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A Single Progenitor Model for GW150914 and GW170104

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The merger of stellar-mass black holes (BHs) is not expected to generate detectable electromagnetic (EM) emission. However, the gravitational wave (GW) events GW150914 and GW170104, detected by the Laser Interferometer Gravitational Wave Observatory (LIGO) to be the result of merging, $\sim 60M_\odot$ binary black holes (BBHs), each have claimed coincident gamma-ray emission. Motivated by the intriguing possibility of an EM counterpart to BBH mergers, we construct a model that can reproduce the observed EM and GW signals for GW150914- and GW170104-like events, from a single-star progenitor. Following Loeb [1], we envision a massive, rapidly rotating star within which a rotating bar instability fractures the core into two overdensities that fragment into clumps which merge to form BHs in a tight binary with arbitrary spin-orbit alignment. Once formed, the BBH inspirals due to gas and gravitational-wave drag until tidal forces trigger strong feeding of the BHs with the surrounding stellar-density gas about 10 seconds before merger. The resulting giga-Eddington accretion peak launches a jet that breaks out of the progenitor star and drives a powerful outflow that clears the gas from the orbit of the binary within one second, preserving the vacuum GW waveform in the LIGO band. The single-progenitor scenario predicts the existence of variability of the gamma-ray burst, modulated at the ~ 0.2 second chirping period of the BBH due to relativistic Doppler boost. The jet breakout should be accompanied by a low-luminosity supernova. Finally, because the BBHs of the single progenitor model do not exist at large separations, they will not be detectable in the low frequency gravitational wave band of the Laser Interferometer Space Antenna (LISA). Hence, the single-progenitor BBHs will be unambiguously discernible from BBHs formed through alternate, double-progenitor evolution scenarios.

I. INTRODUCTION

The Laser Interferometer Gravitational Wave Observatory (LIGO) has conclusively detected gravitational waves (GWs) from the merger of two black holes (BHs) in five different systems [2–6]. In addition to its notoriety as the first detected GW signal, GW150914 also made waves for being a peculiarly [76] high mass system consisting, before merger, of two nearly equal mass BHs adding up to $\sim 65M_\odot$ [7]. The addition of GW170104 and GW170814, similarly high mass, $\sim 50M_\odot$, binaries with nearly equal mass components, has hinted that such high mass, near-unity mass ratio systems may be common.

Perhaps more interesting than LIGO's observation of such unexpected systems is the possibility that two out of the three are associated with an electromagnetic (EM) counterpart. While no electromagnetic counterpart is expected from the merger of stellar-mass BHs [77] [see 8], both GW150914 and GW170104 have been associated with gamma-ray emission carrying total isotropic energy of $\sim 10^{49} - 10^{50}$ ergs, and occurring within half of a second from the peak of the gravitational wave strain [9, 10].

We proceed by assuming the gamma-ray transients are indeed connected to the GW events, and ask what could be their origin? While exotic physics, such as highly charged BHs [*e.g.*, 11, 12] could be conjectured, we consider more standard astrophysical scenarios. In all such scenarios, the generation of $\sim 10^{49}$ ergs of energy must correspond to a giga-Eddington event; a $30M_\odot$ BH must accrete at $\sim 3\times10^9$ times the Eddington rate for one second, or equivalently, $10^{-4}M_\odot$ must be accreted at 10% efficiency within one second in order to achieve these energies.

The standard, double-progenitor binary black hole (BBH) formation channels: (i) isolated evolution of binary systems in the field [*e.g.*, 13–17] and (ii) dynamical capture in clusters [*e.g.*, 17–20], do not naturally allow for this much gas to be present at the time of merger, though recently a number of models have been put forward to challenge this [1, 21–24].

Rather than consider possible scenarios for generation of high density gas in the standard, double-progenitor paradigm, Loeb [1] pointed out that a single progenitor model (previously studied by [25, 26]) can naturally provide the gas densities needed to power the putative gamma-ray transient. In this model, a rotating bar instability forms in the core of a massive rapidly rotating star, forming a dumbbell configuration that fissures into the two proto-BHs, which eventually merge in the LIGO band powering a giga-Eddington accretion burst that results in a collapsar-type event [*e.g.*, 27], possibly powering a gamma-ray transient.

While providing the correct energies of emission, later work pointed out that: (i) gas drag on the BHs inside the collapsing star will unmistakably alter the GW wave form detected by LIGO [28, 29], and (ii) due to the ~ 10 second jet breakout timescale in the collapsar model, the time delay between EM and GW signals would be longer than the observed $\sim \pm 0.5$ seconds [22]. In addition to these issues, the model would naively predict BHs with

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spins that are aligned with the binary orbital angular momentum while GW170104 does not show evidence for significant aligned BH and binary orbital angular momenta [See also Ref. 30].

Here we present a single progenitor model for GW150914- and GW170104-like events in which the above issues are alleviated. We consider a model similar to that of Loeb [1], but where tidal forcing of the binary drives a giga-Eddington accretion event ~ 10 seconds before merger, driving a powerful outflow that: (i) clears the gas surrounding the binary before it reaches the LIGO band, and (ii) can alter the time delay between EM and GW signatures to match the observed $\sim \pm 0.5$ second shift from the peak of the LIGO signal.

