Formation of Binary Black Hole Similar to GW190521 with a Total Mass of $\sim 150 M_\odot$ from Population III Binary Star Evolution

Tomoya Kinugawa\(^{(1)*}\), Takashi Nakamura\(^{(2)}\), and Hiroyuki Nakano\(^{(3)}\)

\(^{(1)}\)Institute for Cosmic Ray Research, The University of Tokyo, Kashiwa, Chiba 277-8582, Japan
\(^{(2)}\)Department of Physics, Graduate School of Science, Kyoto University, Kyoto 606-8502, Japan
\(^{(3)}\)Faculty of Law, Ryukoku University, Kyoto 612-8577, Japan

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ABSTRACT

In case of zero metal (population III) stars, we show that total mass of binary black holes from binary population III star evolution can be $\sim 150 M_\odot$, which agrees with mass of a binary black hole, GW190521 recently discovered by LIGO/Virgo. The event rate of such binary black hole mergers is estimated as $0.13$–$0.66 \text{ yr}^{-1} \text{ Gpc}^{-3}$, which is consistent with the observed value of $0.02$–$0.43 \text{ yr}^{-1} \text{ Gpc}^{-3}$.

Key words: stars: Population III, binaries: general relativity, gravitational waves, black hole mergers

1 INTRODUCTION

GW190521 observed in the LIGO/Virgo third observing run (O3a) (Abbott et al. 2020a,b) is gravitational wave (GW) signal from merging binary black holes (BHs) with primary BH mass of $71$–$106 M_\odot$\(^{1}\), and secondary BH mass of $48$–$83 M_\odot$. The remnant BH after merger has mass of $126$–$170 M_\odot$, so that this object can be considered as an intermediate mass BH in the mass range, $100$–$1000 M_\odot$. The redshift of GW190521 is $0.48$–$1.1$, while the merger rate density is estimated as $0.02$–$0.43 \text{ yr}^{-1} \text{ Gpc}^{-3}$.

Here, we should note that the two component masses of GW190521 are possibly within the pair-instability supernova (PISN) mass gap for $Z > 0.001 Z_\odot$. In Woosley (2017), this PISN mass gap is described as “No black holes between 52 and $133 M_\odot$ are expected from stellar evolution in close binaries”. In more details, for example, Leung et al. (2019) discussed pulsational PISNe (PPISNe) for $Z > 0.001 Z_\odot$ by simulating a helium core without the hydrogen envelope since the simulation of the whole star is computationally expensive. They obtained the lower bound of the PISN mass gap around $50 M_\odot$ so that merging two BHs with mass $\lesssim 50 M_\odot$ are needed to make a BH with mass $\gtrsim 50 M_\odot$ (e.g., Fragione et al. 2020b).

However, the upper limit of the mass of BH for Population (Pop) III stars with $Z = 0$ is different from that for $Z > 0.001 Z_\odot$. Since Pop III stars do not tend to lose the envelope, they will have a different lower bound of the PISN mass gap compared with that of Pop II stars. The CO core mass $M_{\text{CO}}$ range of the PPISN is about $40$–$60 M_\odot$ (Heger & Woosley 2002; Heger et al. 2003; Umeda & Nomoto 2008; Waldman 2008; Yoshida et al. 2016). Calculations of Pop III star evolution (Marigo et al. 2001; Heger & Woosley 2002; Heger et al. 2003; Ekström et al. 2008; Tanikawa et al. 2019) show that in order to make such massive BHs, the zero age main sequence (ZAMS) mass of Pop III has to be more massive than $\sim 100 M_\odot$. Furthermore, Yoon et al. (2012) and Chatzopoulos & Wheeler (2012) computed evolution of Population III metal-free ($Z = 0$) massive stars and Table 1 in Chatzopoulos & Wheeler (2012) shows that a nonrotating Pop III star with ZAMS mass $M_{\text{ZAMS}} = 75 M_\odot$ becomes a BH in core collapse. Thus, the formation of BHs with $M \lesssim 80 M_\odot$ is possible from Pop III stars to explain naturally the existence of GW190521 like binary BHs for Population III binary (see Figure 12 in Yoon et al. (2012) and Figure 5 in Chatzopoulos & Wheeler (2012)).

