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Energetic constraints on electromagnetic signals from double black hole mergers

Lixin Dai,[1,2]★ Jonathan C. McKinney[1,2] and M. Coleman Miller[3,2]

[1]*Department of Physics, University of Maryland, College Park, MD 20742, USA*
[2]*Joint Space-Science Institute, College Park, MD 20742, USA*
[3]*Department of Astronomy, University of Maryland, College Park, MD 20742, USA*

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ABSTRACT

The possible *Fermi* detection of an electromagnetic counterpart to the double black hole merger GW150914 has inspired many theoretical models, some of which propose that the holes spiralled together inside a massive star. However, we show that the heat produced by the dynamical friction on such black hole orbits can exceed the stellar binding energy by a large factor, which means that this heat could destroy the star. The energy scale of the explosion and the terminal velocity of the gas can be much larger than those in conventional supernovae. If the star unbinds before the merger, it would be hard for enough gas to remain near the holes at the merger to produce a gamma-ray burst, and this consideration should be taken into account when models are proposed for electromagnetic counterparts to the coalescence of two stellar-mass black holes. We find that only when the two black holes form very close to the centre can the star certainly avoid destruction. In that case, dynamical friction can make the black holes coalesce faster than they would in vacuum, which leads to a modification of the gravitational waveform that is potentially observable by advanced LIGO.

Key words: black hole physics – gravitational waves – neutrinos – stars: black holes – gamma-ray burst: general – supernovae: general.

1 INTRODUCTION

The LIGO event GW150914 resulted from the coalescence of two black holes of masses of 35^{+5}_{-4} and $29^{+4}_{-4}\,\mathrm{M}_{\odot}$ (Abbott et al. 2016a). The gravitational wave (GW) signal rose in frequency from 35 to 150 Hz in ~0.2 s. Just 0.4 s later, a signal was detected with the *Fermi* Gamma-ray Burst Monitor (Connaughton et al. 2016). The signal lasted ~1 s and the isotropic equivalent luminosity of the non-thermal X-ray component was $\sim 10^{49}\,\mathrm{erg\,s^{-1}}$, if the source was at the distance of GW150914. In some respects, the signal was similar to short gamma-ray burst (GRBs). However, doubts have been raised about the association of the electromagnetic (EM) signal with GW150914 (Greiner et al. 2016), especially given that *INTEGRAL* did not detect the GRB (Savchenko et al. 2016). LIGO later reported one more clear GW detection and a possible detection (Abbott et al. 2016b), but no candidate EM counterparts were found in those events (Abbott et al. 2016c; Racusin et al. 2016; Smartt et al. 2016).

If GW150914 indeed had an EM counterpart, then it means that contrary to previous expectations, the two black holes could not have merged in a near-vacuum, unless they are charged (Fraschetti 2016; Liebling & Palenzuela 2016; Zhang 2016). Independent of whether the GW150914–*Fermi* GRB association is real, it is interesting to explore models that allow the production of a GRB or any EM counterpart during black hole mergers. For example, in order to explain a GRB near the time of the black hole merger, Loeb (2016) proposed a model in which two black holes form via a bar instability inside a collapsing, rapidly rotating massive star. However, Woosley (2016) showed that only inside a star with extreme low metallicity and no mass-loss can two black holes of the desired masses form. The jet production in this model is similar to the 'collapsar' model for long GRBs (Woosley 1993; MacFadyen & Woosley 1999), except that an accretion–jet system forms around the binary black holes instead of forming from a single black hole. Woosley (2016) and Janiuk et al. (2017) also proposed a second model: In a binary stellar system of two massive stars, the more massive star collapses to a black hole first and then enters the envelope of the other star. Eventually, the core of the second star also collapses to a black hole, and an accretion disc–jet system forms around the binary black holes. There are also other models that involve a pre-existing accretion disc (e.g. Murase et al. 2016; Perna, Lazzati & Giacomazzo 2016; Stone, Metzger & Haiman 2016; Bartos et al. 2017) to explain an EM counterpart in double black hole mergers.