Also new to the model, we consider a formation scenario for the BHs within the massive progenitor star that would allow BH spin misalignment (though this is not required by GW observations). As the rotational bar instability ensues, each end of the rotating dumbbell can fragment into multiple clumps with Jeans mass of order a solar mass. As the relaxation time of these clumps is of order a dynamical time, the clumps would quickly randomize their angular momenta before merging into a $30 M_{\odot}$ BH, allowing BHs with spins misaligned with the orbital angular momentum. Additional impacts on the BH after formation can tilt its spin similarly to the way the spin axis of Uranus is tilted by asteroid impacts in the early solar system [*e.g.*, 31].

While some aspects of the above processes are uncertain, including even the association of the GWs and gamma-rays themselves, we stress that the single progenitor model put forth in this article is a real possibility that carries with it predictions that would discern it from other double progenitor scenarios: (i) BBHs formed in our scenario will not exist at large enough separations to emit GWs detectable by the Laser Interferometer Space Antenna [LISA; 32], as suggested by [33, 34] for GW150914; (ii) Accompanying the merger should be a faint supernova; (iii) Because the gamma-ray burst (GRB)-like outflow occurs before merger, the chirping orbital frequency of the binary should be imprinted as variability on the gamma-ray lightcurve; (iv) The delay time between GWs and the short gamma-ray transient is dependent on binary parameters as well as uncertain hydrodynamics. If future work can better pin down the latter, then GW observations that measure binary parameters would constrain theoretical models for the EM time delay.

II. SUMMARY OF OBSERVATIONS

We first summarize the gravitational and electromagnetic observations of the two high-mass BBH LIGO systems with claimed gamma-ray counterparts. Most relevant to our model are the gamma-ray burst durations, energies, and time delays with respect to the GW peak, as well as the BH masses, and the alignment of BH spin relative to the line of sight and to the orbital angular momentum. Because our goal is to characterize the putative EM counterparts, we only summarize the relevant claimed EM detections and do not present an extensive summary of all the EM follow up surveys.

A. GW150914

The gravitational wave event GW150914 is due to the merger of two BHs of masses $36.2^{+5.2}_{-3.8} M_{\odot}$ and $29.1^{+3.7}_{-4.4} M_{\odot}$. The dimensionless spin parameter is $\mathcal{S}_1 = 0.32^{+0.49}_{-0.29}$ for the primary and $\mathcal{S}_2 = 0.44^{+0.50}_{-0.40}$ for the secondary. The spin orientation is not strongly constrained, but if one assumes that the pre- merger spins are aligned with the binary orbital angular momentum, then $\mathcal{S}_1 < 0.2$ and $\mathcal{S}_2 < 0.3$ with 90% probability [7, 35]. It is strongly disfavored that the binary orbital angular momentum is misaligned with the line of sight; the probability that the angle between the total binary orbital angular momentum and the line of sight is between 45° and 135° degrees is 0.35. The peak value of the source-orientation probability distribution function is 160°, 20° from anti- alignment with the line of sight.

The Gamma-ray Burst Monitor (GBM) on board the Fermi satellite claimed a (2.9σ) detection of a gamma-ray transient 0.4 seconds after the merger time recorded in gravitational waves and consistent with a weak short gamma-ray burst. The transient lasted 1 second, and at the gravitational wave inferred luminosity distance of 410 Mpc, a total energy of $1.8^{+1.5}_{-1.0} \times 10^{49}$ ergs was radiated between 1 keV and 10 MeV [9, 36]. The INTEGRAL/SPI-ACS instrument does not detect a coincident gamma-ray signal in the harder, 75 keV-100 MeV range [37].

B. GW170104

The gravitational wave event GW170104 is due to the merger of two BHs of masses $31.2^{+8.4}_{-6.0} M_{\odot}$ and $19.4^{+5.3}_{-5.9} M_{\odot}$. The dimensionless spin parameters of the individual BHs before merger are not strongly constrained, but large values that are aligned with the binary angular orbital momentum are disfavored [4]. The binary orbital angular momentum inclination to the line of sight is not well constrained with broad probability peaks at face-on and edge-on inclinations.

A gamma-ray transient was detected at the $\sim 2.5\sigma$ level, 0.46 ± 0.05 seconds before the GW170104 merger event and lasting 32ms. The luminosity and fluence of this event was also consistent with a weak short gamma-ray burst. At the gravitational wave inferred luminosity distance of 880 Mpc, the total energy in the $0.4 - 40$ MeV band is $E_{\rm iso} \sim 8.3 \times 10^{48}$ erg corresponding to an isotropic luminosity of $L_{\rm iso} \sim 2.6 \times 10^{50}$ erg s^{-1} [10].[78]

Neither the Fermi GBM (10 KeV - 1MeV), the Fermi Large Area Telescope (0.1-1 GeV), the AstroSat-CZTI

(> 100 KeV), or INTEGRAL SPI-ACS reported a detection of a transient similar to the AGILE detection [38–40]. ATLAS and Pan-STARRS did, however, report the detection of a GRB afterglow candidate ATLAS17aeu in the GW170104 error circle 23 hours after the GW event, but we do not consider any connection to GW170104 here since its inferred host galaxy is likely at a redshift larger than the GW source [39, 41].

