HIERARCHICAL FORMATION OF AN INTERMEDIATE MASS BLACK HOLE VIA SEVEN MERGERS: IMPLICATIONS FOR GW190521

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ABSTRACT

The gravitational wave event GW190521 involves the merger of two black holes of \( \sim 85 \, M_\odot \) and \( \sim 66 \, M_\odot \) forming an intermediate-mass black hole (IMBH) of mass \( \sim 142 \, M_\odot \). Both progenitors are challenging to explain within standard stellar evolution as they belong to the upper black-hole mass gap. We propose a dynamical formation pathway for this IMBH based on multiple hierarchical mergers of progenitors in the core of a dense star cluster. We identified such scenarios from analysis of a set of 58 direct N-body simulations using \texttt{NBODY6-gpu}. In one of our canonical runs aimed at describing the evolution of a star cluster with \( N = 10^5 \) stars and typical globular cluster properties, we observe a stellar black hole undergoing a chain of seven binary mergers in 6 Gyr, attaining a final mass of 97.8\( M_\odot \).

We discuss the dynamical interactions that lead to the final IMBH product, as well as the evolution of the black hole population in that simulation. From the analysis of all simulations in our dataset we observe additional smaller chains, tentatively inferring that an IMBH formation through chain mergers is expected in the lifetime of a typical (i.e. median mass) globular cluster with probability \( 0 \lesssim p \lesssim 0.1 \). Using this order-of-magnitude estimate and comoving star formation rates we show our results are broadly consistent with the mean rate implied by GW190521, and we discuss implications for future gravitational wave detections of IMBHs.

Keywords: N-body simulations — Star clusters — Stellar mass black holes — Intermediate-mass black holes

1. INTRODUCTION

On 2020 September 2, the Laser Interferometer Gravitational-Wave Observatory (LIGO) and Virgo collaboration announced the detection of a gravitational wave signal consistent with a Black Hole Binary (BHB) merger producing a remnant BH of mass \( 142 \pm 28 \, M_\odot \) (The LIGO Scientific Collaboration et al. 2020). The event, known as GW190521, involved the merger of component masses \( m_1 = 85 \pm 14 \, M_\odot \) and \( m_2 = 66 \pm 18 \, M_\odot \). These are the heaviest two merging BHs yet observed by LIGO/Virgo (Abbott et al. 2016a,b,c, 2017a,b; The LIGO Scientific Collaboration et al. 2020). The event, known as GW190521, involved the merger of component masses \( m_1 = 85 \pm 14 \, M_\odot \) and \( m_2 = 66 \pm 18 \, M_\odot \). These are the heaviest two merging BHs yet observed by LIGO/Virgo (Abbott et al. 2016a,b,c, 2017a,b; The LIGO Scientific Collaboration et al. 2018; Stoyan et al. 2008; Abbott et al. 2020a,b,c). Interestingly, both masses lie within the supposed upper black hole mass gap, a range of BH masses which is outside what is predicted through standard stellar evolution. The mass gap is thought to originate from pulsation pair-instability supernovae (Marchant et al. 2019). Current theoretical modelling places the lower cutoff at \( \sim 50M_\odot \pm 4M_\odot \) (Marchant et al. 2019; Farmer et al. 2019, 2020; Marchant & Moriya 2020), although it faces uncertainties pertaining to hydrodynamics, relativistic effects and nuclear physics. The modelling therefore implies that at least \( m_1 \) is well within the mass gap and cannot have originated directly from a stellar progenitor.

The existence of physics beyond the standard model could lead to deviations in the pair-instability supernovae process, enabling the production of heavier stellar BHs than current theories permit. Phenomena such as the existence of new light particles (Croon et al. 2020), a different magnetic dipole moment of the electron neu-
trino (Barger et al. 1999; Heger et al. 2009) and the addition of extra spatial dimensions (Padilla 2015) can all alter the supernovae process to produce heavier BHs. Indeed Sakstein et al. (2020) propose such new physics as potential explanations for GW190521.

