

Electromagnetic transients and gravitational waves from white dwarf disruptions by stellar black holes in triple systems

Giacomo Fragione¹,^{1,2,3}★ Brian D. Metzger,⁴ Rosalba Perna,^{5,6} Nathan W. C. Leigh^{7,8} and Bence Kocsis⁹

¹Department of Physics & Astronomy, Northwestern University, Evanston, IL 60202, USA

²Center for Interdisciplinary Exploration & Research in Astrophysics (CIERA), Evanston, IL 60202, USA

³Racah Institute for Physics, The Hebrew University, Jerusalem 91904, Israel

⁴Department of Physics, Columbia University, New York, NY 10027, USA

⁵Department of Physics and Astronomy, Stony Brook University, Stony Brook, NY 11794, USA

⁶Center for Computational Astrophysics, Flatiron Institute, New York, NY 10010, USA

⁷Departamento de Astronomía, Facultad de Ciencias Físicas y Matemáticas, Universidad de Concepción, Concepción, Chile

⁸Department of Astrophysics, American Museum of Natural History, New York, NY 10024, USA

⁹Institute of Physics, Eötvös University, Pázmány P. s. 1/A, Budapest, 1117, Hungary

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ABSTRACT

Mergers of binaries comprising compact objects can give rise to explosive transient events, heralding the birth of exotic objects that cannot be formed through single-star evolution. Using a large number of direct N -body simulations, we explore the possibility that a white dwarf (WD) is dynamically driven to tidal disruption by a stellar-mass black hole (BH) as a consequence of the joint effects of gravitational wave (GW) emission and Lidov–Kozai oscillations imposed by the tidal field of an outer tertiary companion orbiting the inner BH–WD binary. We explore the sensitivity of our results to the distributions of natal kick velocities imparted to the BH and WD upon formation, adiabatic mass loss, semimajor axes and eccentricities of the triples, and stellar-mass ratios. We find rates of WD–tidal disruption events (TDEs) in the range $1.2 \times 10^{-3} - 1.4 \text{ Gpc}^{-3} \text{ yr}^{-1}$ for $z \leq 0.1$, rarer than stellar TDEs in triples by a factor of ~ 3 –30. The uncertainty in the TDE rates may be greatly reduced in the future using GW observations of Galactic binaries and triples with *LISA*. WD–TDEs may give rise to high-energy X-ray or gamma-ray transients of duration similar to long gamma-ray bursts but lacking the signatures of a core-collapse supernova, while being accompanied by a supernova-like optical transient that lasts for only days. WD–BH and WD–NS binaries will also emit GWs in the *LISA* band before the TDE. The discovery and identification of triple-induced WD–TDE events by future time domain surveys and/or GWs could enable the study of the demographics of BHs in nearby galaxies.

Key words: stars: kinematics and dynamics – stars: supernovae: general – stars: white dwarfs – stars: black holes – galaxies: kinematics and dynamics.

1 INTRODUCTION

Mergers of binaries comprising two compact objects have been the subject of numerous theoretical investigations over the past several years. This interest is motivated in part by the fact that such binaries give rise to explosive and potentially luminous transient events, which leave behind exotic objects that cannot otherwise form from

single stars at the end of their lifetimes. The coalescence of binary stellar black holes (BHs) and neutron stars (NSs) has been observed by LIGO–Virgo via their gravitational wave (GW) emission (The LIGO Scientific Collaboration & the Virgo Collaboration 2019). Thanks to the discovery of gamma-ray and non-thermal afterglow emission in coincidence with the LIGO-detected merger GW170817 (Abbott et al. 2017), binary NS mergers are now the confirmed progenitor of at least one short gamma-ray burst (GRB). NS–BH mergers may also produce short GRBs, at least for small mass ratios and high BH spin such that the NS is tidally disrupted

* E-mail: giacomo.fragione@northwestern.edu

outside of the BH horizon (e.g. Foucart, Hinderer & Nissanke 2018). The coalescence of binary white dwarfs (WDs) provides a likely pathway to produce Type Ia supernovae (SNe; Katz & Dong 2012; Maoz, Mannucci & Nelemans 2014; Hamers 2018; Livio & Mazzali 2018; Toonen, Perets & Hamers 2018a)