In summary, both of the above events consisted of nearly equal mass BBHs of order $(30 + 30)M_\odot$ whose merger might have coincided with a gamma-ray transient with total isotropic energy of order 10^{49} ergs. While the BH spin alignments are poorly constrained, the BH spins are consistent with being aligned towards the observer's line of sight, so the possibly beamed signal described below could be pointed toward the observer. While alignment of the BH spins with the binary orbital angular momentum is not ruled out, it is disfavored for large values of the spin magnitude.

A third, high-mass, near-unity mass ratio BBH detected by LIGO, GW170814, has no claimed EM counterpart [6]. As the binary and spin orientations of the LIGO BBH events are poorly constrained, we cannot say whether or not this can be explained by the viewing angle.

III. SINGLE PROGENITOR MODEL

A. BBH formation and spin-orbit alignment

We consider a single, massive $\gtrsim 250M_\odot$, rapidly rotating, low-metallicity star as the progenitor of GW150914- and GW170104-like BBH systems. Such a star would be the natural outcome of the merger of a massive, tight binary system with a common envelope [42–44].

Furthermore, such massive stars are expected to form in nearly equal mass ratio tight binaries and merge within a Hubble time at a rate comparable to the low end of the BBH merger rate inferred by LIGO, ~ 10 Gpc^{-3} yr^{-1} [4]. Ref. [44] uses a Kroupa initial mass function (IMF) to estimate the merger rate of $\gtrsim 60M_\odot$ stars to be ~ 20 Gpc^{-3} yr^{-1}. If we simply extend the back-of- the-envelope argument made by Ref. [44] to only consider stars above $125M_\odot$ (assuming that they exist), and assume that such binaries form in nearly equal mass ratio pairs (see [43]), then because the Kroupa IMF scales as a -2.35 power law in mass, the decrease in the inferred merger rate drops by only a factor of $(60/125)^{-1.35} \sim 3$. Considering further that only three of the five LIGO detections are of the proposed single progenitor type put forth in our model, the rate of stellar mergers above $\sim 125M_\odot$ is not inconsistent with the rate of very massive, nearly equal mass ratio BBH mergers inferred by LIGO.

We require the total stellar mass to be above $\sim 250M_\odot$ so that stellar collapse is not subject to the pair instability supernova mechanism, causing the star to explode, leaving behind no progenitor, or pulsating and losing too much mass to be the progenitor of a $\sim 60M_\odot$ BBH [*e.g.*, 22, 45, 46].

The angular momentum of the star must be below the break-up value of the star, but also above that of the centrifugal barrier which sets the initial separation of the BBHs. As in Ref. [1], we require that the initial separation a_0 of the BBH be large enough to not disturb the LIGO observations ($\sim 10M$). Additionally, in this model, we require that a_0 also be greater than the binary separation at which our EM mechanism turns on, which we describe below occurs around $20r_G$ (where $r_G \equiv GM/c^2$ for M the total BBH mass). Conservatively, we require $a_0 \geq 50r_G$ to constrain the angular momentum budget of the star,

$$1 > \frac{\Omega R_*^2}{j_{\rm max}} \gtrsim 0.01 \left(\frac{R_*}{R_c}\right)^2 \left(\frac{M_*}{300M_\odot}\right)^{-3/4}, \quad (1)$$

where, as in Ref. [1], we posit a star with constant angular velocity Ω and angular momentum profile $j = \Omega r^2$, R_c is the radius of the core that collapses to create the BBH with initial separation $a_0 \ll R_c$, $j_{\rm max}$ is the angular momentum corresponding to break up, M_* is the stellar progenitor total mass, and R_* is the progenitor radius. For a more massive star and a larger required centrifugal barrier than in the model of Ref. [1], we arrive at the same result as Eq. (5) of Ref. [1].

We note, however, that 1D simulations by Heger et al. [47] and Woosley [22] find that braking of stellar rotation via magnetic torques and mass loss could slow the rotation of such massive stars below the required minimum value to create the BBH. The final fate of the stellar core's angular momentum, however, is sensitive to the uncertain mass loss rates and magnetic field implementations used in these 1D calculations. We note this potential complication but proceed by considering the case where the star can collapse with the required angular momentum.

The core of the rapidly rotating, collapsing star will become unstable to a rotating bar instability [25, 26]. The bar will form into a dumbbell configuration, within which the two BHs will form at either end. We envision a formation scenario where the gravitationally unstable gas in each end of the dumbbell fragments in to multiple clumps of mass and size given approximately by the Jeans criterion,

$$\frac{M_J}{30M_\odot} \approx 0.036 \left(\frac{T}{10^9{\rm K}}\right)^{3/2} \left(\frac{\rho}{10^8{\rm cm}^{-3}}\right)^{-1/2} \quad (2)$$

$$\frac{\Lambda_J c^2}{30GM_\odot} \approx 25 \left(\frac{T}{10^9{\rm K}}\right)^{1/2} \left(\frac{\rho}{10^8{\rm cm}^{-3}}\right)^{-1/2}, \quad (3)$$

where a typical core density and temperature is estimated from the models of Fryer et al. [25]. [79] The presence of gravitational perturbations and shearing forces in the rotating collapsing clumps will alter the instability criterion away from the simple Jeans approximation. However, considering even the uncertainty of the temperature and density in each collapsing clump, a more complex treatment of fluid and gravitational instability in the collapsing star is beyond the scope of this study.

