CONSTRAINING NEUTRON STAR RADII IN BLACK HOLE-NEUTRON STAR MERGERS FROM THEIR ELECTROMAGNETIC COUNTERPARTS

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ABSTRACT

Mergers of black hole (BH) and neutron star (NS) binaries are of interest since the emission of gravitational waves (GWs) can be followed by an electromagnetic (EM) counterpart, which could power short gamma-ray bursts. Until now, LIGO/Virgo has only observed a candidate BH-NS event, GW190426_152155, which was not followed by any EM counterpart. We show how the presence (absence) of a remnant disk, which powers the EM counterpart, can be used along with spin measurements by LIGO/Virgo to derive a lower (upper) limit on the radius of the NS. For the case of GW190426_152155, large measurement errors on the spin prevent from placing an upper limit on the NS radius. Our proposed method works best when the aligned component of the BH spin (with respect to the orbital angular momentum) is the largest, and can be used to complement the information that can be extracted from the GW signal to derive valuable information on the NS equation of state.

1. INTRODUCTION

Together with GWTC-1, from the first two observational runs (Abbott et al. 2019), the new candidate events presented in Abbott et al. (2020), from the first half of the third observational run, comprise GWTC-2. Among its events, there are both black holes (BHs) and neutron stars (NSs) merging in binary systems. Thanks to the growing number of detected events, compact objects can be constrained with unparalleled precision and gravitational wave (GW) events provide an unprecedented opportunity to probe fundamental physics (The LIGO Scientific Collaboration et al. 2020a,c).

The origin of binary mergers is still highly debated. Several possible scenarios could potentially account for most of the observed events (e.g., Antonini & Perets 2012; Belczynski et al. 2016; Askar et al. 2017; Liu & Lai 2018; Banerjee et al. 2018; Fragione & Kocsis 2018; Rodriguez et al. 2018; Fragione et al. 2019; Fragione & Kocsis 2019; Hamers & Samsing 2019; Kremer et al. 2019; Rasskazov & Kocsis 2019). Since several models account for roughly the same rate, first analyses of the LIGO/Virgo data have shown that the observed population is likely composed of mergers originated in more than one scenario (e.g., Wong et al. 2020; Zevin et al. 2020). The contribution of different astrophysical channels will be hopefully disentangled using a combination of the mass, spin, redshift, and eccentricity distributions in the upcoming years.

Despite the growing number of events, there is only a candidate BH-NS merger, namely GW190426_152155. Therefore, LIGO has only set a 90% upper limit of $\sim 600$ Gpc$^{-3}$ yr$^{-1}$ on the rate of BH-NS mergers. As for BH-BH and NS-NS systems, the origin of BH-NS binaries is still highly uncertain. While BH-NS binaries can be produced in isolation as a result of binary evolution (e.g., de Mink & Mandel 2016; Kruckow et al. 2018), more challenging is the process of forming BH-NS binaries through dynamical assembly in star clusters. A number of authors showed that NSs are generally prevented from forming NS-NS and BH-NS binaries in a star cluster as a result of the strong heating due to BH in the cluster core (Fragione et al. 2018; Ye et al. 2019; Fragione & Banerjee 2020; Ye et al. 2020), although some authors have claimed higher rates (Rastello et al. 2020; Santoliquido et al. 2020). Only after most of the BHs have been ejected from the cluster core, NSs can efficiently segregate in the innermost regions and possibly form binaries, that eventually merge. Recently, Fragione & Loeb (2019a,b) have shown that BH-NS mergers can be a natural outcome of the dynamical evolution of massive triple stellar systems.

What makes BH-NS mergers interesting is the possibility that they can produce an electromagnetic (EM) counterpart after merger. The lifetime of merging BH-NS binaries spans three phases (for a recent short review see Foucart 2020), which include the inspiral ($\gtrsim 10^5$ yr) due to GW emission, the merger phase ($\sim 1$ ms) that can result in either the tidal disruption of the NS or its plunge into the BH, and, for disrupting systems only, a post-merger phase ($\sim 1$ s) during which more matter is ejected or accreted onto the BH.

The merger will be followed by an EM counterpart only if the NS is disrupted by the tidal field of the BH, leading to mass ejection and the formation of an accretion torus around it. Otherwise, the NS plunges into the BH and the merger resembles a BH-BH merger. In this Letter, we show how to use this information along with spin measurements by LIGO/Virgo to constrain the properties of BH-NS mergers. In particular, we discuss how to derive a lower (upper) limit based on the presence (absence) of an EM counterpart.

The Letter is organized as follows. In Section 2, we describe the prescriptions we use to compute whether a BH-NS merger produces an accretion disk. In Section 3, we discuss how to use this information to constrain the properties of merging BHs and NSs, and apply our method to the candidate event GW190426_152155. Finally, we draw our conclusions, in Section 4.