Mergers of NS–WD and BH–WD binaries are expected to occur as well. To date, ~ 20 NS–WD binaries have been confirmed in our Galaxy (van Kerkwijk et al. 2005), while only one field BH–WD binary candidate is presently known (Bahramian et al. 2017). In such binaries, the WD may approach the NS or BH close enough to be disrupted as a tidal disruption event (WD–TDE). For example, such coalescence events could result from GW emission in isolation (Metzger 2012) or as a consequence of non-coherent scatterings in star clusters (Leigh et al. 2014; Kremer et al. 2019).

What makes the mergers of NS–WD and BH–WD binaries of particular interest is the possibility that they could generate peculiar transients. Several works have characterized the possible electromagnetic (EM) signatures of the tidal disruption of a WD by an NS or a BH (Fryer et al. 1999; King, Olsson & Davies 2007; Metzger 2012; Fernández & Metzger 2013; Margalit & Metzger 2016; Bobrick, Davies & Church 2017; Toonen et al. 2018a; Fernández, Margalit & Metzger 2019; Zenati, Perets & Toonen 2019). In particular, such events may produce a high-energy transient similar to a GRB, or thermal emission similar to a short-lived supernova (Metzger 2012; Zenati et al. 2019). Interesting is also the case in which the WD is disrupted by an intermediate-mass black hole (IMBH; Rosswog, Ramirez-Ruiz & Hix 2008; MacLeod et al. 2016; Fragione et al. 2018); tidal compression during such WD–IMBH events could generate a large quantity of ^{56}Ni capable of powering a peculiar Type Ia-like supernova. NS–WD, BH–WD, and IMBH–WD encounters also produce GW emission up to the point of disruption, observable by the planned *LISA* detector.

In this paper, given the preponderance of triples in the Galaxy (e.g. Leigh & Geller 2013), we explore a new triple channel of WD–BH merger events, in which the WD is driven sufficiently close to the BH to be tidally disrupted as a consequence of the joint effect of GW emission and Lidov–Kozai (LK) evolution imposed by the tidal field of a third companion that orbits the BH–WD binary. We start from the progenitors of the BH and WD and model the effects of natal kicks during the formation of the compact objects (e.g. BH birth in a supernova) and the survival of the triples. Given the many uncertainties involved in the modelling of binary evolution, we explore a variety of models that make different assumptions about the distributions of natal kicks, semimajor axes and eccentricities of the triple, and initial stellar-mass ratios. In total, we run $\sim 10^4$ direct *N*-body simulations to explore the prospects for BH–WD systems. We determine how the probability of a WD–TDE depends on these assumptions, map the parameter distributions of merging systems back to the initial distributions, and compute the WD–TDE rate in the Universe through the triple channel.

The paper is organized as follows. In Section 2, we present our numerical methods and describe the properties of the triple population that we evolve. In Section 3, we discuss the parameters of the merging systems. The implications for possible EM counterparts are presented in Section 4, and for GWs in Section 5. Finally, in Section 6, we discuss the implications of our findings and draw our conclusions.

2 TRIPLE POPULATION

General schemes for population synthesis in triples have been developed by a number of authors (Perets & Kratter 2012; Toonen,

Hamers & Portegies Zwart 2016; Toonen, Perets & Hamers 2018b; Toonen et al. 2018c). The stellar triples in our simulations are initialized as follows. In total, we consider nine different sets of initial conditions (see Table 1).

