranging from $10^{49}$ to $10^{53}$ erg and from $10$ to $10^{-5}$ cm$^{-3}$, respectively.

The outcome of these simulations is summarized in Figure 2. For an on-axis observer ($\theta_v = 0$), bright explosions ($E_{K,iso} > 10^{50}$ erg) in an ISM environment with $n > 0.01$ cm$^{-3}$ are likely to be detected (for short bursts the typical kinetic energy ranges between $10^{51}$ erg and $10^{54}$ erg). Mergers in a rarefied environment ($n < 10^{-2}$ cm$^{-3}$), such as those kicked out of their host galaxy, have instead a low probability to be detected via their afterglow, even if observed on-axis.

We carried out a similar set of simulations for off-axis GRB explosions. In this case, we fixed the density to $n=0.1$ cm$^{-3}$ and varied the viewing angle from 0 to 25 deg. The probability of detection is shown in Figure 2. According to the posterior distributions reported by Abbott et al. (2021b), the inclination angle of GW200115 has a probability of $\approx 10\%$ of being $\lesssim 15$ deg. For this range of angles, our simulations show that the off-axis afterglow would have a high probability ($> 50\%$) of being detected when the GRB energy is higher than $10^{51}$ erg. Therefore, the combination of GW and EM constraints disfavors small ($\lesssim 15$ deg) viewing angles.

The sensitivity of our observations decreases for larger viewing angles. We can not detect events far from the jet axis (e.g. $\theta_v > 20$ deg) even assuming high energy explosions ($\sim 10^{53}$ erg). For example, an explosion similar to GRB 170817A would not have been detected.

3.3. Kilonova emission

Compact object mergers can drive outflows of neutron-rich material expanding at sub-relativistic speeds. The radioactive decay of this ejecta powers a luminous optical and near-infrared transient, known as kilonova or macronova. We offer constraints on a potential kilonova associated with GW200115 inside the field covered by the DDOTI observations, by comparing our deepest upper limit of $w > 20.5$ AB mag to the Los Alamos National Laboratory grid of kilonova simulations (Wollaeger et al. 2021). Wollaeger et al. (2021) renders each of the 900 simulated kilonovae in 54 disparate viewing angles, distributed uniformly in cosine and each subtending an equal solid angle. In total, this results in 48,600 kilonova models to compare to observations. This grid includes 900 multi-dimensional radiative transfer simulations, which jointly evolve dynamical (lanthanide-rich) and wind (lanthanide-poor) ejecta components, spanning a diverse set of ejecta masses, velocities, morphologies, and compositions (see Wollaeger et al. 2021 and references therein). These state-of-the-art simulations rely on updated lanthanide opacities from Fontes et al. (2020). Although we can exclude kilonovae spanning a broad range of viewing angles, the majority of simulated kilonovae excluded by our observations correspond to events observed near the polar axis. Similar conclusions were obtained by Anand et al. (2021), although they only rule out near-polar viewing angles and make no constraints on edge-on inclinations (see their Extended Data Figure 4). These differences are due to the different ejecta morphology used in the simulations.

Simulated kilonova spectra are converted to lightcurves in DDOTI’s observer frame for six luminosity distances within the 90% credible interval on GW200115’s inferred distance:
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4. SUMMARY

Our results are summarized in Figure 4, which reports the upper limits from DDOTI and other wide-field optical facilities. They are compared with the expected magnitude of a kilonova from a NSBH merger with a maximally spinning BH (Barbieri et al. 2020) and the magnitude of AT2017gfo, rescaled at a distance of 300 Mpc and at 22 h after the merger. For GW200115, the analysis of the gravitational wave signal does not allow us to put strong constraints on the BH spin magnitude (Abbott et al. 2021b), however our EM upper limits disfavor high values of the spin parameter that would lead to high wind ejecta masses. We caution that this result is only valid within the field covered by DDOTI observations, however it shows the potential of joint EM-GW analysis for well-localized sources.

ACKNOWLEDGEMENTS

We thank the staff of the Observatorio Astronómico Nacional. DDOTI is funded by CONACyT (LN 260369,
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EAC’s contributions were supported by the National Science Foundation grant PHY-1607611. EAC’s contributions were supported by the US Department of Energy through the Los Alamos National Laboratory. Los Alamos National Laboratory is operated by Triad National Security, LLC, for the National Nuclear Security Administration of U.S. Department of Energy (Contract No. 89233218CNA000001). This research used resources provided by the Los Alamos National Laboratory Institutional Computing Program, which is supported by the U.S. Department of Energy National Nuclear Security Administration under Contract No. 89233218CNA000001. The work was also partially supported by the National Aeronautics and Space Administration through grant 80NSSC18K0429 issued through the Astrophysics Data Analysis Program and the National Science Foundation grant 2108950.