Several concerns have been expressed regarding these models. For example, Kimura, Takahashi & Toma (2017) perform a detailed calculation to explore the model of Perna et al. (2016), and find that

★ E-mail: cosimo@umd.edu

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the mass of the dead disc needs to be much greater than the mass of the disc proposed in Perna et al. (2016) to explain the accretion rate and observed GRB luminosity. As another example, Lyutikov (2016) found that the magnetic flux needed to trigger such a jet is as high as 10^{12} Gauss and is difficult to form in such environments.

In this Letter, we raise a concern that has been discussed extensively in the context of common envelopes (see the review by Ivanova et al. 2013) but so far has not received much attention in EM counterpart analyses. When two black holes orbit within a star, the heat produced by dynamical friction can eject most of the stellar material. If this happens, there may not be enough material to form a GRB once the two black holes merge, and thus the coalescence will be similar to a merger in vacuum. On the other hand, if dense stellar material is still around at merger, then the gravitational waveform can be different from that in vacuum. In the future, if dual EM–GW signals are observed from double stellar-mass black hole mergers, then one should need to include these considerations when proposing a stellar model to explain the EM counterpart.

In Section 2, we use a simple stellar model to calculate the heat generated by dynamical friction when two black holes spiral inside a star. We compare this heat with the binding energy of the star, and find that in most scenarios the injected heat is many times the binding energy. In Section 3, we calculate the coalescence time of the black holes including the effect of dynamical friction. We find that the gravitational radiation waveform can be modified from that in vacuum. In Section 4, we discuss some caveats such as whether the energy released can radiate away as neutrinos, and show EM observational signatures when the star unbinds. In the last section, we summarize and discuss our results.

2 HEAT PRODUCED BY DYNAMICAL FRICTION

As the two black holes orbit each other inside a star, dynamical friction and gravitational radiation reduce the separation between the black holes until they eventually merge. If dynamical friction dominates the inspiral, then most of the gravitational binding energy between the black holes is converted to heat. As we show in Section 2.1, the released gravitational energy can be many times greater than the self-binding energy of the star, which means that the inspiral has the potential to destroy the star.

We focus on dynamical friction because we believe that the energy released in this way is understood more robustly than the energy release from accretion on to the holes, which we do not include in our analysis. In a qualitative sense, the reason for the uncertainty in the accretion energy release involves two factors. First, the rate at which gas reaches a few gravitational radii from the holes (where the energy release is greatest) depends on highly uncertain physics involving winds and other processes (e.g. Miller 2015). Secondly, at the very super-Eddington accretion rates that would be expected in a dense gaseous environment such as a stellar interior, photon trapping could lead to extremely radiatively inefficient flows (Begelman 1978; Abramowicz et al. 1988), and the efficiency of such accretion is still under investigation (Ohsuga et al. 2005; Jiang, Stone & Davis 2014; McKinney, Dai & Avara 2015; Sądowski & Narayan 2016).

The injection of energy due to dynamical friction occurs on a length-scale $R_{\rm DF} \sim GM_{\rm BH}/(v^2 + c_{\rm s}^2)$, where $M_{\rm BH}$ is the black hole mass, G is the gravitational constant, $c_{\rm s}$ is the sound speed of the gas and v is the net speed of the hole relative to the gas. This is a far larger scale than the gravitational radius $R_{\rm g} = GM_{\rm BH}/c^2$ (c is the speed of light); indeed, if the stellar mass interior to the black hole orbit is less than or comparable to the black hole mass

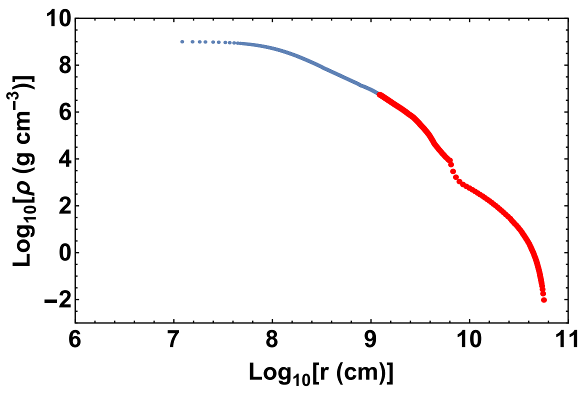

Figure 1. The density–radius plot of R150A when the central density reaches $\sim 10^9$ g cm^{-3}, when core collapse is about to start. The blue points show the inner portion of the star with a mass of 60 $M_\odot$, which can later collapse to two 30 $M_\odot$ black holes. The red points show the outer portion of the star with a mass of 90 $M_\odot$. Data kindly provided by S. Woosley.