Each swarm of tens of $\sim M_\odot$ clumps (one swarm at either end of the dumbbell configuration) will be born with the same orbital angular momentum and spin angular momentum, but will interact with itself gravitationally and be slowed via gas drag. For a swarm of $N \sim 30 M_\odot / M_J \sim 30$ clumps, the relaxation time of the proto-BH swarm is [*e.g.*, §1.21 of Ref. 48],

$$t_{\rm relax} = \frac{N}{8{\rm lnN}} \Omega^{-1}_{\rm swarm} \sim \Omega^{-1}_{\rm swarm} = \sqrt{\frac{(R_c/2)^3}{G M_\bullet}}, \quad (4)$$

equal roughly to the dynamical time of the swarm, $\Omega^{-1}_{\rm swarm}$. Here $M_\bullet$ is the mass of the single BH formed by the swarm and we assume a maximum extent of each swarm to be half the core radius. Assuming that the clumps have a size smaller than the Jeans length, we can compare the relaxation time to the time until the first collision of two clumps and solve for the minimum core radius at which the clump collision time is longer than the swarm dynamical time. Assuming $N = M_\bullet / M_J$ clumps with collisional cross section $\sigma_{\rm coll} = \pi (\Lambda_J/2)^2$, moving at speed $v_{\rm swarm} = (R_c/2)\Omega_{\rm swarm}$ in a volume $\mathcal{V} = (4\pi/3)(R_c/2)^3$, where $M_\bullet$ is the mass of the single BH formed by the swarm, we estimate the collision time as,

$$t_{\rm coll} \equiv \frac{\mathcal{V}}{N \sigma_{\rm coll} v_{\rm swarm}} = \frac{M_J}{M_\bullet} \frac{4 R_c^2}{\pi \Lambda_J^2} \Omega^{-1}_{\rm swarm} \quad (5)$$

(neglecting a factor of $3/\pi$). Then the limit on the core radius, for which the swarm dynamical time is shorter than the collision time, is

$$R_c \gtrsim \frac{1}{2} \sqrt{\pi \frac{M_\bullet}{M_J}} \Lambda_J \approx 5.2 \times 10^8 {\rm cm} \ \left(\frac{{\rm M}_\bullet}{30 {\rm M}_\odot} \right)^{1/2}, \quad (6)$$

where we use the values for the Jeans mass and length above. This required core size is consistent with the stellar size and the angular momentum budget of Eq. (1).

It is also useful to compare the clump collision time with the free-fall time in each Jeans unstable clump. The free-fall time of a clump is simply the dynamical time in the clump, which we can relate to the dynamical time of the entire swarm of clumps by $\Omega^{-1}_{\rm clump} = \sqrt{M_\bullet / M_J (\Lambda_J/R_c)^3} \Omega^{-1}_{\rm swarm}$. Then the condition on the initial core radius that ensures that individual clumps collide before collapsing is,

$$R_c \lesssim \left(\frac{\pi}{4} \right)^{2/7} \left(\frac{M_\bullet}{M_J} \right)^{3/7} \Lambda_J \approx 4.3 \times 10^8 {\rm cm} \ \left(\frac{{\rm M}_\bullet}{30 {\rm M}_\odot} \right)^{3/7}. \quad (7)$$

Putting together Eqs. (6) and (7), we see that if the core is small enough for collisions to merge the clumps before they are dynamically stirred, then collisions between clumps will also occur before the clumps collapse.

Because of the angular momentum budget of Eq. (1), however, we expect that the core will not collapse to a size as small as the limit in Eq. (7). More specifically, For stars with radii greater than $\sim 4 \times 10^{10}$ cm, the core would acquire more than the maximum break-up angular momentum when collapsing below the limiting size in Eq. (7). Put another way, this limiting size is approaching $\sim 50 r_G$ for a $60 M_\odot$ binary, at which point the core radius is not much larger than the required binary separation. Hence, we favor larger core radii, and thus the scenario where we are left with a swarm of $\sim M_\odot$ sized clumps that eventually merge due to gas plus gravitational-radiation drag and collisions.

The timescale for the clumps of each swarm to merge into a $\sim 30 M_\odot$ BH, vs the timescale for the two ends of the dumbbell configuration to come together is uncertain. To estimate an upper limit on the timescale for clumps to form into the final 30 $M_\odot$ BH, we compute the collision time of a swarm of ~ 30 Jeans-mass BHs with collisional cross section equal to the ISCO, and in a region the size of half the core radius. This time is shorter than the GW-decay time for a $30 M_\odot + 30 M_\odot$ binary separated by the core radius, regardless of the initial core radius.

Because the timescale for the swarm to be brought together via gas drag must be at least a dynamical time for the stellar densities considered here and because the clumps will collapse before colliding, we conclude that in this fragmentation scenario the swarm of clumps will be able to stir itself sufficiently to randomize the clump orbital angular momentum vectors away from their birth directions before collisions and gas plus gravitational- radiation drag collapse the swarm into a BH.