In all models, we adopt the Kroupa (2001) initial mass function in the relevant mass range

$$f(m) = 0.0795 M_{\odot}^{-1} (m/M_{\odot})^{-2.3} \quad \text{if } m \geq 0.5 M_{\odot}, \quad (1)$$

where the constant coefficient takes into account the fraction of stars with $m < 0.5 M_{\odot}$ such that the integral of $\int_0^{\infty} f(m) dm = 1$. We draw the stellar progenitor of the most massive star in the inner binary m_1 from the mass range $20 M_{\odot}$ – $150 M_{\odot}$, which we assume collapses to a BH. The exact value of the BH mass depends on details of the stellar evolution related to, for example, metallicity, stellar winds, and rotation. However, for simplicity, we assume that $M_{\text{BH}} = m_1/3$ (Sillsbee & Tremaine 2017; Fragione et al. 2019b). In our *fiducial* model, we adopt a flat mass ratio distribution for both the inner and outer orbit (Sana et al. 2012; Duchêne & Kraus 2013).¹ The mass of the secondary in the inner binary is sampled within the range of 1 – $8 M_{\odot}$. We assume that this star gives birth to a WD of mass (Hurley, Pols & Tout 2000)

$$M_{\text{WD}} = 0.109 m_2 + 0.394 \quad (2)$$

and radius

$$R_{\text{WD}} = \max \left[10 \text{ km}, 0.01 R_{\odot} \sqrt{\left(\frac{M_{\text{ch}}}{M_{\text{WD}}} \right)^{2/3} - \left(\frac{M_{\text{WD}}}{M_{\text{ch}}} \right)^{2/3}} \right], \quad (3)$$

where $M_{\text{ch}} = 1.44 M_{\odot}$ is the Chandrasekhar mass. The mass of the third companion (m_3) is drawn from the range of 0.5 – $150 M_{\odot}$. We note that we assume that if the mass of the tertiary is in the range of 1 – $8 M_{\odot}$, it generates a WD, if in the range of $8 M_{\odot}$ – $20 M_{\odot}$, it collapses to an NS of mass $1.3 M_{\odot}$, and if in the range of $20 M_{\odot}$ – $150 M_{\odot}$ it collapses to a BH of mass $m_3/3$ (Sillsbee & Tremaine 2017). We run one model where all the masses are drawn independently from each other from equation (1). For comparison, we also estimate how the final WD–TDE rate changes if the mass ratio distribution is assumed to be log-uniform (Sana et al. 2013). The distributions of the inner and outer semimajor axes, a_{in} and a_{out} (respectively), are assumed to be log-uniform (Kobulnicky et al. 2014), but we also consider a model with uniform distributions of inner and outer semimajor axes. Other alternatives would include lognormal and other power laws (Moe & Di Stefano 2017; Igoshev, Perets & Michaely 2019). We set as a minimum initial orbital separation $a_{\text{in}}(1 - e_{\text{in}}^2) \approx 10 \text{ AU}$ to avoid mass transfer (e.g. Antonini, Toonen & Hamers 2017) and adopt different values for the initial maximum separation of the triple $a_3^{\text{max}} = 2000 \text{ AU}$ – 5000 AU – 7000 AU (Sana et al. 2014). For what concerns the orbital eccentricities e_{in} and e_{out} , we assume flat distributions (e.g. Geller et al. 2019). For comparison, we run one additional model where we take a thermal distribution of eccentricities. Finally, the initial mutual inclination i between the inner and outer orbits is drawn

¹ Note that this is different from Sillsbee & Tremaine (2017), who assumed a log-uniform mass ratio distribution, $f(q) \propto q^{-1}$. Duchêne & Kraus (2013) find that $f(q) \propto q^{1.16 \pm 0.16}$ and $q^{-0.01 \pm 0.03}$ for solar-type stars with period less than or larger than $10^{5.5} \text{ d}$, respectively, while Sana et al. (2013) find $f(q) \propto q^{-1.0 \pm 0.4}$ for massive O-type stars.

Table 1. Models: name, mean of WD kick-velocity distribution (σ), eccentricity distribution ($f(e)$), maximum outer semimajor axis of the stellar progenitor triple (a_3^{\max}), fraction of stable systems after SNe (f_{stable}), fraction of WD–TDEs from the N -body simulations ($f_{\text{WD-TDE}}$), and fraction of stable systems assuming adiabatic mass loss ($f_{\text{stable}}^{(\text{ad})}$).