then $R_{\rm DF}$ is comparable to the orbital radius. We do note that this same comparison of radii means that if most of the matter reaches the black holes and the resulting accretion is at least moderately radiatively efficient, then accretion could contribute significantly to the overall energy budget. Therefore, by only including the heat generated by dynamical friction, we get a conservative estimate of whether the star is disrupted.

There are several scenarios that can lead to two black holes orbiting inside a star from different initial separations. It is intuitive that the star has the best chance to survive when the black holes are formed very close to the centre of the star and little heat is injected during their short inspiral until merger. Therefore, we shall start from the close-origin scenario, and will carry out a quantitative analysis to show that the star can be destroyed even in this case.

2.1 Two black holes formed within one massive star

Woosley (2016) showed that when a fast-rotating massive star goes through chemically homogeneous evolution with no mass-loss, it is possible to form two black holes in the collapsing core due to bifurcation of angular momentum (Fryer, Woosley & Heger 2001; Reisswig et al. 2013). An example of a successful evolution is provided by his model R150A, in which the star has an initial mass of 150 $M_\odot$ in the main-sequence phase. Core collapse starts when the central density reaches $\sim 10^9$ g cm^{-3}. A snapshot of the density–radius profile at this stage is shown in Fig. 1. As the two black holes are formed in the centre, and the gravitational binding and thermal energy of the star are only $\sim$1 per cent of the rest-mass energy of the star, the initial inner 60 $M_\odot$ of the star (marked by blue points) will correspond to the part that collapses to form two 30 $M_\odot$ black holes. The outer envelope of 90 $M_\odot$ (marked by red points) will redistribute and surround the black holes during core collapse and later evolution.

Inspired by the R150 model, we consider a star with an initial mass of 150 $M_\odot$. We suppose that two black holes, each of mass 30 $M_\odot$, form at an initial distance $R_{\rm I}$ from the centre of the star during core collapse. As the two black holes spiral in, the core continues to collapse and accrete on to the black holes, so the density profile in the collapsing region will become different from Fig. 1. Woosley & Weaver (1995) show that when a massive star is in the pre-supernova phase, the density in the central region is approximately a power-law function of radius ρ–$\propto$–$r^{-\gamma}$ with an

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index up to $\gamma \sim 2.5$. When an accretion disc forms around the central black hole, the disc region has a density that is also a power-law function of radius, but with an index that is more likely to be $\gamma \sim 1.5$ (MacFadyen & Woosley 1999; Popham, Woosley & Fryer 1999). Here, we simplify by assuming that the stellar density profile in the central region where the black holes coalesce is a single, time-independent, power law. If the central density at R_c is ρ_c, then

$$\rho(r) = \rho_c \left(\frac{r}{R_c}\right)^{-\gamma}, \quad (1)$$

where R_c is taken to be the gravitational radius of a 30 $M_\odot$ black hole, which is 4.4×10^6 cm.

We wish to determine whether the star can withstand the heat produced during the binary black hole coalescence, as a function of ρ_c, γ and R_I. The stellar material needs to be dense enough to form black holes, so we consider a central density range $10^8 \leq \rho_c \leq 10^{12}$ g cm^{-3} (Popham et al. 1999). R_I has a lower limit of $R_c = 4.4 \times 10^6$ cm, and the star has the greatest likelihood of survival if R_I is as small as possible. We allow γ to vary between 1.5 (Bondi free-falling profile) and 2.5 (pre-supernova phase profile).