Then formation of the final BH from a part of this swarm could lead to misalignment of the BH spin with the collapsing star's spin angular momentum, and hence the eventual binary orbital angular momentum. The clumps that do not form the final BH could escape (not greatly affecting the mass budget as the stellar core can be much more massive than $60 M_\odot$ [22]) or remain to impact either of the BHs in a collision that could misalign the BH further, analogously to the processes that misalign the planets' spin axes in the early solar system.

The evolution of the BH angular momentum due to clump collisions will follow a random walk. The final angular momentum of the BH can be estimated from the root mean square (rms) angular momentum delivered during the bombardment of clumps with a given mass and velocity distribution. We use Eq. (20) of [49] to make a pureley Newtonian estimate of the expected rms angular momentum delivered to the BH, assuming only one impact and assuming no angular momentum loss to gravitational radiation. To be conservative we assume a clump mass $M_{\rm clump}$ equal to the Jeans mass of Eq. (3) (though the clump may have increased in mass between collapse and impact) and a radius, $r_{\rm clump}$, equal to the clump Schwarzschild radius (though the clump may be larger and hence deliver more angular momentum). Then the rms angular momentum delivered by one impact and written in terms of the total BH spin angular momentum before merger is,

$$\frac{\Delta L}{L_\bullet^i} \approx 0.08(\mathcal{S}^i)^{-1}\left(\frac{1+\chi}{5/4}\right)^{1/2}\left(\frac{M_{\rm clump}}{M_\odot}\right)\left(\frac{M_\bullet^i}{29M_\odot}\right)^{-1}\left(\frac{M_\bullet^f}{30M_\odot}\right)^{-1/2}\left(\frac{2r_G^i+r_{\rm clump}}{r^f}\right)^{1/2}, \tag{8}$$

where $-1 \le \mathcal{S} \le 1$ is the dimensionless BH spin parameter, $L_\bullet^i \equiv \mathcal{S}G(M_\bullet^i)^2/c$ is the BH angular momentum, χ is the squared ratio of impact speed to escape speed from the BH (the speed of light), and the superscript i (f) denotes the quantity before (after) impact. Hence, the clump impacts can alter the BH spin by $\sim 8\%$ for an initially maximumly spinning BH. For a two times more massive clump, and an initial BH spin of $\mathcal{S} = 0.16$, the above ratio reaches unity, and the clump impact could completely rearrange the BH spin. Note that the above result implies that the BH spin would have a value $\mathcal{S} \sim N^{-1/2} \sim 0.2$ for $N \sim 25$, this is in agreement with the observed spins of GW150914.

While the above processes could result in a BBH with misaligned spins, they do not require it, they simply offer a channel for misalignment to occur. Such a misalignment could lead to spin-orbital precession of the binary. Precession could leave an observational imprint in the GW [*e.g.*, 50] and EM [51] signatures of inspiral. However, precession could be problematic for jet breakout [52], quenching the EM counterpart, or shortening what would otherwise be longer bursts. There is presently no strong evidence for precession in the LIGO data [4, 53].

The final state of the collapsing clumps that make up the two proto-BH swarms is not clear. Given their initial compact size (Λ_J), they could collapse to BHs, but future work needs to clarify this. If the clumps do not collapse to BHs, then feeding of either proto-BH by clump collisions could lead to large EM bursts that could clear out gas, possibly via jets, from the core before merger of the final $30M_\odot + 30M_\odot$ BBH.

If multiple clumps can collapse to black holes before collapse into one of the components of the larger BBH, then mergers of smaller BHs within each end of the rotating bar instability could generate non-standard GW signals in the LIGO band [See 54] prior to the main merger of the two $\sim 30M_\odot$ BBHs. While the timing of these non-standard GW signals relative to the final merger is uncertain, we estimate that they would occur before the main GW event by at least a merger time of the final $30{+}30M_\odot$ BBH system. Considering orbital decay due only to GWs and a $50r_G$ initial separation of the $30{+}30M_\odot$ system, we find that the putative smaller BBH mergers would occur on order minutes before the main BBH LIGO signal. Mergers of $1M_\odot + 1M_\odot$ BHs, which have a ~ 30 times smaller chirp mass, will have a strain that is ∼two orders of magnitude lower than that of the final $30M_\odot + 30M_\odot$ merger. Mergers of $1M_\odot + 29M_\odot$ or $15M_\odot + 15M_\odot$ BHs, however, would have ~ 25 or ~ 3 times smaller strains respectively. Further study of this possibility may warrant a search in the existing LIGO data.

Gravitational wave recoil kicks from these pre-mergers will depend on the eccentricity and spins of the merging BHs, but for the final mergers of $\sim 1 + 30M_\odot$ BHs, the sensitive mass ratio dependence of the kick velocity makes the kick small. Using a maximum kick velocity of ~ 4000 km/s for optimal spin alignment and mass ratio of $q \le 1 = M_2/M_1 = 2/3$ [55], the kick for a $q = 1/30$ BBH drops by a factor of $q^2/(1+q)^5/0.035$ to $\lesssim 100$ km/s. This is small compared to the sound speed ($\sim 10^3$ km/s for $T \sim 10^9$ K) and also compared to the binary orbital speed, even at a binary separation of $100M$ ($\sim 10^4$ km/s). We note that it is possible that the rare, largest possible kicks between equal mass BHs in the swarm could marginally unbind them from the swarm.