Name	σ_{BH} (km s $^{-1}$)	σ_{WD} (km s $^{-1}$)	$f(q)$	$f(a)$	$f(e)$	a_3^{\max} (AU)	f_{stable}	$f_{\text{WD-TDE}}$	$f_{\text{stable}}^{(\text{ad})}$
A1	34	0.5	Uniform	Log-uniform	Uniform	5000	7.2×10^{-5}	0.21	4.6×10^{-4}
A2	13	0.5	Uniform	Log-uniform	Uniform	5000	5.2×10^{-4}	0.15	5.1×10^{-3}
A3	0	0.5	Uniform	Log-uniform	Uniform	5000	1.2×10^{-2}	0.16	2.4×10^{-1}
A4	0	0	Uniform	Log-uniform	Uniform	5000	1.1×10^{-2}	0.14	2.1×10^{-1}
B1	34	0.5	Uniform	Uniform	Uniform	5000	1.6×10^{-5}	0.19	4.9×10^{-5}
C1	34	0.5	Uniform	Log-uniform	Thermal	5000	1.0×10^{-4}	0.20	4.7×10^{-4}
D1	34	0.5	Uniform	Log-uniform	Uniform	2000	1.0×10^{-4}	0.28	6.6×10^{-4}
D2	34	0.5	Uniform	Log-uniform	Uniform	7000	7.3×10^{-5}	0.24	5.0×10^{-4}
E1	34	0.5	–	Log-uniform	Uniform	5000	1.7×10^{-3}	0.31	9.4×10^{-3}

from an isotropic distribution, while the other relevant angles are drawn from uniform distributions.²

After sampling the relevant parameters, we check that the initial configuration satisfies the stability criterion of Mardling & Aarseth (2001) for stable hierarchical triples. If this is not the case, we sample again the triple parameters as explained above. Otherwise, we let the primary star in the inner binary undergo an SN explosion and instantaneously convert it to a BH. We note that in reality, not all the mass is ejected during the SN process, but part of it can be lost previously through stellar winds (Perets & Kratter 2012; Michaely & Perets 2014, 2019). As a consequence, the Blaauw kick due to mass loss would be typically smaller, thus possibly unbinding a smaller number of triples. As a result of the mass loss, the exploding star is imparted a kick to its centre of mass (Blaauw 1961), and the system receives a natal kick due to recoil from an asymmetric supernova explosion. We assume that the BH natal velocity kick is drawn from a Maxwellian distribution

$$p(v_k) \propto v_k^2 e^{-v_k^2/\sigma^2}, \quad (4)$$

with a mean velocity σ . We implement momentum-conserving kicks, in which we assume that the momentum imparted to a BH is the same as the momentum given to an NS (Fryer & Kalogera 2001). As a consequence, the kick velocities for the BHs are lowered by a factor of $1.4 M_{\odot}/M_{\text{BH}}$ with respect to those of NSs. The value of σ is highly uncertain. We adopt $\sigma = 260 \text{ km s}^{-1}$ for NSs, consistent with the distribution deduced by Hobbs et al. (2005), but we also run an additional model where we set $\sigma = 100 \text{ km s}^{-1}$, consistent with the distribution of natal kicks found by Arzoumanian, Chernoff & Cordes (2002). We also explore a model where no natal kick is imparted during BH formation.

We update the orbital elements of the triple as appropriate (Pijloo, Caputo & Portegies Zwart 2012; Lu & Naoz 2019; Fragione et al. 2019b), checking that the new configuration satisfies the stability criterion for stable hierarchical triples (Mardling & Aarseth 2001). If the system remains stable, we assume that the secondary forms a WD. Also in this case, we assume that the WD natal velocity kick is drawn from a Maxwellian distribution. We consider both models in which the WDs receive no natal velocity kick ($\sigma_{\text{WD}} = 0 \text{ km s}^{-1}$) and models where the mean velocity is $\sigma_{\text{WD}} = 0.5 \text{ km s}^{-1}$. This is consistent with the new findings of El-Badry & Rix (2018), who found breaks in the separation distribution of MS–WD and WD–WD binaries in *Gaia* data, which could be explained if WDs