For the initial black hole separations of greatest interest, the gas mass within the black hole orbit is small compared to the masses of the black holes. In this situation, Escala et al. (2004) show that the gas close to the binary forms an ellipsoid, and the resulting tidal force between the ellipsoid and the outer spherical gas removes the orbital energy of the binary with an efficiency comparable to that of dynamical friction. Therefore, we assume that for each black hole, the heat is produced at the rate given by dynamical friction when the orbital speed v_{BH} is much greater than the sound speed c_s:

$$P_{DF} = 4\pi\rho(GM_{BH})^2 v_{BH}^{-1} \quad (2)$$

(Chandrasekhar 1943; Ostriker 1999), where ρ is the density of the ambient medium.

The maximum radiation power that can escape from the surface of the star is the Eddington luminosity $L_{Edd} \approx 2 \times 10^{40} (M/150\,M_\odot)$ erg s^{-1}. When each black hole is at a distance r from the centre, the instantaneous dynamical friction power is

$$P_{DF} = 10^{49.4+2.4\times(2.5-\gamma)} \frac{\rho_c}{10^8 \text{g cm}^{-3}} \left(\frac{r}{10^9 \text{cm}}\right)^{0.5-\gamma} \text{erg s}^{-1}. \quad (3)$$

P_{DF} is at least nine orders of magnitude above the Eddington luminosity, so heat cannot escape from the stellar envelope through radiative diffusion. Instead, the heat is expected to eject stellar mass. It is therefore important to determine whether the total injected energy exceeds the self-binding energy of the star. If it does, then the star could be destroyed. We note that in a standard common envelope scenario, the efficiency of converting black hole gravitational binding energy to eject gas is usually assumed to be $\lesssim 0.5$. However, our system is embedded deeply inside dense stellar material instead of a tenuous envelope, so the time needed for the energy to escape is much longer than the time needed for the holes to coalesce.

The total injected heat can be calculated by integrating the dynamical friction power along the path of the black hole inspiral. As the gravitational radiation power depends strongly on the separation, $P_{GR} \propto r^{-5}$, whereas the dynamical friction power $P_{DF} \propto r^{0.5-\gamma}$ has a much weaker dependence on radius, there is a distance R_{eq} at which the two contribute equally to the inspiral. When the black hole orbital radius $r > R_{eq}$, dynamical friction dominates and the injected heat is simply the change in the black hole gravitational binding energy as the binary orbit shrinks. In contrast, when $r < R_{eq}$, gravitational radiation takes over. Thus, in this phase, we compute the injected heat by integrating the P_{DF} along the pure gravitational inspiral path from R_{eq} until merger. Denser gas environment and a larger initial separation naturally lead to greater heat production.

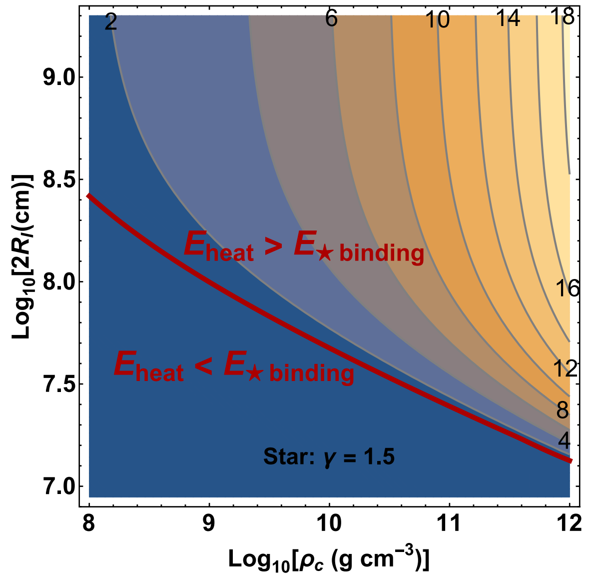

Figure 2. Contour plot of the ratio of total amount of dynamical-friction-generated heat to the stellar binding energy, during the coalescence of two 30 $M_\odot$ black holes within the remaining stellar material after core collapse. The value labelled on the contour is E_{heat}/E_B. The x-axis is the stellar central density, and the stellar density in the core region goes as $\rho(r) \propto r^{-1.5}$. The y-axis shows the initial separation between the two black holes. This figure shows that only when the two black holes are formed very close to each other (below the red curve) can the star survive the heat produced until merger. Otherwise, the heat is many times greater than the stellar binding energy, so it is hard for the star to withstand the heat and stay intact. When most of the stellar material is ejected, there may not be enough gas left to produce a detectable EM signal at merger.

