Hubble Constant Measurement with GW190521 as an Eccentric Black Hole Merger

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ABSTRACT

Gravitational wave observations can be used to accurately measure the Hubble constant \(H_0\) and could help understand the present discrepancy between constraints from Type Ia supernovae and the cosmic microwave background. Neutron star mergers are primarily used for this purpose as their electromagnetic emission can be used to greatly reduce measurement uncertainties. Here we estimate \(H_0\) using the recently observed black hole merger GW190521 and its candidate electromagnetic counterpart found by ZTF using a highly eccentric explanation of the properties of GW190521. We find that the reconstructed distance of GW190521 and the redshift of the candidate host galaxy are more consistent with standard cosmology for our eccentric model than if we reconstruct the source parameters assuming no eccentricity. We obtain \(H_0 = 88.6^{+17.7}_{-34.3} \text{km s}^{-1}\text{Mpc}^{-1}\) for GW190521, and \(H_0 = 73.4^{+6.3}_{-10.7} \text{km s}^{-1}\text{Mpc}^{-1}\) in combination with the results of the neutron star merger GW170817. Our results indicate that future \(H_0\) computations using black hole mergers will need to account for possible eccentricity. For extreme cases, the orbital velocity of binaries in AGN disks can represent a significant systematic uncertainty.

1. INTRODUCTION

With a total mass of around 150 M\(_\odot\), the binary black hole merger GW190521 was the heaviest system detected to date through gravitational waves by LIGO and Virgo (Aasi et al. 2015; Acernese et al. 2015; Abbott et al. 2020a). The heavier black hole in the binary had a mass of about 85 M\(_\odot\). Such a mass is not expected from stellar evolution due to pair instability that prevents some of the most massive stars from leaving a compact remnant (Woosley et al. 2007; Abbott et al. 2020b). In addition, the black holes’ spins are found to be large and misaligned with the binary orbit, disfavoring the possibility that the system is originated from a stellar binary (Abbott et al. 2020b).

A possible explanation for the observed properties of GW190521 is that it is a so-called hierarchical merger—the black holes in the binary are themselves the remnants of past black hole mergers (Miller & Hamilton 2002; O’Leary et al. 2006; Giersz et al. 2015). This scenario can naturally lead to masses in excess to the \(\sim 65 \text{M}_\odot\) pair-instability limit. It also results in higher black hole spins. The merger of two black holes with the same mass and no spin will produce a remnant black hole with 0.7 dimensionless spin (Lousto et al. 2010), consistent with the reconstructed spins of 0.69\(^{+0.27}_{-0.62}\) and 0.73\(^{+0.24}_{-0.64}\) for the two black holes in GW190521 (Abbott et al. 2020a). In addition, the hierarchical merger scenario implies that black holes form a binary after a chance encounter, in which their spin will be randomly oriented. This is consistent with the reconstructed misalignment between the binary orbit and black hole spins in GW190521 (Abbott et al. 2020a).

By comparing the observed gravitational waveform to numerical relativity simulations, Gayathri et al. (2020b) found that GW190521 is probably a highly eccentric merger (hereafter UF/RIT model). This result further supports the binary’s origin as a dynamical encounter within a dense black hole population. Binaries lose any existing eccentricity over time due to gravitational radiation, therefore only binaries that formed soon before merger can retain any eccentricity. Such formation is possible in chance encounters but not in systems originating in isolated stellar binaries.

Active Galactic Nuclei (AGNs) represent a well-suited environment to produce hierarchical black hole mergers (Bartos et al. 2017b,a; Stone et al. 2017; McKernan et al. 2018; Yang et al. 2019b,a; Tagawa et al. 2020b,a; Yang et al. 2020). Galactic nuclei harbor a dense population of black holes (O’Leary et al. 2009; Hailey et al. 2018) which are further compressed through interaction with the AGN disk. Dynamical friction will align the orbits of some of the black holes with the disk plane, where

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they migrate inward and can merge with each other. As merger remnants can remain within the disk, consecutive mergers are common and could represent the majority of AGN-assisted mergers. Several black hole mergers previously discovered by LIGO/Virgo have properties suggestive of their possible AGN origin (Yang et al. 2019b; Gayathri et al. 2020a; Yang et al. 2020).