incur a natal velocity kick at their formation,³ with a magnitude of $\sim 0.75 \text{ km s}^{-1}$. After the second SN event, we update again the orbital elements of the triple and again check that it is stable. Finally, if the third companion is more massive than $1 M_{\odot}$, we let it undergo conversion into a WD, NS, or BH of mass $m_3^{\text{fin}} = 0.109 m_3 + 0.394$, $m_3^{\text{fin}} = 1.3 M_{\odot}$, $m_3^{\text{fin}} = m_3/3$, if $1 M_{\odot} \leq m_3 < 8 M_{\odot}$, $8 M_{\odot} \leq m_3 < 20 M_{\odot}$, $m_3 > 20 M_{\odot}$, respectively. If $m_3 < 1$, then $m_3^{\text{fin}} = m_3$. Many systems turn out to occupy a quasi-secular regime, for which the behaviour is somewhat different and more chaotic than the secular LK mechanism (Antonini & Perets 2012; Fragione et al. 2019a).

Table 1 reports the fraction of systems that are stable after all the SNe have taken place; this is denoted by f_{stable} for each of our models.

We integrate the triple systems by means of the ARCHAIN code (Mikkola & Merritt 2006, 2008), including PN corrections up to order PN2.5. We perform ~ 1000 simulations for each model in Table 1 and impose a number of stopping conditions as follows:

(i) The system undergoes 1000 LK cycles, i.e. the total time exceeds $1000 T_{\text{LK}}$, where the triple LK time-scale is

$$T_{\text{LK}} = \frac{8}{15\pi} \frac{m_{\text{tot}}}{m_3^{\text{fin}}} \frac{P_{\text{out}}^2}{P_{\text{in}}} (1 - e_{\text{out}}^2)^{3/2}, \quad (5)$$

where $m_{\text{tot}} = M_{\text{BH}} + M_{\text{WD}} + m_3^{\text{fin}}$ and P_{in} and P_{out} are the inner and outer orbital periods, respectively.

(ii) The WD is tidally disrupted by the BH in the inner binary due to a high orbital eccentricity. This occurs whenever their relative distance becomes smaller than the tidal disruption radius,

$$R_t = R_{\text{WD}} \left(\frac{M_{\text{BH}}}{M_{\text{WD}}} \right)^{1/3}. \quad (6)$$

(iii) The system age exceeds 10 Gyr.

3 RESULTS

3.1 Inclination

A BH–WD binary is expected to be significantly perturbed by the tidal field of the third companion whenever its orbital plane is sufficiently inclined with respect to the outer orbit (Kozai 1962; Lidov 1962). Fig. 1 shows the inclination probability distribution

²Tokovinin (2017) has shown that low-mass triples with separations $\lesssim 1000$ AU have a much flatter configuration.

³This could reflect the mass loss in the intermediate regime between prompt and adiabatic mass loss, rather than a natal kick.

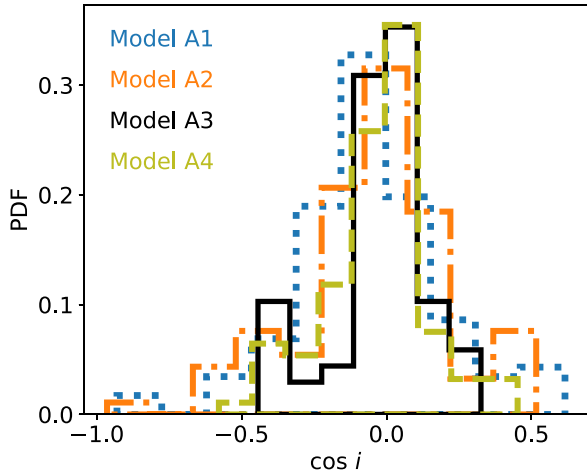


Figure 1. Inclination PDF of merging BH–MS binaries in triples for $a_3^{\max} = 5000$ AU and different values of the mean kick velocity σ_{BH} and σ_{WD} (models A1–A4).

function (PDF) of systems that lead to a WD–TDE. We show the distributions for $a_3^{\max} = 5000$ AU and different values of σ_{BH} and σ_{WD} , models A1–A4 (see Table 1). Most of the WD–TDEs in triples occur when the inclination approaches $\sim 90^\circ$, since in this case the LK mechanism is efficient at pumping e_{in} up to unity.