We calculate the gravitational binding energy of the outer envelope of the star with 90 $M_\odot$ before core collapse happens. This envelope remains as gas surrounding the black holes after the core collapse, and heat produced during core collapse and black hole accretion can only be injected into it and make it less bound. Moreover, neutrino production is negligible in this envelope, so energy cannot escape efficiently. Therefore, the binding energy calculated this way is an upper bound to the net binding energy of the star after the formation of the black holes:

$$E_B \leq \int \frac{G(m(r) + 60M_\odot)}{r} 4\pi r^2 \rho(r) dr \approx 9.9 \times 10^{53} \text{erg}. \quad (4)$$

If E_{heat}, the total amount of heat produced by dynamical friction from R_I until merger, exceeds this maximum stellar binding energy, then the star can be disrupted.

We show the ratio of E_{heat} to E_B in Fig. 2 for $\gamma = 1.5$. It is clear that only when the two black holes form very close to each other (e.g. $R_I \lesssim 10^8$ cm when $\rho_c \geq 10^9$ g cm^{-3}) can the star survive the heat that is injected. A steeper density profile $\gamma = 2.5$ would allow the condition for the star to remain bound to be slightly relaxed (e.g. $R_I \lesssim 10^{8.5}$ cm when $\rho_c \geq 10^9$ g cm^{-3}).

2.2 Other scenarios

We have shown that the energy injected by dynamical friction is sufficient to destroy the star unless the black holes are formed

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extremely close to each other. It therefore follows that if the black holes are created *outside* the star, the star is extremely susceptible to destruction. Thus energy injection must be considered in all such scenarios. As an example, Woosley (2016) proposed that in a massive binary system, one star can evolve into a black hole and then spiral into the other star and, during the inspiral, the core of the second star can collapse to a black hole. Another possibility would be a triple system in which two massive stars collapse to black holes and are then enveloped by the third star when it becomes a giant.

It is likely that the nature of gas ejection will differ between specific scenarios. If the black holes are formed deep within the star then the injected energy might not have time to escape before the holes merge. This could result in an explosion that ejects the whole envelope. If instead the holes are created outside the star, it seems more likely that the stellar envelope will be gradually peeled off and thus that matter will be continuously unbound.

3 MODIFIED INSPIRAL INSIDE A STAR

When two black holes spiral inside a star instead of in vacuum, their coalescence time is shorter than the gravitational inspiral time-scale due to the effect of dynamical friction. As the GW frequency is twice the orbital frequency of the binary, the GW signal will sweep from low frequency to high frequency faster than in vacuum.

If the black holes are formed close enough so that the star stays intact until merger, we can observe modifications of the GW signal, as we show in Fig. 3. Therefore, GW signals can potentially disclose whether a merger happens in vacuum or in a star, and can be used to constrain the stellar parameters. For a star with $\rho_c \sim 10^9$ g cm^{-3}, it is hard to tell whether the 30 M$_\odot$ black holes merge inside a star or in vacuum with the current LIGO sensitivity. However, when ground-based detectors become more sensitive at lower frequencies, we will be able to see deviations between an inspiral inside a star and a gravitational inspiral. Advanced LIGO (aLIGO) can certainly tell if the inspiral is in vacuum or in a star with $\rho_c \gtrsim 10^{10}$ g cm^{-3}.