Following the public alert issued by LIGO/Virgo on the detection of GW190521 (LIGO & Virgo 2019), the Zwicky Transient Facility (ZTF) carried out a search for excess optical emission from an AGN within the publicly available localization volume of GW190521. It identified a possible counterpart that was interpreted as being due to the accreting black hole remnant of the GW190521 merger (Graham et al. 2020). As this is the first such observation and since there are open questions about the emission processes involved, more studies and probably further similar detections are needed to confidently establish the connection between the transient and GW190521. However, for the purposes of understanding the consequences of such a connection, in the following we assume that the electromagnetic emission is indeed produced by the merger remnant.

In this paper we constrained $H_0$ using GW190521 and its candidate ZTF counterpart. We used the reconstructed properties of GW190521 by the UF/RIT model in which the event was a highly eccentric black hole binary with eccentricity $e \approx 0.7$ (Gayathri et al. 2020b). For both models we assumed that the electromagnetic counterpart is always detectable from this source type independently from the source direction and distance. We adopted a uniform volumetric source probability density, which is a good approximation of the expected distribution of AGN-assisted mergers (Yang et al. 2020). We further adopted a uniform prior on the cosine of the binary’s inclination. For our $e \approx 0.7$ model we adopted mass and spin parameters from the maximum-likelihood waveform (Gayathri et al. 2020b). For our $e = 0$ model we used uniform probability densities for the black hole masses within $[30 M_\odot, 200 M_\odot]$, uniform spin amplitudes and isotropic spin orientations. Finally, we neglected selection effects related to the $H_0$-dependence of the source population density at $z_{\text{ZTF}}$, which are not expected to be significant at $z \sim 0.4$ (Farr, W.M. 2020).

In Fig. 1 we show $p(d_L|D_{\text{GW}}, \Omega_{\text{ZTF}})$ for the UF/RIT model with $e \approx 0.7$ (Gayathri et al. 2020b) and also one derived using the NRSur7dq4 waveform model (Varma et al. 2019) assuming $e = 0$. We find that the distributions are markedly different for these two cases (see also Calderón Bustillo et al. 2020).

The ZTF candidate counterpart was associated with AGN J124942.3+344929 with measured redshift $z_{\text{ZTF}} = 0.438$ (Graham et al. 2020). In Fig. 2 we also show the distance of the ZTF candidate assuming Planck 2018 cosmology (Aghanim et al. 2018). We see that both $e \approx 0.7$ and $e = 0$ models are consistent with this distance, with somewhat higher probability density for the eccentric case.
using the UF/RIT model with

Figure 2. Sky location reconstructed for GW190521

sity and Ω

Here,

the apparent host AGN candidate J124942.3+344929 (Gra-

2020b).

In the inset panel, the reticle marks the position of

2020)

once we have an estimated redshift for the source, for

detection of electromagnetic emission from the binary. If we are able to identify a binary’s host galaxy, the host galaxy provides information on the binary’s redshift. As gravitational wave localization is typically limited, the host galaxy identification relies primarily on the detection of electromagnetic emission from the binary. Once we have an estimated redshift for the source, for fixed \(d_L\) one can estimate the Hubble constant (Hogg 1999) using

\[
H_0(d_L, z) = \frac{c(1+z)}{d_L} \int_0^z \frac{dz'}{E(z')}
\]

with

\[
E(z) = \sqrt{\Omega_r(1+z)^4 + \Omega_m(1+z)^3 + \Omega_k(1+z)^2 + \Omega_{\Lambda}}.
\]

Here, \(c\) is the speed of light, \(\Omega_r\) is the radiation energy density, \(\Omega_m\) is matter density, \(\Omega_{\Lambda}\) is the dark energy density and \(\Omega_k\) is the curvature of our Universe. We adopted a set of cosmology parameters \(\{H_0, \Omega_r, \Omega_m, \Omega_{\Lambda}\} = \{67.8\text{ km s}^{-1}\text{ Mpc}^{-1}, 0, 0.306, 0, 0.694\}\) measured by the Planck satellite (Aghanim et al. 2018). We considered these parameters fixed when recovering \(H_0\) as their uncertainties are much smaller than other uncertainties here. Given the Gpc distance scale of the event, we neglected the peculiar velocity of the host galaxy.