However, without invoking non-standard physics, there are other possible mechanisms that can form higher mass BHs, particularly in dense environments through dynamical interactions. BHBs may form and evolve via gravitational interactions with other compact bodies in a dense stellar environment such as a globular cluster (GC) (O’Leary et al. 2006; Banerjee et al. 2010; O’Leary et al. 2007; Tanikawa 2013; Choksi et al. 2018). In these dense environments, the BH product of a previous BHB merger can go on to form a new BHB and merge again, which we henceforth refer to as second-generation BHs. This process can continue, creating a chain of mergers (O’Leary et al. 2016; Fishbach et al. 2017; Gerosa & Berti 2017; Yang et al. 2019; Antonini et al. 2019; Gerosa & Berti 2017; Samsing & Ilan 2018; Rodriguez et al. 2019; Gerosa et al. 2020; Safarzadeh et al. 2019; Gayathri et al. 2020; Kimball et al. 2020; Doctor et al. 2020; Baibhav et al. 2020). Such hierarchical mergers allow BHs to reach masses above what is achievable through stellar evolution. In particular, GCs have been shown as effective nurseries to host such hierarchical mergers, and that populating the mass gap is possible through this dynamical channel (Gerosa & Berti 2017; Samsing & Hotokezaka 2020). While Intermediate Mass Black Holes (IMBHs) with $M_{IMBH} \gtrsim 100 \, M_\odot$ have not been reported to originate in dynamical simulations of BHB chain mergers, indicating such a scenario is uncommon, recent work suggests that repeated mergers between BHs and very massive stars in young stars clusters are a promising channel to form an IMBH within the first 15 Myr from star cluster formation (Rizzuto et al. 2020).

In this letter, we use a set of direct N-body simulations of dense star cluster evolution that include both gravity and stellar evolution (Anagnostou et al. 2020) to investigate hierarchical BHB mergers as a potential formation channel for IMBHs within GCs over timescales compared to their typical ages (i.e. $\sim 10$ Gyr). In Section 2, we briefly describe our simulation framework, including code and initial conditions. In Section 3 we explore in detail one simulation that shows the evolution of a specific BH - henceforth referred to as “Snowball” - undergoing seven BHB merger in 12.5 Gyr to reach a final mass $m_{BH} = 97.8 M_\odot$. From the length distribution of merger chains within the full set of simulated clusters, in Section 4 we estimate the comoving rate of IMBH formation in a typical GC. Finally, in Section 5 we discuss implications of this formation channel for the recently announced GW190521 detection, as well as for future gravitational wave detections.

2. METHOD

This work is based on a set of 58 direct N-body simulations of mid-sized star clusters previously presented in Anagnostou et al. (2020), run using NBODY6 with GPU support (Nitadori & Aarseth 2012). The set of simulations contain $5 \times 10^4 \leq N \leq 2 \times 10^5$ initial stars, and utilizes a range of initial conditions (see Anagnostou et al. 2020 for more detail). In this letter we focus on a specific simulation, with the following: $N_0 = 100,000$ particles, primordial binary fraction $f = 0$, metallicity $Z = 0.001$, initial half mass radius $r_{h,0} = 2.5$pc and dimensionless King concentration parameter $W_0 = 7$. Stellar masses are drawn from a Kroupa 2001 initial mass function between $0.08 \, M_\odot$ and $100 \, M_\odot$. The core initial radius is 0.56 pc with a tidal radius of 71.5 pc. The cluster is assumed to under-fill its tidal radius by a factor of three. The tidal radius is calculated by placing the cluster into a circular orbit around a point-mass galaxy with a galactocentric distance of 23.3kpc. We also initialize the cluster in dynamical equilibrium and without mass segregation. The cluster model is representative of an average mid-sized GC (see Heggie & Hut 2003 Table 1.1). The stellar metallicity of $Z = 0.001 \ ([\text{Fe/H}] \approx -1.33)$ is approximately the median metallicity for Milky Way GCs (Harris 1996). Natal kicks are applied to stellar remnants, drawn from a Maxwellian distribution with a velocity dispersion of $\sigma_k \approx 1000 \, ms^{-1}$, the initial velocity dispersion of the cluster (see de Vita et al. 2019 for further explanation). Recoil kicks to BHB merger remnants due to asymmetric emission of gravitational waves are calculated in post-processing using an analytic approximation for recoil velocity presented in Sopuerta et al. (2006) (see Anagnostou et al. 2020) for details.

