METALLICITY DEPENDENCE OF BLACK HOLE MAIN SEQUENCE BINARIES DETECTABLE WITH GAIA

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ABSTRACT

LIGO has detected gravitational waves from massive binary black holes mergers. In order to explain the origin of such massive stellar black holes, extreme metal poor stars including first stars are focused on. However, black holes do not have the information of the metallicity. In order to check the metallicity dependence of the black hole formation, we focus on the black hole-main sequence binary (BH-MS) and the astrometry observatory Gaia. Using the binary population synthesis method, we find that Gaia can detect \( \sim 200 \) BH-MSs whose metallicity is \( Z_\odot \) and \( \sim 400 \) BH-MSs whose metallicity is \( 0.1 Z_\odot \). Using the spectroscopic observation with 4-m class telescopes such as Anglo-Australian Telescope, Mayall telescope, and Kyoto university 3.8m telescope, we can check the metallicity of BH-MSs. The metallicity dependence of the black hole formation might be revealed by the astrometry and spectroscopic observation.

1. INTRODUCTION

LIGO has detected gravitational waves from binary black holes mergers (Abbott et al. 2016a,b,c). Some black holes of the gravitational wave sources are \( \sim 30 M_\odot \). On the other hand, the masses of black hole candidates of X-ray binaries are typically \( \sim 10 M_\odot \) (Ozel et al. 2010). Thus, the origin of massive black holes might be different from general black holes. In order to explain the origin of such massive stellar black holes, extreme metal poor stars including first stars are focused on (Kinugawa et al. 2014; Kinugawa et al. 2016; Belczynski et al. 2016; Hartwig et al. 2016; Inayoshi et al. 2017; Miyamoto et al. 2017). However, since black holes do not have the information of the metallicity, it might be difficult to determine the population of black hole progenitors until we detect the binary black hole merger at high redshift (Nakamura et al. 2016).

In order to check the metallicity dependence of the black hole formation, we focus on the black hole-main sequence binary (BH-MS). The astrometry observatory Gaia can detect \( 2 \times 10^5 \) BH-MSs (Mashian & Loeb 2017; Breivik et al. 2017; Yamaguchi et al. 2018; Yalinewich et al. 2018). The main sequence star has the information of the metallicity and we can get the metallicity of the black hole formation environment. In this paper, we calculate the binary evolution using the population synthesis method to estimate the BH-MS detection rate. Especially, we calculate two metallicity cases such as \( Z_\odot \) and \( 10\% Z_\odot \) and consider the metallicity dependence of the BH-MSs.

2. METHOD

In order to study the BH-MS progenitor evolution, we have to calculate binary evolutions. In the case of the binary evolutions, binary interactions make a stellar evolution to change from single stellar evolution. Furthermore, how binary interactions take effect depends on the initial binary parameters. Thus, we use the Monte Carlo method called as the population synthesis to calculate BH-MS rates. Our binary population synthesis code is based on the BSE code (Hurley et al. 2002). We rewrite the wind mass loss rate (Kinugawa & Asanad 2017) and the common envelope parts (Kinugawa et al. 2014) of the BSE code.

In the part of the wind mass loss, the Wolf Rayet stellar wind mass loss and the mass loss rate of the luminous blue variable stars are updated as

\[
\dot{M}_{\text{WR}} = 10^{-13} L_1^{1.5} \left( \frac{Z}{Z_\odot} \right)^{0.86} M_\odot \text{yr}^{-1}, \quad (1)
\]

and

\[
\dot{M}_{\text{HD}} = 1.5 \times 10^{-4} M_\odot \text{yr}^{-1}, \quad (2)
\]

where \( L \) and \( Z \) are the luminosity, and the metallicity, respectively (Belczynski et al. 2010a).

When the stellar radius become large and the stellar surface is captured by the gravitational force of the companion, a mass transfer occurs. If the separation rapidly shrinks or the stellar radius rapidly expands during the mass transfer, the mass transfer becomes dynamical unstable. In this case, the companion plunges into the envelope of the donor giant star. This phase is called as the common envelope phase. In this phase, the orbit shrinks and the donor envelope evaporates. After this phase, there is a merged star or a binary which consists of the companion and the core of the donor giant star. In the common envelope part, we use the formula of the common envelope as

\[
\alpha \left( \frac{G M_{r,1} M_2}{2 a_1} - \frac{G M_1 M_2}{2 a_1} \right) = \frac{G M_1 M_{\text{env},1}}{\lambda R_1}, \quad (3)
\]

where \( M_1, M_{r,1}, M_{\text{env},1}, M_2, a_1 \), and \( a_2 \) are the mass of the donor giant star, the mass of the donor giant’s core, the mass of the donor giant’s envelope, the mass of the companion star, the initial separation, and the separation after the common envelope phase, respectively (Webbink 1984). We use \( \alpha \lambda = 1 \). After the CE phase, if the separation \( a_1 \) is less than the sum of the giant’s core radius and the companion stellar radius or the donor...
giant is a Hertzsprung gap phase, the binary will merge (Belczynski et al. 2007).