We also neglected any motion of the binary within the galaxy. Considering the mass of the supermassive black hole in the candidate AGN, \(M_{\text{SMBH}} = 10^5 - 10^6 \text{ M}_\odot\) (Graham et al. 2020), and the characteristic distance \(10^{-2}\text{ pc}\) of the merger from the supermassive black hole, the rotational velocity of the binary is \(10^4\text{ km s}^{-1}\). For the reconstructed distance of GW190521, this is a \(1 - 30\%\) error on the reconstructed Hubble constant depending on the orientation of the AGN disk plane and the mass and luminosity distance of the supermassive black hole. This is smaller than the statistical error here, but will need to be examined more carefully if a larger number of AGN-assisted binaries are used to measure \(H_0\).

We computed the probability density of the Hubble constant using the distance probability density:

\[
p(H_0|D_{\text{GW}}, \Omega_{ZTF}, z_{ZTF}) = p(d_L(H_0, z_{ZTF})|D_{\text{GW}}, \Omega_{ZTF}) \frac{\partial}{\partial d_L}H_0(d_L, z_{ZTF})
\]

where \(d_L(H_0, z_{ZTF})\) is the inverse function of Eq. 1.

For comparison, see Mukherjee et al. (2020) and (Chen et al. 2020) who also computed \(p(H_0|D_{\text{GW}}, \Omega_{ZTF}, z_{ZTF})\) for GW190521 for \(e = 0\).

4. RESULTS

Our \(H_0\) probability density from GW190521 based on the UF/RIT model (Gayathri et al. 2020b) and the ZTF candidate counterpart is shown in Fig. 3. Numerically it is \(H_0 = 88.6^{+17.3}_{-34.3}\text{ km s}^{-1}\text{ Mpc}^{-1}\). For comparison we show our \(H_0\) estimate for \(e = 0\). We see that the distribution from the eccentric model has its maximum near the \(H_0\) values measured using type Ia supernovae, which give a local expansion rate of \(H_0 = 74.03 \pm 1.42\text{ km s}^{-1}\text{ Mpc}^{-1}\) (Riess et al. 2019), and the estimate from cosmic microwave background observations measured by the Planck satellite, which gives \(H_0 = 67.4 \pm 0.5\text{ km s}^{-1}\text{ Mpc}^{-1}\) (Aghanim et al. 2018). The uncertainty is nevertheless significant. Our \(e = 0\) result is also consistent with the Type Ia / Planck \(H_0\) estimate.

We also show in Fig. 3 the expected \(H_0\) estimate after combining the distributions obtained for GW190521 with that of GW170817. We see that the improvement by this combination, as measured by the height of the
Figure 3. $H_0$ measurements for GW190521 with its ZTF candidate counterpart and GW170817. The following $H_0$ probability densities are shown: GW170817 (purple); GW190521 with eccentric model (red); combined GW170817 and GW190521 with eccentric model (blue); GW190521 with $e=0$ (gray); cosmic microwave background results by Planck (orange); and type Ia supernova results by ShoES (green). Shaded areas for the latter two results show 95% confidence intervals. Vertical dashed lines for the gravitational-wave results indicate 68% credible intervals.

probability density distribution, is a few percent, i.e. most information still comes from GW170817.

5. CONCLUSION

We estimated the Hubble constant using the luminosity distance of the gravitational wave signal GW190521 and the redshift of its candidate electromagnetic counterpart detected by ZTF, assuming that the association is real. For GW190521 we used the highly eccentric UF/RIT model (Gayathri et al. 2020b) with $e \approx 0.7$, and for comparison a non-eccentric model similar to that of Abbott et al. (2020a). Our conclusions are as follows.

- We find $H_0 = 88.6^{+17.1}_{-34.3}$ km s$^{-1}$ Mpc$^{-1}$ for GW190521 as a highly eccentric merger with $e \approx 0.7$.
- Combining GW190521 and GW170817, we find $H_0 = 73.4^{+6.9}_{-10.7}$ km s$^{-1}$ Mpc$^{-1}$.
- $H_0$ measurements using black hole mergers could be strongly affected if eccentricity is present and is not accounted for.
- $H_0$ measurements using multiple AGN-assisted black hole mergers or mergers in galactic nuclei need to consider the effect of Doppler shift due to the binary’s orbital velocity that in extreme cases can introduce a large systematic uncertainty.

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