Single stars and binaries evolve according to the “SSE” and “BSE” algorithms respectively (Hurley et al. 2000, 2013), which are designed to handle complex evolutionary processes, including common envelope evolution and mass transfer, collisions and supernova kicks. The cluster is evolved for a total of 12.5 Gyr. For information on the complete set of simulations, further detail on the code used, and full discussion of initial conditions see Anagnostou et al. 2020 and de Vita et al. 2019 (see also MacLeod et al. 2016).

3. THE MERGER CHAIN

Snowball starts as a 58.1 $M_\odot$ main sequence star. After $\sim 6.4$ Myr the star goes supernova and forms a
26 M☉ remnant BH, the second most massive BH produced through stellar evolution in the simulation. As this specific simulation does not include primordial stellar binaries, any BHB that emerges must form dynamically through strong interactions. Remarkably, throughout the simulation Snowball is involved in nine mergers; seven BHB mergers, and two involving a main sequence star. All seven BH mergers occur within the cluster core. This is expected, as Snowball spends the majority of its lifetime near to the centre of the cluster (r ≲ 0.7r_c) due to mass segregation resulting from (partial) energy equipartition in star clusters over the two-body relaxation timescale (see Trenti & van der Marel 2013). Snowball gains mass through each successive BH merger until it reaches its final mass of 97.8 M☉ as shown in Figure 1. All nine mergers occur within the first 6.5 Gyr. Note that all BHB mergers in this simulation occur within this single branch, i.e. there are no BHB mergers outside of this merger chain. Hence all Snowball merger companions are first-generation BHs.

Once Snowball migrates to the core by t ≈ 11.7 Myr, it experiences multiple close interactions with other mass-segregated BHs before forming its first BHB, with an eccentricity of 0.92 and a period of 99 days. The binary remains in the core for 64 Myr, undergoing various three-body interactions, hardening (with the period reducing to 63 days) and altering the eccentricity before being disrupted, exchanging the secondary component for a 26.14M☉ BH, the most massive BH in the cluster at that time. The lower panel in Figure 2 displays the evolution of Snowballs binary eccentricity. It is clear that the many scattering events significantly alter the BHB eccentricity, with extremes of e = 0.0008 (near circular) to e = 0.999 (maximally eccentric). After five more three-body interactions the binary is again disrupted at t ≈ 230 Myr, exchanging the 26.14M☉ BH for a 25.34M☉ BH and ejecting the heavier former companion, making Snowball the most massive body in the cluster. The newly formed binary is fairly eccentric, at e = 0.97.

The process of forming a high eccentricity BHB, undergoing multiple strong interactions and an eventual exchange event occurs twice more, until Snowball forms its first merging BHB with a m_2 = 22.2M☉ companion, corresponding to a mass ratio of 0.86. The binary forms at t = 258.7 Myr with P = 1732 days and e = 0.41. After undergoing nine hardening events the binary separation is lowered sufficiently to allow for significant gravitational radiation, leading to inspiral and eventual merger.
Figure 2. Evolution of the binary period (top panel) and eccentricity (bottom panel) for the various BHBs that Snowball is part of. BHB mergers are displayed as vertical black lines, and three-body exchange events involving the Snowball BHB are displayed as vertical dotted green lines. The eccentricity is given between 0 (circular) and 1 (parabolic), the period in days, and the time in megayears. The period of time in which Snowball is part of a hierarchical triple BH system is highlighted in red in the bottom panel. Note that there is a sharp upper bound for the periods of 1000 days, as this is the upper cutoff for which \texttt{NBODY6} regularises binaries.

At $t \approx 300$ Myr. This merger nearly doubles Snowball mass to $37.1 M_\odot$.

Soon after this first merger, at $t = 322$ Myr, Snowball forms a new BHB with a $23.34 M_\odot$ companion at $r = 0.2 r_c$. The remaining 6 BHB mergers follow a relatively similar evolution. In the top panel of Figure 2 we display the evolution of Snowball’s binary period. The 7 BHB mergers are indicated with vertical black lines. The binaries often form initially with large periods, which rapidly decrease through successive dynamical interactions with other BHs and bodies in the core. We indicate the interactions that cause an exchange by dotted vertical green lines. The rate of BHB hardening tends to decrease as the binary evolves, first hardening rapidly and then slowly reducing their separation until an inspiral occurs, spending most of their lives with small separations. This is partly because the cross-section for three-body interactions of hard binaries is proportional to the semi-major axis (Celoria et al. 2018). Hence the hardening rate decreases as the binary orbit tightens, slowing the period loss.