2. REMNANT MASS IN BLACK HOLE-NEUTRON STAR MERGERS

To compute whether a BH-NS merger produces an EM signature, we compute the remnant baryon mass ($M_{\text{rem}}$) outside the BH after merger. If $M_{\text{rem}} > 0$, a disk is formed and there is EM emission after merger (Foucart 2012; Foucart et al. 2020).
We use the remnant mass\textsuperscript{1} as calibrated by Foucart et al. (2018) using numerical relativity calculations\textsuperscript{2},

\[
M_{\text{rem}} = \left[ \max \left( \frac{1-2C_{\text{NS}}}{\eta^{1/3}}\frac{\alpha}{\beta} + \gamma \right) \right] \delta,
\]

where \(C_{\text{NS}} = G M_{\text{NS}}/(R_{\text{NS}} c^{2})\) is the NS compaction, which depends on the equation of state,

\[
\eta = \frac{Q}{1+Q^2},
\]

with \(Q = M_{\text{BH}}/M_{\text{NS}}\), is the symmetric mass ratio, and (in units \(G = c = 1\)),

\[
\hat{r}_{\text{ISCO}} = \frac{r_{\text{ISCO}}}{M_{\text{BH}}} = 3 + Z_{2} - \text{sgn}(\chi_{\text{BH}}) \sqrt{(3-Z_{1})(3+Z_{1}+3Z_{2})},
\]

is the innermost stable circular orbit (ISCO) radius (Bardeen et al. 1972) with

\[
Z_{1} = 1 + (1-\chi_{\text{BH}})^{1/3}(1+\chi_{\text{BH}})^{1/3} + (1-\chi_{\text{BH}})\]

\[
Z_{2} = \sqrt{3\chi_{\text{BH}} + Z_{1}^2},
\]

as a solution of

\[
Z(r) = (r(r-6))^2 - a^2(2(r^2 + 4r - 10) - 9a^2) = 0.
\]

In Eq. 1, \((\alpha, \beta, \gamma, \delta) = (0.406, 0.139, 0.255, 1.761)\) are fitting parameters to numerical relativity simulations (Foucart 2012; Foucart et al. 2013, 2018). Eq. 1 assumes that the BH spin is aligned to the orbital angular momentum. In the case it is inclined by an angle \(I\), the same fitting formulae can be used by replacing the ISCO radius by the radius of the innermost stable spherical orbit (ISSO), which is the solution of (Stone et al. 2013)

\[
S(r) = r^8 Z(r) + a^2(1-C^2)(a^2(1-C^2)Y(r) - 2a^4 X(r)),
\]

where \(C = \cos I\), and

\[
X(r) = a^2(3a^2 + 4r(2r^2 - 3)) + r^2(15r^2 - 24r + 8) - 6a^2(r^2 - 4)
\]

\[
Y(r) = a^4(7a^4 + r^2(7r^2 - 4r + 36) + 6r(r - 2)) \times (a^6 + 2a^2(6a^2(3a^2 + 3r^2(r - 2))).
\]

Alternatively, Eq. 1 can be used considering only the aligned component of the BH spin

\[
\chi_{\text{BH}||} = \chi_{\text{BH}} \cos \theta_{\text{BH}}.
\]

Figure 1 shows the maximum value of the mass ratio \(M_{\text{BH}}/M_{\text{NS}}\) for which a BH-NS system will disrupt as a function of the NS radius \(R_{\text{NS}}\) and BH spin \(\chi_{\text{BH}}\), assuming \(M_{\text{NS}} = 1.3 M_{\odot}\), for different inclinations \(I\) between the BH spin and the orbital angular momentum. For \(I = 0^\circ\), the maximum mass ratio for disrupting systems is as high as \(\approx 22\) for highly-spinning BHs. In the case \(I = 45^\circ\), the maximum mass ratio reduces to \(\approx 6\). Obviously, \(I = 90^\circ\) is symmetric with respect to the the case \(I = 0^\circ\). This is because the case \(I = 0^\circ\) can be used for any inclination \(I\) with the substitution \(\chi_{\text{BH}} \rightarrow \chi_{\text{BH}||}\). Thus, whether or not a BH-NS merger is followed by an EM counterpart is essentially determined by the symmetric mass ratio, the NS compaction, and the aligned component of the BH spin.

\textsuperscript{1} In units of the initial mass of the NS.