3.2 Mass of black hole and white dwarf

Fig. 2 shows the cumulative distribution function (CDF) of M_{BH} (top panel) and M_{WD} (bottom panel) for systems that produce a WD–TDE for models A1–A4. Systems with high values of σ_{BH} prefer higher BH masses. This is explained by our assumption of momentum-conserving kicks, where BHs receive a kick scaled by $1/M_{\text{BH}}$. Thus, more massive BHs are imparted lower velocity kicks on average and are more likely to be retained in bound triples, which eventually produce a WD–TDE. The distribution of the mass of the WDs does not display a strong dependence on the assumed mean velocity kicks for BHs and WDs.

3.3 Inner and outer semimajor axes

The choice of σ_{BH} affects the distribution of the orbital parameters of BH–WD systems that lead to a WD–TDE. Fig. 3 shows the CDF of the inner (left) and outer (right) semimajor axes (top) and eccentricities (bottom) of BH–WD binaries in triples that lead to a WD–TDE for different values of σ_{BH} and σ_{WD} . As also shown in Fragione et al. (2019b), we find that larger mean natal kicks imply smaller inner and outer semimajor axes. This is because high-velocity kicks preferentially unbind triple systems with wide orbits. The inner and outer eccentricities, however, do not depend on the assumed value of σ_{BH} . Also, the value of σ_{WD} does not affect the distribution of the orbital elements of systems that produce a WD–TDE.

Fig. 4 shows how the distributions of a_{in} and a_{out} of BH–WD systems that lead to a WD–TDE depend on the initial distribution of the orbital elements and a_3^{\max} . We find that larger values of a_3^{\max} lead to larger inner and outer semimajor axes, though the dependence on this parameter is not significant. Model C1, where

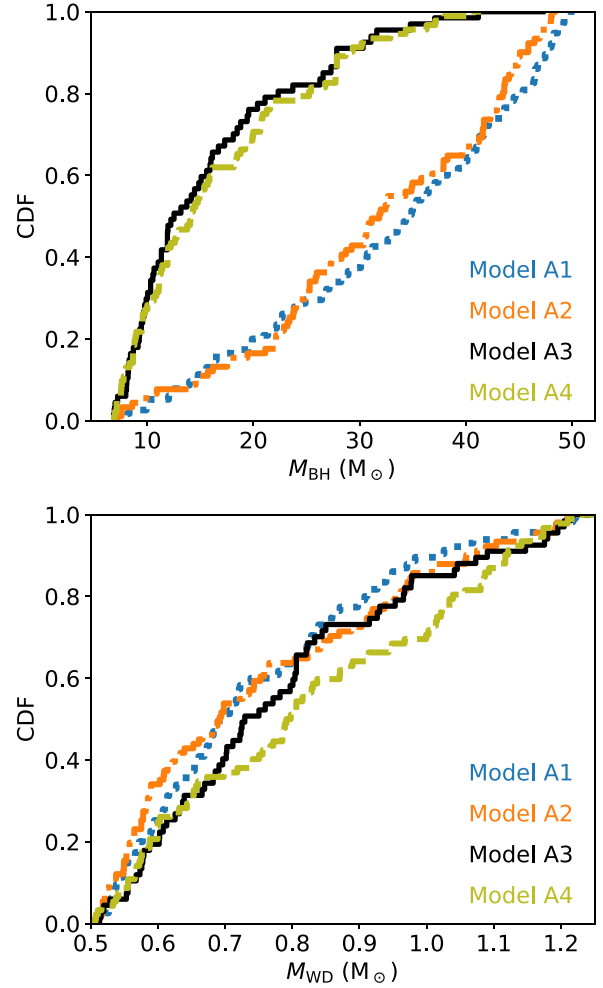


Figure 2. Cumulative distribution function of the mass of BHs (top) and WDs (bottom) in BH–WD binaries in triples that lead to a WD–TDE for different values of σ_{BH} and σ_{WD} (models A1–A4).