If such smaller BHs can form, the rate of mergers between smaller BHs or between smaller BHs and the larger proto-BH in the LIGO band will depend upon the redshift distribution of the single progenitor systems discussed here.

Finally, we note that the conditions in the collapsing star that lead to fragmentation vs. direct collapse within each end of the rotating-bar instability should be studied in future simulations which can capture the effects of self-gravity and cooling needed to understand this process further (e.g., in analogy to understanding a similar process in the context of supermassive black hole seeds [56]).

B. Electromagnetic Emission

We now consider the energetics and timescale of an EM counterpart of the BBH merger. We carry out a calculation similar to that of Ref. [21], but in the setting of the single progenitor model.

Once the BHs form they will be driven together by gas torques, accretion, and gravitational radiation losses [*e.g.*, 29]. Accretion flows will form around each binary component and will be driven onto the BHs via the magneto-rotational instability [MRI; 57] and also spiral shock driven angular momentum transport from disk perturbations due to the companion [see 58–60]. The outer edge of the disk around each BH is given by the tidal truncation radius [61, 62],

$$r^s_{\rm out} \sim 0.27 q^{0.3} a \qquad (9)$$
$$r^p_{\rm out} = q^{-0.6} r^s_{\rm out}, \qquad (10)$$

which coincides with the location where orbit crossings exclude the possibility of stable orbits at larger radii. Here $q = M_s/M_p$; $M_p > M_s$ is the binary mass ratio, and s and p represent secondary and primary, respectively.

The time for the material to be transported inwards to the BH from radius r is given by the viscous time there,

$$t^s_{\rm in} \equiv \frac{2}{3}\frac{r^2}{\nu} = \frac{2}{3}\frac{\mathcal{H}^{-2}}{\alpha}\sqrt{\frac{r^3}{GM}}\sqrt{1+1/q}$$
$$t^p_{\rm in} = q^{1/2} t^s_{\rm in}, \qquad (11)$$

where M is the total binary mass and $\mathcal{H}$ is the dimensionless aspect ratio (height over radius) of the disk. Here the 2/3 prefactor is valid for a steady-state disk and we have calculated the coefficient of kinematic viscosity, ν, using the Shakura-Sunyaev α-prescription [63].

When the GW-decay timescale of the binary is longer than the viscous time at the outer edge of the disk, the disk will evolve adiabatically and accrete at the viscous rate onto each BH. However, when $t_{\rm GW} \leq t_{\rm in}$, at a binary separation of

$$\frac{a^s_{\rm burst}}{r_G} \leq \left(\frac{512}{15}\right)^{2/5} \frac{\mathcal{H}^{-4/5}}{\alpha^{2/5}} \frac{\left(0.27 q^{0.3}\right)^{3/5}}{(1+q)^{2/5}(1+1/q)^{1/5}}$$
$$a^p_{\rm burst} = a^s_{\rm burst} q^{-0.16}, \qquad (12)$$

the binary torque will drive the disk into the BH faster than the disk can viscously respond and trigger a super-Eddington accretion event. [80]

The resulting super-Eddington accretion burst occurs at time $t_{\rm burst} = t_{\rm GW}(a_{\rm burst})$ before merger,

$$t_{\rm burst} = 7.7 s \left(\frac{a_{\rm burst}}{24 r_G}\right)^4 \left(\frac{M}{60 M_\odot}\right)^{-3} \left(\frac{(1+q)(1+\frac{1}{q})}{4}\right), \qquad (13)$$

where $a = 24 r_G$ corresponds to $a_{\rm burst}$ with $M = 60 M_\odot$, $q = 1$, and fiducial, pre-burst disk parameters of $\mathcal{H} = 0.05$ and $\alpha = 0.24$.

Given an efficiency η for converting matter into energy, the luminosity of the event is,

$$\mathcal{L} = \eta \dot{M} c^2 \gtrsim \eta \frac{r^3_{\rm out}(a_{\rm burst})\mathcal{H}}{t_{\rm burst}} \rho c^2$$
$$\gtrsim 1.1 \times 10^{49} {\rm erg\ s^{-1}} \left(\frac{\eta}{0.1}\right) \left(\frac{\rho}{10^8 {\rm g\ cm^{-3}}}\right), \qquad (14)$$

where we use numbers corresponding to accretion onto the secondary BH, we continue to use the fiducial disk parameters stated above, and the inequality is written because the time of the accretion event must be less than $t_{\rm burst}$ and we have not taken into account any beaming factors. Note that for stellar core densities of $\rho \sim 10^{10}{\rm g\ cm^{-3}}$, even efficiencies of order 10^{-3} could still generate the observed luminosities.