At the end of star evolution, we need to calculate the black hole mass. In order to calculate the BH mass, we use the equation (1) of Belczynski et al. (2002).

To calculate binary evolutions, we need initial binary parameters such as primary mass $M_1$, mass ratio $q = M_2/M_1$, separation $a$, and eccentricity $e$. We use initial distributions as $f(M_1) \propto M_1^{2.35}$ (5 M$_\odot < M_1 < 100$ M$_\odot$), $f(q) = \text{const.}$ (0.1 M$_\odot < M_1 < 1$), $f(a) \propto 1/a$ ($a_{\text{min}} < a < 10^6$ R$_\odot$), and $f(e) \propto e$ ($0 < e < 1$), where $a_{\text{min}}$ is a minimum separation at which a mass transfer does not occur.

We calculate $10^5$ binaries for two metallicity models such as $Z = Z_\odot$ and $Z = 10\%Z_\odot$. We choose BH-MSs whose periods $P$ are 50 days $< P < 5$ yrs, because in this paper we adopt the astrometric satellite Gaia whose cadence for each object and nominal mission period are roughly 50 days and 5 years, respectively. Here, the condition that the orbital period is larger than 50 days is more stringent than the condition that the binary orbit is detected with the Gaia astrometry for most parts of parameter space we focus on in this paper, so that we neglect the latter condition. We use the star formation rate as constant ($SFR \approx 2.5 M_\odot/\text{yr}$) for 10 Gyrs (Misiriotis et al. 2006), and assume $Z_\odot : 10\%Z_\odot = 1 : 1$ (Panter et al. 2008; Belczynski et al. 2012) and the binary fraction $f_B = 0.5$.

3. RESULT

We calculate the numbers of BH-MSs in the entire galaxy $N_G$ for each metallicity as

$$N_G = \frac{1}{N_{\text{total}}} \sum_{i=1}^{N_{\text{BHMS}}} \frac{f_B}{1 + f_B} \cdot \frac{SFR}{2} \cdot \text{t}_{\text{life},i} \cdot f_{\text{IMF}},$$

(4)

where $N_{\text{total}} = (10^5)$, $N_{\text{BHMS}}$, $t_{\text{life},i}$, and $f_{\text{IMF}}$ are the number of total binaries, the number of BH-MSs whose periods are 50 days $< P < 5$ yrs for $10^5$ binaries, the life time of the BH-MS, and the IMF normalization factor, respectively.

Figure 1 shows the mass distribution of black holes which are the components of BH-MSs in the entire galaxy. Figure 2 shows the mass distribution of main sequence stars which are the components of BH-MSs in the entire galaxy. Mass distributions of main-sequence companions do not show dependence on the metallicity. On the other hand, the black hole mass distributions show that the maximum mass for $Z = 10\%Z_\odot$ is clearly more massive than that for $Z = Z_\odot$.

In order to calculate the number of BH-MSs detected by Gaia, we assume the spatial distribution of BH-MSs in the entire galaxy as

$$\rho_{\text{BHMS}} = \rho_0 \exp \left( - \frac{z}{h_z} - \frac{r - r_0}{h_r} \right)$$

(5)

where $\rho_0$, $z$, $r$, $r_0$ ($= 8.5$ kpc), $h_z$ ($= 250$ pc), and $h_r$ ($= 3.5$ kpc) are the normalization factor of the spatial distribution, the distance perpendicular to the galactic plane, the distance from the galactic center, the distance from the galactic center to the sun, the scale length for the exponential stellar distribution parallel to the galactic plane, and the scale length for the exponential distribution parallel to the galactic plane, respectively. The normalization factor of the spatial distribution is calculated by

$$\rho_0 = \frac{1}{\int_0^\infty dr \int_0^\infty \exp \left( - \frac{z}{h_z} - \frac{r - r_0}{h_r} \right)}.$$

(6)

We use the spherical coordinate centered at the earth, $(D, b, l)$, as

$$r = [r_0^2 + D^2 \cos^2 b - 2Dr_0 \cos b \cos l]^{1/2},$$

(7)

$$z = D \sin b,$$

(8)

where $D$, $b$, and $l$ are the distance from the earth, the galactic latitude, and the galactic longitude. The number of BH-MSs detected by Gaia $N_D$ is calculated by

$$N_D = \frac{1}{N_{\text{total}}} \sum_{i=1}^{N_{\text{BHMS}}} \frac{f_B}{1 + f_B} \cdot \frac{SFR}{2} \cdot \text{t}_{\text{life},i} \cdot f_{\text{IMF}} \cdot \int_0^{\pi/2} \cos b \, db \int_0^{\infty} \frac{D_{\text{max}}(M)}{D^2} dD \rho_0,$$

(9)

where $D_{\text{max}}(M)$ is the maximum detectable distance of the BH-MS whose main sequence mass is $M$.