Although most scattering events follow Heggie’s law (Heggie 1975), some soften the BHB involved instead. Most of these softening events occur due to an exchange. The attendant interval of chaotic three-body dynamics can dramatically alter the orbital parameters of the newly formed binary, leading to significant softening. This is most evident in the string of exchange events that occur between $400 \lesssim t \lesssim 500$ Myr, leading up to the second BHB merger. The top panel of Figure 2 shows the effects of such interactions, whereby the period varies non monotonically between 320 and 592 days.

Scattering events harden binaries and can impart significant recoil velocities which send even IMBHs out of the cluster core (de Vita et al. 2018). Anagnostou et al. (2020) found that $\sim 80\%$ of all ejections follow a three-body encounter with another BH, with the rest being ejected via binary-binary scattering. Although the various BHBs which Snowball is a part of do experience significant recoil, they are not sufficient to eject the binary. At most, the BHB is flung outside the cluster core, where it migrates back towards the centre to undergo further scattering events. Although Snowball is never ejected, over the full BH population in the simulation, $\sim 67$ binary-single interactions lead to the ejection of a BH. In particular, Snowball plays a large part in the depletion of BHs in the core, being responsible for ejecting 43 BHs. As the number of BHs in the core is depleted over time (starting from an initial $N_{BH} = 74$ formed from stellar evolution and retained in the cluster after natal kicks) the number of 3-body hardening events likewise decreases.

Throughout the simulation, 10 other BHBs not containing Snowball form in the core, however, none remains long enough to either merge or be ejected, with the longest binary only surviving $\sim 31$ Myr. Seven out of ten of these BHBs undergo an exchange encounter with Snowball, wherein the preexisting binary exchanges a component for Snowball. Six of the seven newly unbound BHs are ejected from the cluster as a result of the interaction. Exchange encounters are more frequent within the first few gigayears when there is still a sufficiently high number of relatively massive BHs in the core, with only four out of 28 exchanges occurring after $t = 2$ Gyr. This is because exchange events, in general, require BHs of comparable mass (Heggie 1975). On the
other hand, scattering events that don’t result in exchange remain relatively common, occurring every few Myr at least until \( \sim 10 \) Gyr, after-which the BH population has mostly evaporated (see also Morscher et al. 2013 for a Monte Carlo investigation of the BH population in star clusters).

The specifics of Snowballs mass gain are obviously dependant on the mass of the companion BHs involved in the merger. However, our results clearly show that any BHB within a cluster core is likely to undergo multiple exchange events. Previous scattering experiments also show that the lighter of the two binary components is preferentially ejected from the system in favour of the intruder (Sigurdsson & Hernquist 1993). This process systematically increases the companion mass before merger. Hence, heavier BHs are more likely to merge than lighter ones, which is indeed what we see here. All seven Snowball BHB mergers involve a secondary BH which is in the heaviest 5\% of all BHs at the time of merger.

3.1. Final State

By the time Snowball has completed the seventh BHB merger, there are only a total of 19 BHs left in the cluster. Snowball forms another binary at \( t = 6.65 \) Gyr, shortly after the last merger. Snowball spends the last 6 Gyr bound to its companion BH at the centre of the cluster, only briefly leaving the core 4 times due to recoil from scattering events (spending a total of 0.032 Gyr out of 6 Gyr at \( r > r_c \)).

At \( t \approx 7.9 \) Gyr, this final binary forms a hierarchical triple system. The system undergoes Kozai-Lidov oscillations (Lidov 1962; Kozai 1962), driving the inner binary to as high as \( e = 0.99 \) (see the red highlighted section in Figure 2). During this time the inner binary still experiences 10 three-body scattering events. Throughout the next 2 Gyr the outer component of the triple system is exchanged nine times, ejecting the previously bound outer component from the cluster in all but one of these cases. Eventually, the BHB triple system is disrupted at \( t \approx 9.94 \) Gyr.

After 10.8 Gyr Snowball and its companion are the only BHs surviving in the cluster. During the last \( \sim 200 \) Myr, the BHB once again forms a triple system with a white dwarf. This hierarchical triple remains until the end of the simulation.