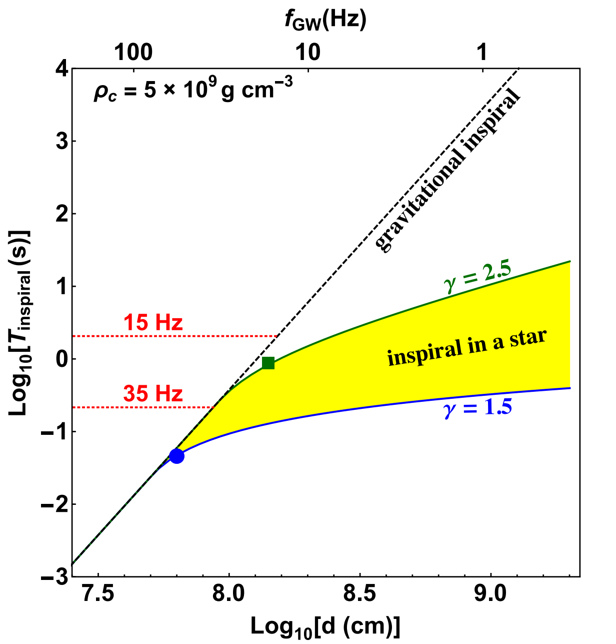

Figure 3. The remaining coalescence time (y-axis) of two 30 M$_\odot$ black holes in the stellar central region with $\rho_c = 5 \times 10^9$ g cm^{-3}, as a function of the distance d between two black holes (lower x-axis), or the corresponding GW frequency (upper x-axis). The black dashed line shows a gravitational inspiral in vacuum for comparison. The yellow-shaded region shows the inspiral within the star, taking account of how dynamical friction speeds up coalescence but assuming the star remains intact against heat. The blue curve uses a model with a density index $\gamma = 1.5$, and the blue circle indicates the initial distance between black holes which gives $E_{heat} = E_B$. The green curve uses a model with $\gamma = 2.5$, and the green square is the initial distance that gives $E_{heat} = E_B$. We note that, if the black holes are formed to the right of blue circle and the green square, the star is likely to be disrupted by the heat accumulated before merger. The two red dotted lines show the current and future LIGO sensitive low-frequency bands.

4 ELECTROMAGNETIC OBSERVATIONAL SIGNATURES AND CAVEATS

The total heat injected to the star by dynamical friction is $\gtrsim 10^{54}$ erg. This is ten times greater than the energy bucket in conventional supernovae. If all stellar gas is ejected at the same speed, it will have a terminal speed $v \gtrsim 0.1c$. ^{56}Ni can be produced as the temperature of the ejected material in the core goes beyond 5×10^9 K. These observational signatures are consistent with some of the superluminous supernovae (e.g. Gal-Yam 2012), though more quantitative studies need to be done for direct comparisons.

Similar to the scenario in a core-collapse supernova (Woosley & Janka 2005), if the stellar core reaches a very high temperature due to heat injected by dynamical friction, it can emit huge neutrino fluxes. We thank the referee for suggesting checking these fluxes.

If we assume that the total dynamical-friction-generated heat is evenly distributed in the region confined by the initial binary orbit, and the nucleons, photons, neutrinos, and (pair-produced) electrons and positrons are in thermal equilibrium, a direct calculation shows that their temperature will reach 10^{10-11} K. At this temperature, neutrino production through the pair neutrino process is enormous (Itoh et al. 1989) and neutrinos can carry away a significant portion of the heat. The neutrino–nucleon scattering dominates the neutrino opacity in the dense core region, and its cross-section is $\sigma \sim 10^{-44}$ cm^2 $(\epsilon / m_e c^2)^2$, where ϵ is the energy of the neutrino and m_e is the electron rest mass (Ruffert, Janka & Schaefer 1996). We then show in Fig. 4 that when the stellar density is high ($\rho_c \gtrsim 10^{9.5}$ g cm^{-3}), the stellar medium is optically thick for neutrinos, so a fraction of the energy and angular momentum carried by neutrinos will be deposited to the star. In order to determine how much neutrino energy can serve to unbind the star, a self-consistent, multidimensional simulation (including convective instability and magnetic modifications) is needed to treat the physics carefully (e.g. Bethe 1993; Woosley & Janka 2005). We hope the qualitative discussions in this Letter can inspire more quantitative analysis on this topic.