Here, we derive $D_{\text{max}}(M)$ including the signal to noise ratio of distance and the precision of astrometric measurement with Gaia. Generally, the absolute magnitude in $V$-band $M_V$ can be represented with the apparent magnitude in $V$-band $m_V$, and $D$: $M_V = M_V(m_V, D)$ (e.g., Eq. 26 in Yamaguchi et al. 2018), where we assume the interstellar extinction $A_V = D/1$kpc. In addition, the main sequence mass $M$ can be assumed to be a function of $M_V$: $M(M_V)$ (e.g., Eq. 27 in Yamaguchi et al. 2018). Thus, the main sequence mass is represented as $M(m_V, D)$. When we impose the condition that the signal to noise ratio exceeds 10 for the reliable distance measurement, we obtain the condition equation $D/1$kpc $< 10^2/\sigma_\pi(G)$, where $\sigma_\pi$ is the precision of parallax measurement in $G$-band in unit of micro-arcsecond (Gaia Collaboration et al. 2016). By equating the $G$-band magnitude with $V$-band magnitude, which is justified in Yamaguchi et al. (2018), we obtain $D_{\text{max}} = 10^2\sigma_\pi(m_V)$. Eventually, we derive the function $D_{\text{max}}(M)$ by solving this equation and $M(m_V, D_{\text{max}})$ as simultaneous equations.

Table 1 shows the numbers of BH-MSs $N_{\text{BHMS}}$ whose periods are 50 days $< P < 5$ yrs for $10^5$ binaries, the numbers of such BH-MSs in the entire galaxy $N_G$, and the number of BH-MSs detected by Gaia $N_D$ for each metallicity case. The numbers of binaries with $Z = 10\%Z_\odot$ are about twice larger than the those with $Z = Z_\odot$. There are two reasons. First, since the mass loss is not so effective in the low metallicity case, they can evolve to more massive compact object. Second, the low metallicity binaries are more hard to merge within a common envelope phase than the high metallicity binaries, because the Hertzsprung gap phase of the low metallicity stars is shorter than that of the high metallicity binaries (Belczynski et al. 2010).

Figure 3 shows the mass distribution of black holes in BH-MSs detected by Gaia. Figure 4 shows the mass distribution of main sequence stars in BH-MSs detected by Gaia. The mass distribution of main-sequence stars in BH-MSs detected by Gaia is clearly more massive than that of the high metallicity stars.
TABLE 1
The numbers of BH-MSs $N_{BHMS}$ whose periods are $50$ days $< P < 5$ yrs for $10^5$ binaries, the numbers of such BH-MSs in the entire galaxy $N_G$, and the number of BH-MSs detected by Gaia $N_D$ for each metallicity case.

| metallicity | $Z=Z_{\odot}$ | $10\%Z_{\odot}$ |
|-------------|----------------|-----------------|
| $N_{BHMS}$  | 1322           | 2841            |
| $N_G$       | 4985           | 9586            |
| $N_D$       | 234            | 412             |

**Fig. 1.**—The mass distribution of black holes which are the components of BH-MSs in the entire galaxy.

**Fig. 2.**—The mass distribution of main sequence stars which are the components of BH-MSs in the entire galaxy.

Gaia. As with Fig. 1 and Fig. 2, only black hole mass distributions detected by Gaia depend on the metallicity. The mass distribution of black holes detected by Gaia is almost the same in shape as that for the entire galaxy. On the other hand, in the case of the main-sequence companion, the number of low mass main-sequence companion is clearly smaller than that of main sequence stars of BH-MSs in the entire galaxy. This is because the low mass components are hard to be detected by Gaia due to their faintness.

4. CONCLUSION AND DISCUSSION

We reveal that Gaia can identify $\sim 600$ BH-MSs. This number is almost the same as the BH-MS detection number of Yamaguchi et al. (2018), which is a few times larger than that of Yalinewich et al. (2018). On the other hand, that of Breivik et al. (2017) is 6-30 times larger than our result. Furthermore, that of Mashian & Loeb (2017) is $\sim 300$ times larger than our result. We consider the BH-MS detection fraction by Gaia for two metallicity cases. Figure 3 and 4 show that the MS mass distributions are not so different, but the BH mass distributions obviously depend on the metallicity. If the BH-MS whose BH mass is more massive than $\sim 18 M_{\odot}$ is detected by Gaia, it might be Pop II origin.

The metallicity of each binary can be measured with a follow-up spectroscopic observation. A main-sequence star in Pop II binaries should show a low metallicity and its typical brightness is expected to be $V \lesssim 20$ mag, as the limiting magnitude of Gaia is 20 magnitude in G-band. Thus, this low metallicity can be measured with spectroscopic observations using 4m-class telescopes, such as AAT (Anglo-Australian Telescope) at NSW, Mayall telescope at Kitt Peak, and Kyoto university 3.8m telescope at Okayama.

If the metallicity of black hole progenitor is revealed by the Gaia astrometry and follow-up observations, we can know the metallicity dependence of the black hole mass distribution. Although the gravitational wave observation has revealed the existence of the massive stellar black hole and will describe the black hole mass distribution, it cannot reveal the metallicity of the progenitor. Gaia can be the powerful tool for the research of the black hole progenitor study.

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