4. MERGER CHAIN STATISTICS

To estimate the likelihood of encountering Snowball-like chains in typical compact star clusters, we consider our full set of \( N = 58 \) simulations and construct a probability density function of merger chain length. We define the merger chain length \( L \) as the total number of BHB mergers involved in producing the final multi-generation BH. Based on this definition Snowball has a chain length of seven. We also denote the generation of a BH as \( \text{BH}_{\text{gen}} \). Across all 58 simulations, we observe 18 chains with \( L = 1 \), 28 chains with \( 2 \leq L \leq 4 \), and Snowball with \( L = 7 \). Table 1 lists the number of merger chains both with and without gravitational recoil taken into account. Note that the 56 (47 with recoil) total merger chains corresponds to 97 (75 with recoil) total BHB mergers.

| Chain length | Number (no recoil) | Number (recoil) |
|--------------|--------------------|-----------------|
| 1            | 18                 | 33              |
| 2            | 16                 | 7               |
| 3            | 8                  | 3               |
| 4            | 4                  | 3               |
| 5            | 0                  | 0               |
| 6            | 0                  | 0               |
| 7            | 1                  | 1               |
| **Total**    | **56**             | **47**          |

Table 1. Summary of the prevalence of different merger chain lengths across our 58 simulations. We report the number of chains both with and without gravitational recoil taken into account. Approximately half of the 97 in-cluster mergers only involve BHs produced directly through core collapse. 18 of these second generations BHs, with BHs \( m_2 \geq 2 \), never merge again, increasing to 33 when gravitational recoil is accounted for. 47 mergers involve a BH with \( \text{BH}_{\text{gen}} \geq 2 \). In 36 of these mergers \( m_2 \) is a first-generation BH, with \( m_1 \) being the multi-generational object. This is expected as hierarchically formed BHs are on average heavier than those formed through core collapse, and thus are more likely to be the heavier element in a BHB. Mergers involving an object with \( \text{BH}_{\text{gen}} \geq 2 \) involve a first-generation BH merging with the higher generation BH, with only three exceptions. One is a merger between two second-generation BHs, and the other two are between a second and third generation BH. These three mergers represent the only such mergers between two previous merger remnants. Hence we conclude two or more chains are unlikely to exist simultaneously within a mid-sized GC. Once a BHB merges, its product is likely to be the most massive body in the cluster, and
thus sink to the cluster centre due to dynamical friction, even if recoil is imparted (as long as the resulting BH remains bound). The massive BH dominates dynamically within the dense core, likely undergoing many dynamical interactions with other single and binary BHs. Hence, any BHB that forms is likely to interact with the second generation BH, in which case an exchange event will preferentially unbind $m_2$, forming a new BHB with the second generation BH (Sigurdsson & Hernquist 1993).

4.1. Snowball event rate estimation

To estimate the comoving rate of Snowball-like merger chains to an order of magnitude, we can use the equation

$$R_{\text{snowball}} \approx \frac{R_* f_{\text{GC}} f_{\text{Snowball}}}{M_{\text{GC}}}$$  \hspace{1cm} (1)

where $R_*$ is the comoving star formation rate [units: $M_\odot \text{yr}^{-1} \text{Mpc}^{-3}$] at the characteristic time of star cluster formation and within the volume observed by LIGO, $f_{\text{GC}} \approx 10^{-3}$ is an order-of-magnitude estimate of the fraction of star formation that occurs within a dense star cluster, $f_{\text{Snowball}}$ is the fraction of those clusters that are likely to produce Snowball like merger chains, estimated from our simulations, and $M_{\text{GC}} \approx 6.5 \times 10^4 M_\odot$ is the characteristic mass of a dense star cluster in our runs.

A detailed estimation of $R_{\text{snowball}}$ would require to take into account both the redshift dependence of $R_*(z)$ and the distribution of time delays between formation of the cluster and a chain merger event. However, uncertainties in $f_{\text{GC}}$, $f_{\text{Snowball}}$, and $M_{\text{GC}}$ dominate Eq. 1, thus to remain in the spirit of an estimate to only an order of magnitude, we can neglect redshift dependency for $R_*$, adopting an appropriate average value for it, and assume the merger time delay distribution is a delta function at the cluster’s age. Given that LIGO is sensitive to high mass merger events out to $z \sim 1$ – 1.5 (Chen et al. 2017), and that most of the volume is thus at cosmological distances, we assume $R_* \approx 0.1 M_\odot \text{yr}^{-1} \text{Mpc}^{-3}$, corresponding to the comoving star formation rate at $z \approx 1.2$ from Madau & Dickinson (2014, Figure 9, left panel).