The existence of mass gap BHs like GW190521 is suggested by Pop III binary evolutions (Kinugawa et al. 2016; Kinugawa et al. 2020a; Tanikawa et al. 2020). Furthermore, a recent calculation of Pop III stellar evolution also supports this result (Farrell et al. 2020). In this Letter, we discuss the formation process of GW190521 like binary BHs and estimate the event rate in the population synthesis simulations of Pop III binary stars (Kinugawa et al. 2020a).

We should note that there are many proposals and discussions to explain BHs within the PISN mass gap.
and their dynamics immediately after the announcement of GW190521 (Carr et al. 2019; Calderón Bustillo et al. 2020a; Sakstein et al. 2020; De Luca et al. 2020; Vovchenko et al. 2020; Wang et al. 2020; Moffat 2020; Romero-Shaw et al. 2020; Frigione et al. 2020a; Calderón Bustillo et al. 2020b; Gayathri et al. 2020; Fishbach & Holz 2020; Farrell et al. 2020), including modified gravity, primordial BHs, orbital eccentricity, numerical relativity simulations, repeated mergers in a dense star cluster, BH masses from Pop III stars and so on.

\section{Analysis}

First of all, we discuss the effect of the rotational velocity of Pop III stars at ZAMS. When the end state of Pop III stars is described by Kerr BHs, the angular momentum of BH should satisfy the following inequality as

\[ J_{\text{BH}} < M \left( \frac{G M}{c} \right). \]

(1)

Assuming no angular momentum loss of the star up to the formation of BH, we may regard that the angular momentum at ZAMS is equal to that of the final BH, that is, \( J_{\text{ZAMS}} = J_{\text{BH}} \). The Pop III stars at ZAMS have rotational energy as

\[ E_{\text{rot}} \sim \frac{J_{\text{ZAMS}}^2}{I}, \]

(2)

where \( I \) is the moment of inertia of the Pop III stars. The gravitational energy of the stars is written as

\[ E_{\text{grav}} \sim \frac{G M^2}{R}, \]

(3)

where \( R \) is the stellar radius. Comparing the rotational energy (Eq. (2)) with the gravitational energy (Eq. (3)) and Eq. (1), we have

\[ \frac{E_{\text{rot}}}{E_{\text{grav}}} < \frac{G M^2 R}{I c^2}, \]

(4)

where \( \kappa \) is defined by \( I = \kappa M R^2 \). Using the values of \( M, R \) and \( \kappa \) for Pop III stars at ZAMS, we can estimate the upper limit of the effect of rotation. The stellar radius at ZAMS (\( R_{\text{ZAMS}} \)) is given by Kinugawa et al. (2014),

\[ \frac{R_{\text{ZAMS}}}{R_\odot} = 1.22095 + 2.70041 \times 10^{-2} \left( \frac{M}{10 M_\odot} \right)^{-2} + 0.13547 \left( \frac{M}{10 M_\odot} \right)^{-1} - 1.95541 \times 10^{-2} \left( \frac{M}{10 M_\odot} \right)^{-3} + 8.7585 \times 10^{-4} \left( \frac{M}{10 M_\odot} \right)^{4}. \]

(5)

For \( M_{\text{ZAMS}} = 10-100 M_\odot \), we have

\[ \frac{G M}{c^2 R} \sim 1.6 \times 10^{-5} - 5 \times 10^{-5}. \]

(6)

If \( \kappa \gg 5 \times 10^{-5} \), we may ignore the effect of the rotation so that we use the results of the evolution of spherically symmetric Pop III stars. In practice, \( \kappa = 0.21 \) for the core, and \( O(0.1) - O(0.01) \) for the outer layer (Hurley et al. 2002; Kinugawa et al. 2014) so that the rotational energy is at most 0.01 times the gravitational energy. \(^2\) Therefore, we can use the results of evolution of spherically symmetric Pop III stars as good approximation to rotating ones.