\textsuperscript{2} Assuming circular binaries. For examples of general relativistic simulations of eccentric BH-NS interactions, see Stephens et al. (2011).
3. CONSTRAINING NEUTRON STAR RADIUS

To constrain the NS radius, information on the BH spin is needed. GW measurements are especially sensitive to the effective spin, which is the following combination of the BH and NS spins (Abbott et al. 2016; Vitale et al. 2017),

\[
\chi_{\text{eff}} = \frac{M_{\text{BH}} \chi_{\text{BH}} \cos^2 \theta_{\text{BH}} + M_{\text{NS}} \chi_{\text{NS}} \cos^2 \theta_{\text{NS}}}{M_{\text{BH}} + M_{\text{NS}}},
\]

where

\[
\chi_i = \frac{c S_i}{G M_i^2},
\]

is the dimensionless Kerr parameter and \( S_i = |S_i| \) is the magnitude of the intrinsic spin. Approximating the NS as a rotating sphere, it can be shown that

\[
\chi_{\text{NS}} \approx \frac{\nu}{1 \text{ms}^{-1}},
\]

where \( \nu \) is the rotational frequency of the NS. Therefore, the NS spin will be typically small, except in the case the NS is a (rare) millisecond pulsar. In the more typical case the NS is not a millisecond pulsar, and considering that \( M_{\text{BH}} > M_{\text{NS}} \), inverting Eq. 11 yields

\[
\chi_{\text{BH}||} \approx \chi_{\text{eff}} \frac{M_{\text{BH}} + M_{\text{NS}}}{M_{\text{BH}}}. \tag{14}
\]

This implies that the aligned component of the BH spin can be approximated by Eq. 14 using the values inferred by LIGO/Virgo analysis pipeline whenever the NS is not a fast rotator. This information, along with the presence or not of an EM counterpart, can be used to constrain the NS radius.

Figure 2 illustrates a proof-of-concept case on how to constrain the NS radius by using the information on the effective spin and the maximum value of the mass ratio \( M_{\text{BH}}/M_{\text{NS}} \) for which a BH-NS system disrupts the NS. We consider \( M_{\text{NS}} = 1.5 M_\odot \) and assume that \( M_{\text{BH}}/M_{\text{NS}} = 2.5 \) and that the aligned component of the BH spin is measured to \( \chi_{\text{BH}||} \in [0,0.1] \). Left panel: no observation of tidal disruption results in an upper limit on the NS radius; right panel: tidal disruption of the NS results in a lower limit on the NS radius.

3.1. Application to GW190426_152155

GW190426_152155 is the candidate event with the highest false alarm rate (1.4 yr\(^{-1}\)) among the LIGO/Virgo events in GWTC-2. Assuming it is a signal of astrophysical origin, the LIGO/Virgo collaboration has estimated its component masses to be \( 5.7^{+4.0}_{-2.9} M_\odot \) and \( 1.5^{+0.8}_{-0.8} M_\odot \), rendering it the first candidate BH-NS merger. The data are uninformative about potential tidal effects, parametrized by (Flanagan & Hinderer 2008)

\[
\tilde{\Lambda} = \frac{32 M_{\text{NS}}^2 (M_{\text{NS}} + 12 M_{\text{BH}})}{39 (M_{\text{NS}} + M_{\text{BH}})^3} \frac{k_2}{C_{\text{NS}}},
\]

where \( k_2 \) is the second Love number. The effective spin of the systems has been measured to \( 0.03^{+0.33}_{-0.30} \).

Figure 3 illustrates the case our method is applied to GW190426_152155 (Abbott et al. 2020). For this event, no EM counterpart has been observed (The LIGO Scientific Collaboration et al. 2020b), implying a plunging of the NS onto the BH. Measurement errors on the effective spin are too large to place an upper limit on the NS radius for this candidate event. If an EM counterpart had been observed, we would have been able to place a lower limit on the NS radius, \( R_{\text{NS}} \gtrsim 12.5 \text{ km} \).

4. CONCLUSIONS

BH-NS mergers are interesting since they could produce an EM counterpart in the form of a short gamma-ray burst,
which can provide crucial information on their origin and NS structure. Despite the growing number of events, there is only one candidate BH-NS merger, namely GW190426_152155.

We have shown how to use information on the EM counterpart in BH-NS mergers can be used to place constraints on the NS radius. In particular, we have illustrated how to derive a lower (upper) limit based on the presence (absence) of an accretion disk that powers the EM counterpart (Fouchart et al. 2018). We have concluded that our method works best when the aligned component of the BH spin is the largest. For the case of the candidate BH-NS merger GW190426_152155, for which no EM counterpart has been observed (The LIGO Scientific Collaboration et al. 2020b), large measurement errors on the spin prevent from placing an upper limit on the NS radius for this candidate event.

While obtaining precise models for the observable EM signals powered by BH-NS binaries can be challenging, the dependence of these signals on the properties of BH-NS binaries is essential for extracting valuable information. This can complement the information that can be obtained from the GW signal, either from the potential tidal dephrasing or the cut-off frequency when disruption occurs (\(\sim 1\, \text{kHz}\)), to help constrain the equation of state of NSs (Lackey et al. 2014; Pannarale et al. 2015).

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