In reality, heat is gradually injected as black holes spiral in. If the core can respond quickly and expand, its temperature will not increase so much. We calculate the sound-crossing time of the core, and compare it to the inspiral time in Fig. 4. When the stellar density is low, the inspiral time is longer than the sound-crossing time. This means that the core will heat up less and probably not produce an enormous amount of neutrinos. Therefore, the star is likely to unbind in this regime.

We emphasize that the destruction of the star is not necessarily absolute also due to other considerations. We have a complex system, so there can be ways that a small amount of matter can remain in the system. For example, if the gas is Rayleigh–Taylor unstable, then it is conceivable that some mass could reach the holes in dense filaments, although some simulations in the possibly comparable context of Bondi–Hoyle accretion on to black holes find that such filaments are easily evaporated (e.g. Park & Ricotti 2011, 2012). Focused high-resolution simulations in the stellar context would be

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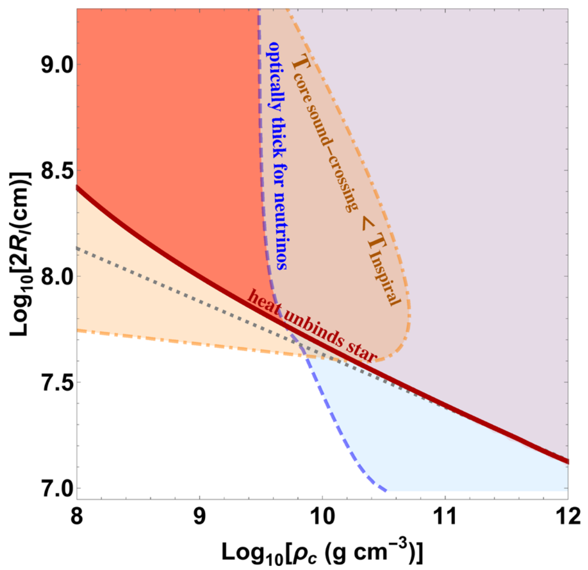

Figure 4. This plot shows various regimes. The *x* and *y*-axes are the same as in Fig. 2. The shaded region above the red solid line shows when the dynamical friction generated heat can unbind the star. Most of the heat is injected before gravitational radiation takes over dynamical friction (the grey dotted line). The shaded region to the right of the blue dashed line shows when the stellar medium is optically thick for the neutrinos produced in the core. The shaded region to the left of the orange dot–dashed line shows when the sound-crossing time of the core is shorter than the binary inspiral time.

needed to address this question. For the putative *Fermi* counterpart to GW150914, only $\sim 10^{-5}\,M_{\odot}$ of gas is required for the observed EM power (Connaughton et al. 2016). It will be difficult to rule out such a small retention fraction. However, any model that proposes an EM counterpart due to inspiral inside a star will need to make a clear case that significant matter can remain bound despite the large amount of energy that is injected due to dynamical friction.

5 SUMMARY

When two black holes orbit within a star, they have the potential to produce joint EM–GW signals. Here, we find that the heat produced because of dynamical friction between the black holes and the stellar medium is energetically sufficient to eject all of the gas from the system, which would therefore make it hard to produce detectable EM signals close to merger. These considerations apply to any model that uses a star to provide material for the EM signal, for example, formation of two black holes inside one star, or one black hole entering another star (and eventually merging with the black hole collapsed from its core), or two black holes entering a third star.

If such scenarios do play out in nature, they can lead to new observational signatures in both the EM and GW domains. If heat generated during the coalescence is orders of magnitude higher than the stellar binding energy, as we demonstrated, the result could be a violent explosion. The energy scale of the explosion would be much larger than a conventional supernovae and the speed of gas can reach $\gtrsim$10 per cent of the speed of the light. On the other hand, if the star can stay intact until merger, dynamical friction will make the black holes coalesce faster than they would in vacuum. Therefore, the GW signal can have a different waveform than that from a gravitational inspiral in vacuum. This effect could be detected with ground-based instruments (such as aLIGO) with improved sensitivity at low frequencies, and should be included in the templates used to search for GW signals from double black hole mergers. When such modified gravitational waveforms are detected in the future, one can more efficiently conduct a search for the associated EM signals.

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