Next, we discuss Pop III binary evolution. In our previous work (Kinugawa et al. 2020a), we performed Pop III binary evolution by using population synthesis simulations for various models with different initial conditions, that is, the initial mass function, initial mass ratio, separation and eccentricity distributions of binaries and different binary evolution parameters such as the mass transfer rate of the donor, the accretion fraction of transferred stellar mass, the common envelope parameters, and the tidal coefficient factor. As a result, we found that the Chirp mass distribution of binary BHs from Pop III binaries has a peak at \( M_{\text{chirp}} \sim 30 M_\odot \) and the merger rate densities of Pop III binary BHs at \( z = 0 \) are \( 3.3-21.2 \) yr\(^{-1}\) Gpc\(^{-3}\) for seven different models. \(^3\) This is consistent with the LIGO/Virgo result of \( 9.7-101 \) yr\(^{-1}\) Gpc\(^{-3}\) (Abbott et al. 2019).

\(^2\) For polytropes, we have \( \kappa = 0.4, 0.261, 0.155, 0.0754, 0.0226 \) and 0.00690 for the polytropic indexes of \( n = 0, 1, 2, 3, 4 \) and 4.5, respectively.

\(^3\) Here, the chirp mass is defined by

\[ M_{\text{chirp}} = \left( \frac{M_1 M_2}{M_1 + M_2} \right)^{3/5}, \]

(7)

where \( M_1 \) and \( M_2 \) are the mass of the primary and the secondary objects, respectively.
Figures 1, 2, and 3 show the mass distribution of primary and secondary BHs whose chirp masses are more massive than $56 \, M_\odot$ because the chirp mass of GW190521 is estimated as $56-77 \, M_\odot$ (Abbott et al. 2020a).

Figures 2 and 3 show the mass distribution of primary and secondary BHs whose chirp masses are more massive than $56 \, M_\odot$ and merge within the Hubble time. If we consider the perfect envelope loss due to PPISN, the maximum BH mass is $\sim 80 \, M_\odot$ from orange lines in Figures 2 and 3. Some of Pop III stars with ZAMS mass $\sim 90-100 \, M_\odot$, which avoid the PPISN and lose a part of envelope via a mass transfer, can be the progenitor of such massive BHs. On the other hand, if there is no envelope loss by Pop III PPISN, the maximum mass reaches $\sim 105 \, M_\odot$ from blue lines in Figures 2 and 3. Note that the gray area in Figures 2 and 3 is the mass range of the primary BH of GW190521 so that our extreme two theoretical predictions shown by blue and orange lines are both consistent with observed values of mass of the primary and the secondary BHs.

In the no mass ejection model, the event rate of GW190521 like binary BH mergers at the present day is estimated as 0.66 yr$^{-1}$ Gpc$^{-3}$. On the other hand, the perfect PPISN model gives 0.13 yr$^{-1}$ Gpc$^{-3}$. Regarding that these two values are coming from the extreme theoretical models, our theoretical rate is evaluated as 0.13–0.66 yr$^{-1}$ Gpc$^{-3}$.

This theoretical rate is consistent with the observed one of 0.02–0.43 yr$^{-1}$ Gpc$^{-3}$ from GW190521.

Finally, we estimate the maximum observable redshift $z_{\text{max}}$ for LIGO O3a-Livingston (O3a-L), LIGO O5, Einstein Telescope (ET-B), and Cosmic Explorer (CE2). Using an inspiral-merger-ringdown waveform shown in Nakamura et al. (2016), we calculate the signal-to-noise ratio (SNR) of GW events in fitted sensitivity curves for O3a-L ($f_{\text{low}} = 10 \text{ Hz}$), O5 ($f_{\text{low}} = 10 \text{ Hz}$), ET-B ($f_{\text{low}} = 1 \text{ Hz}$), and CE2 ($f_{\text{low}} = 5 \text{ Hz}$) used in Kinugawa et al. (2020b). Here, $f_{\text{low}}$ is the lower frequency cutoff and we set the higher frequency cutoff $f_{\text{high}} = 3000 \text{ Hz}$ although we do not need such high frequency for heavy binary BHs below. Then, the maximum observable redshift by setting the averaged SNR $= 8$ is obtained for a BH binary with mass ($75 \, M_\odot$, $75 \, M_\odot$) as 0.709 for O3a-L, 1.60 for O5, 10.8 for ET-B, and 19.3 for CE2, respectively. For a BH binary with mass ($80 \, M_\odot$, $80 \, M_\odot$), $z_{\text{max}}$ becomes 0.734 for O3a-L, 1.61 for O5, 10.6 for ET-B, and 18.4 for CE2, respectively. The above calculations are summarized in Table 2.
The first detected GW event, GW150914 whose BH masses within the PISN mass gap for Pop III stars like GW190521. The maximum observable redshift $z_{\text{max}}$ for GW190521 like binaries for 4 ground based GW detector configurations: LIGO O3a-Livingston (O3a-L), LIGO O5 (O5), Einstein Telescope (ET-B) and Cosmic Explorer (CE2). The mass is shown in the solar mass $M_\odot$.