This luminosity is approximately 3×10^9 the Eddington value and will drive a powerful outflow or relativistic jet. At the burst time of approximately 8 seconds before merger, given in Eq. (13), this outflow will clear out the gas surrounding the binary within a sound crossing time,

$$t_{\rm clear} \lesssim \frac{a_{\rm burst}}{\mathcal{H} v_{\rm orb}} \qquad (15)$$
$$\approx 0.7 s \left(\frac{a_{\rm burst}}{24 r_G}\right) \left(\frac{c/\sqrt{24}}{v_{\rm orb}}\right) \left(\frac{\mathcal{H}}{0.05}\right)^{-1}.$$

We take this as an upper limit because the ambient sound speed is likely larger than what we have assumed in the thin accretion flows around each BH. Then the remaining ~ 7 seconds to merger will be unaffected by gas torques and will not [as suggested in Refs. 28, 29] affect the LIGO waveform which begins at ~ 0.2 seconds before merger.

The quantity $t_{\rm clear}$ also provides an estimate for the duration of the burst; once the gas is cleared from the binary orbit, the accretion event will stop being powered. This $\lesssim 1$ second timescale is in agreement with the observed durations of the GW150914 (~ 1 second) and GW170104 ($\sim 3.2 \times 10^{-2}$ seconds) gamma-ray transients.

There will be a delay between the super-Eddington accretion event plus jet launching and the time at which the jet breaks out of the supermassive star, generating the high-energy transient. Woosley [22] argued that the stellar radius calculated in model R150A of Ref. [22], plus the jet speed inside of the star calculated in Ref. [52], implies a delay of $\sim 10^{11}{\rm cm}/c/3 \sim 10$ seconds after $t_{\rm burst}$, which yields a time of ~ 2 seconds after merger, and because the GWs take ~ 3 seconds to reach the edge of the star as well, a delay time between EM and GW emission of order 1 second.

We point out that, within our model, jets could be launched from both BHs. Simulations of super-massive BBH systems show that the jets launched from each BH can combine into a single, larger jet near to the binary [64]. A similar situation would be realized in our model. This could result in a larger jet opening angle and higher probability of observing the event along the jet axis than in the single-BH collapsar model.

While the fiducial system parameters chosen here yield a remarkable match to the timescale observed between the GW and gamma-ray emission in GW150914 and GW170104, we note that this delay timescale is highly dependent on system parameters. The delay time depends on the gravitational wave decay timescale, the critical binary separation at which the accretion event occurs, and the radius and density of the collapsing star. In turn, these properties depend on the binary mass, mass ratio, and the hydrodynamical properties of the accretion flow around each black hole (parameterized by α and $\mathcal{H}$).

As an illustration of this parameter dependence, let us assume that the secondary launches the observed jet with pre-burst accretion disk aspect ratio $\mathcal{H} = 0.05$, stellar breakout radius 10^{11} cm, and a jet speed inside the star of $c/3$, then the predicted time lag for GW150914 is the observed 0.46 seconds after merger if $\alpha = 0.275$. The predicted time lag for GW170104 is the predicted 0.4 seconds before merger if $\alpha = 0.205$. We note that this is in agreement with the values of $\alpha \sim 0.1 - 0.3$ expected during the outbursting state of accretion onto BHs in cataclysmic variable systems and also consistent with the values measured in simulations which resolve the MRI [see 60, and references therein]). Alternatively, if we assume a breakout radius of 7×10^{11} cm [65], and fix the pre-burst viscosity parameter to $\alpha = 0.24$, we find that $\mathcal{H} \sim 35.0$ to match the EM time delay for GW150914, and $\mathcal{H} \sim 39.2$ to match the value for GW170104. Hence, our model reproduces the observed EM-GW time delay when using standard values of α, $\mathcal{H}$, and the breakout radius. However, results are quite sensitive to these parameters; precision to the third decimal in α and to the first decimal in $\mathcal{H}$ is required to fix the delay time to the reported hundredth of a second level precision. Reassuringly however, similar parameters are required for both systems.

IV. DISCUSSION AND IMPLICATIONS

We briefly compare our single progenitor model with related work in the literature and then discuss implications of the model that can be used to test it.

Dai et al. [28] point out that, in models where the BBH orbits within the stellar core, the orbital energy of the BBH will be converted into heat in the surrounding gas via dynamical friction and could unbound the star before the GRB-like event occurs. In our single progenitor model, we require a more massive star than in Ref. [28], having a higher binding energy and a lower central density [25], causing the unbinding by dynamical friction early in the BBH inspiral to be more difficult. Indeed for a central stellar density of 10^8 g cm^{-3}, and a $\gamma = 2.5$ power law fall off in the density of the stellar core (Eq. (1) of Ref. [28]), Figure 3 of Ref. [28] shows that the energy injected into the gas via dynamical friction is below the binding energy of the progenitor star (even for a progenitor half as massive as that considered here), as long as the initial separation of the BBH is $\lesssim 10^{10}$ cm. This is in agreement with our bounds on the initial binary separation in Eqs (1) and (6). A final word on the fate of the gas in the vicinity of the BBH before merger, however, must rely on more detailed calculations that include heating and cooling of the gas and eventually radiation.

A few other scenarios have been put forth to explain a gamma-ray counterpart to a BBH merger. Woosley [22] and Janiuk et al. [24] envision a close binary consisting of a BH and high mass star in which the BH spirals into the star causing it to collapse into a BH. These scenarios could result in a similar outcome as the single progenitor model; they do not, however, provide a natural explanation for the near-unity mass ratios observed in GW150914 and GW170401 and may be more susceptible to the unbinding of the star as discussed above.