an initial thermal distribution of e_{in} and e_{out} is assumed, predicts a distribution similar to model D2, where $a_3^{\max} = 7000$ AU. The CDFs are significantly affected by the choice of the initial distribution for a_{in} and a_{out} . We find that ~ 50 per cent of the BH–WD systems that lead to a WD–TDE have $a_{\text{in}} \lesssim 50$ AU and $a_{\text{out}} \lesssim 1000$ AU in model A1 ($f(a)$ log-uniform) and $a_{\text{in}} \lesssim 200$ AU and $a_{\text{out}} \lesssim 5000$ AU in model B1 ($f(a)$ uniform). Also in this case, the distributions for e_{in} and e_{out} do not depend on the details of the initial conditions.

3.4 Rates

Fig. 5 reports the distribution of WD–TDE times for all models (see Table 1). The shape of these CDFs is quite universal and does not depend on the assumed value of the mean kick velocity for BHs and WDs, nor on the initial distribution of semimajor axes and eccentricities. In order to compute the WD–TDE rate from BH–WD mergers in triples, we follow a similar calculation to that in Silsbee & Tremaine (2017) and in Fragione et al. (2019b). We assume that the local star formation rate is $\eta_{\text{SFR}} = 0.025 \text{ M}_\odot \text{ Mpc}^{-3} \text{ yr}^{-1}$; thus, the number of stars formed per unit mass, volume, and