| $(M_1, M_2)$ | O3a-L | O5 | ET-B | CE2 |
|--------------|-------|----|------|-----|
| (75, 75)     | 0.709 | 1.60 | 10.8 | 19.3 |
| (80, 80)     | 0.734 | 1.61 | 10.6 | 18.4 |

3 DISCUSSION

In the population synthesis simulations of Pop III binary stars, we can simultaneously explain the formation of binaries that consist of a BH and mass gap compact object (MGCO) with mass $2-5 M_\odot$ (Kinugawa et al. 2020b) like GW190814, and those consist of BHs with mass $\sim 80 M_\odot$ within the PISN mass gap for Pop III stars like GW190521. The first detected GW event, GW150914 whose BH masses are $\sim 30 M_\odot$ has been predicted before the first detection by Kinugawa et al. (2014). It is very interesting that Pop III model can interpret origins of three different class of GW sources, that is, massive BH binary of mass $\sim 30 M_\odot$ like GW150914, BH and MGCO of mass $\sim 2.5 M_\odot$ like GW190814, and very massive binary BH of mass $\sim 80 M_\odot$ like GW190521. It will be triple the fun!

Liu & Bromm (2020) have considered another possibility of Pop III binary BH mergers whose origin is by dynamical capture recently. They calculated the merger rate of Pop III binary BHs made by dynamical capture in cosmological hydrodynamic simulations. Although their merger rate (0.04 yr$^{-1}$ Gpc$^{-3}$) is smaller than that for our field binary case, the Pop III binary BHs made by dynamical capture might have different features from Pop III binary BHs from field binaries such as large eccentricity, different mass spectrum, and so on. These differences might be observed by ET and another future GW observations. While the origin of binary BHs will be made clear by the GW observation of the redshift $z > 10$ (see Table 2), i.e., in the ET-B era. The cumulative event rate of Pop I/II saturates at $z \lesssim 5$, and that of Pop III is at $z \sim 10$ (Nakamura et al. 2016).

In this paper, we did not focus on the spin values of binary BHs. The spin estimation for GW190521 has large uncertainty as the nondimensional spin parameters $x_1 = 0.07-0.96$ and $x_2 = 0.09-0.97$ although there is a weak preference for a spinning, precessing binary BH, i.e., the BH spins may be misaligned from the orbital angular momentum. Furthermore, according to LIGO Scientific Collaboration and Virgo Collaboration, (2020), the orientation of spins projected on the orbital plane is not determined. Observing the long-infrared phase with space based GW detectors (see, e.g., B-DECIGO in Isoyama et al. (2018) and TianQin in Mei et al. (2020), we will be able to access more precise information on the spins.

Table 2. The maximum observable redshift $z_{\text{max}}$ for GW190521 like binaries for 4 ground based GW detector configurations: LIGO O3a-Livingston (O3a-L), LIGO O5 (O5), Einstein Telescope (ET-B) and Cosmic Explorer (CE2). The mass is shown in the solar mass $M_\odot$.

| Initial mass function | Initial mass ratio | Initial separation | Initial eccentricity |
|-----------------------|-------------------|-------------------|---------------------|
| flat                  | flat              | $10 M_\odot < M_1 < 150 M_\odot$ | $10 M_2 / M_1 < q < 1$ | $\log a_{\text{min}} < \log (a/R_\odot) < 6$ | $0 < e < 1$ |

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