As noted, the model proposed in Ref. [21] for generating the super-Eddington accretion event, is similar to that presented here, except that in Ref. [21], the gas needed for accretion is derived from a fossil disk which slowly builds up in density as the binary comes together. In the fossil disk scenario, the EM emission is prompt, not requiring time to break out from a surrounding medium. Hence Ref. [21] uses $\mathcal{H} = 1/3$ and $\alpha = 0.1$ in order to cause the super-Eddington event to occur much closer to merger. While the model of Ref. [21] hinges on the long term survival and then slow pile up of this fossil disk, which has been disputed by Ref. [66], it may still be viable and we discuss here the predictions of the single progenitor model that would differentiate it from alternate scenarios such as the fossil disk scenario:

- The systems envisioned here will not exist at the $\sim 10^3 r_G$ orbital separations that would be needed to place them in the high frequency end of the LISA [32] band. We predict that LISA will not be sensitive to BBHs in our single progenitor model, and hence the LISA observations would derive a different BBH merger rate than LIGO as they will probe a different population of BBHs. The single progenitor model presented here could be ruled out if LISA and LIGO can link together GW observations of a GW150914-like event [*e.g.*, 33, 34] for which gamma rays are detected near merger.

- A low-luminosity supernova corresponding to the clearing of the gas in the progenitor star envelope after the jet breakout should follow the GW and EM signals in our single progenitor model. Similarly, the post merger remnant could host a radio-afterglow [67]. Future work should address the observability of these signatures.

- If the hydrodynamic properties of the accretion flow onto each BH, as well as the stellar parameters, could be determined with better accuracy, then the binary mass and mass ratio, measured from GWs, would allow us to predict the EM and GW time delay and test the single progenitor model.

- When the relativistic outflow is launched, the binary period is approximately 0.2 seconds. If the transient discussed here lasts of order one second, as suggested by Eq. (16) and the Fermi-GRB observation associated with GW150914, then when the jet breaks out, its intensity would be modulated due to the relativistic Doppler boost [*e.g.*, 68], starting at a period of a fraction of a second but chirping up in frequency by a few percent over ~ 5 orbits due to the orbital decay. If the EM chirp is detectable [see also 69–71], then it would constrain the astrophysical factors which generate the EM and GW time delay discussed above.

Furthermore, we make the following falsifiable statements pertaining to our model:

- Firstly, as we have stated, our model is sensitive to parameters. Because our model can explain the gamma-ray emission from both GW150914 and GW170104 with a narrow, self-consistent range of parameters, this implies that this mechanism may only operate within this narrow range and that future events should also be explainable by this narrow range. Furthermore, if a gamma-ray event indeed occurred for two out of the three LIGO events for which our mechanism applies, and three out of five LIGO events are of the near-equal mass, high mass BBH variety, then such gamma-ray counterparts should be common.

- Our model involves a jet that must have a wide enough opening angle to be detected in two out of three events. Because GW observations can constrain the source orientation, future observation could falsify our model via constraints on the jet scale.

- If each BH in the final BBH is formed from swarms of smaller BHs, then LIGO, or future GW instruments should see this signal for sufficiently nearby events.

V. CONCLUSIONS

While the association between sub-second duration gamma-ray transients and the merger of $30M_{\odot}$ BBHs is far from being firmly established, the now two $\sim 3\sigma$ detections of such transients within 0.5 seconds of a BBH merger motivates us to further examine the previously unexpected possibility that BBH mergers can generate bright EM counterparts.

We have expanded upon the model of Loeb [1] for such an EM counterpart to develop a scenario where bright EM emission from the more massive GW150914- and GW170104-like BBH mergers is generated through a single progenitor model. In the single progenitor model, the core of a very massive ($\sim 300M_{\odot}$), rapidly rotating star fragments via a rotational bar instability and eventually forms two $\sim 30M_{\odot}$ BHs. At approximately 10 seconds before merger the BHs are fed by a burst of super-Eddington accretion from the surrounding stellar-density matter due to the rapidly increasing tidal torques of their companions. The accretion event can generate $\gtrsim 10^{49}$ erg s^{-1} luminosities during a powerful outflow that clears the binary orbit of gas and launches a jet that breaks out from the massive star within a few seconds of the merger, resulting in an EM and GW time lag of $\lesssim 1$ second for the model parameters assumed here.

Whether or not this scenario reflects reality will ultimately be tested with future LIGO observations and their EM follow up, as well as multi-band GW observations with the upcoming LISA mission. Future gamma-ray plus BBH merger associations will warrant further, more detailed analysis of the model presented here.

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[79] If the temperature in the fragmentation region is closer to 10^{10}K, at the same density of $\sim 10^8$ g cm^{-3}, then the Jeans mass is closer to $30 M_{\odot}$ and we do not expect a swarm of clumps to form, rather the BH will be formed with spin angular momentum aligned with the binary orbital angular momentum.
[80] See, for example, an analogue in the case of supermassive black hole binaries: [74, 75, and references therein].