Based on the results presented in Table 1, we assume $f_{\text{Snowball}} \approx 0.02$ (one IMBH chain event out of over 50 simulations). A more precise characterisation is challenging from a single chain instance discovered in our set of simulations, but the rate could be higher taking into account that Snowball originated from a canonical simulation (therefore arguably more representative of dense star cluster properties than other runs). Given these assumptions, we estimate the Snowball event rate to be

$$R_{\text{snowball}} \approx 0.03 \text{Gpc}^{-3} \text{yr}^{-1}. \hspace{1cm} (2)$$

Remarkably, this is within the 90% confidence interval of the inferred rate of mergers similar to GW190521, estimated by Abbott et al. 2020d as $0.13 \pm 0.01 \text{Gpc}^{-3} \text{yr}^{-1}$. This agreement between observed and estimated rate is reassuring to qualitatively support the plausibility of formation of IMBHs through chain mergers in dense stellar systems, but of course a deeper quantitative investigation is needed to further assess the scenario we propose.

5. DISCUSSION

In this work we analyze the hierarchical mergers of BHs formed within simulated GCs, investigating the dynamical formation of an IMBH. The analysis is based on a set of direct NBODY6 simulations of realistic mid-sized cluster models previously presented in Anagnostou et al. (2020). We present a detailed investigation into the evolution of “Snowball”, a BH that undergoes seven BHB mergers, attaining a final mass of $\sim 98 M_\odot$.

Our results prove that long merger chains (with seven events in our case) are possible in a standard simulation, without the need for special tweaking. We discuss this formation channel as a possible method for forming BH masses in the upper mass gap through repeated mergers.

Based on Table 1, we predict that median mass GCs are much more likely to host single merger chains than two or more chains. However, as both $m_1$ and $m_2$ are $\gtrsim 50 M_\odot$, it is highly likely that GW190521 formed via a merger between two BH$_{\text{gen}} > 1$ BHs through a chain with $L$ comparable to Snowball’s. This may suggest that GW190521 originated in a massive star cluster, where the BH population is sufficiently large to sustain two chains beyond the lengths observed in our mid-sized simulated systems. However, we cannot rule out the possibility of such a merger chain within clusters similar to ours. With a larger set of simulations, it is possible we would discover a multiple chains that eventually combine with sufficient length to produce a $\sim 140 M_\odot$ BH.

The last merger in chains with $L > 1$ occur at $t = 4735$ Myr on average in our 58 simulations. Thus when considering dynamical formation, it appears that the formation of IMBHs in relatively young GCs ($t \lesssim 6$ Gyr) is preferred, when there is still a sufficient population of BHs in the core. If true, this means that hierarchical mergers are more likely to occur at cosmological distances, when the star formation rate is higher and there was a higher proportion of young GCs. Their lower metallicity compared to young star clusters in the local Universe is also expected to favor formation of more massive BH seeds from stellar evolution. In principle, such distant sources are more difficult to detect. How-
ever, the larger average chirp mass from hierarchical mergers leads to a larger gravitational strain.

The current work shows that “Snowball-like” merger chains are a plausible method for producing BH masses within the upper mass gap, and that hierarchical mergers depend on the dynamical interactions within dense stellar environments. Furthermore, detailed investigations involving a larger sample of direct N-body simulations will allow us to better constrain the chain multiplicity distribution, as well as the likelihood to produce IMBHs through this pathway.

The hierarchical merger pathway provides a natural method for forming BHs within the BH mass gap, without the need for new physics, but that does not mean that such new physics is absent. Regardless of the origin of GW190521, this remarkable detection represents the first confirmed detection of an IMBH and will likely spark increased interest in the formation and evolution of these stellar behemoths. The full release catalogue of O3 events is also poised to enable further investigation into the mass gap and the hierarchical merger pathway.

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