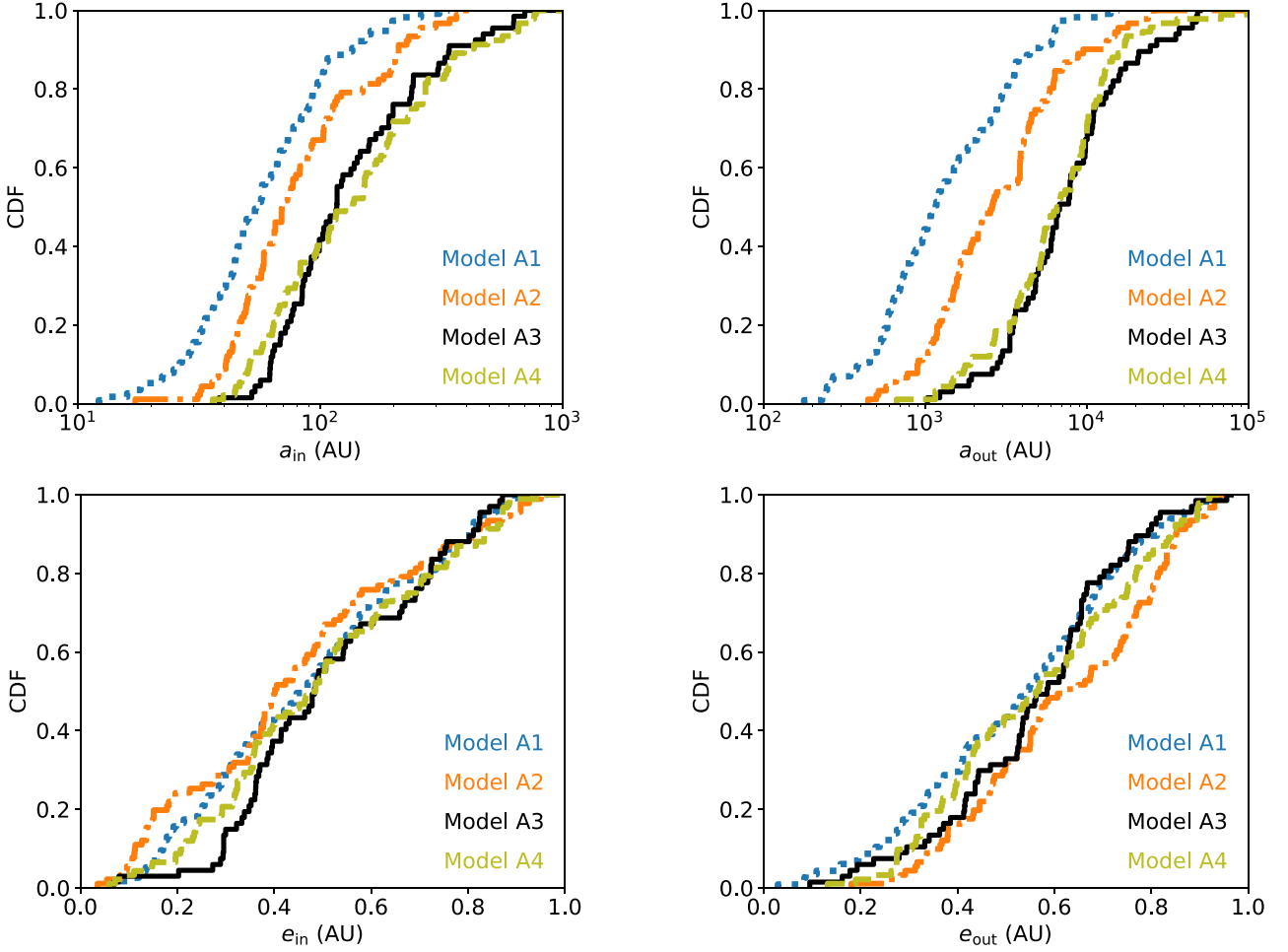


Figure 3. Cumulative distribution function of the initial inner (left) and outer (right) semimajor axes (top) and eccentricities (bottom) of BH–WD binaries in triples that lead to a WD–TDE for different values of σ_{BH} and σ_{WD} (models A1–A4).

time is given by (Bothwell et al. 2011)

$$\begin{aligned} \dot{n}(m) &= \frac{\eta_{\text{SFR}} f(m)}{\langle m \rangle} \\ &= 5.2 \times 10^6 \left(\frac{m}{M_{\odot}} \right)^{-2.3} M_{\odot}^{-1} \text{Gpc}^{-3} \text{yr}^{-1}, \end{aligned} \quad (7)$$

where $\langle m \rangle = 0.38 M_{\odot}$ is the average stellar mass. Adopting a constant star formation rate, the WD–TDE rate in triples is then,

$$\begin{aligned} \mathcal{R}_{\text{WD-TDE}} &= \eta(1 - \kappa)(1 - \zeta)f_3 \\ &\quad \times f_{\text{stable}} f_{\text{WD-TDE}} \int_{20 M_{\odot}}^{150 M_{\odot}} \dot{n}(m_1) dm_1 \\ &= 7.4 \times 10^4 \eta(1 - \kappa)(1 - \zeta)f_3 \\ &\quad \times f_{\text{stable}} f_{\text{WD-TDE}} \text{Gpc}^{-3} \text{yr}^{-1}. \end{aligned} \quad (8)$$

Here, f_3 is the fraction of stars in triples, f_{stable} is the fraction of sampled systems that are stable after the SN events take place, and $f_{\text{WD-TDE}}$ is the fraction of systems that produce a WD–TDE (see Table 1). The factor η assures that, when sampling the mass ratio q_{12} of the inner binary, the secondary ($1 M_{\odot} \leq m_2 = q_{12}m_1 \leq 8 M_{\odot}$)

produces a WD,

$$\eta = \frac{\int_{0.01 M_{\odot}}^{150 M_{\odot}} dm_1 f_{\text{IMF}}(m_1) \int_{1 M_{\odot}/m_1}^{8 M_{\odot}/m_1} dq_{12} f_q(q_{12})}{\int_{20 M_{\odot}}^{150 M_{\odot}} dm_1 f_{\text{IMF}}(m_1)}, \quad (9)$$

where $f_q(q_{12})$ is the mass ratio distribution of the inner binary. We get $\eta = 0.21$ and $\eta = 0.25$ for uniform and log-uniform mass ratio distributions, respectively. The factors ζ and κ take into account two main processes during the earlier evolution of the system, which prohibit a WD–TDE (Shappee & Thompson 2013). The first comes from the fact that stellar triples can merge during their main sequence (MS) life before the primary forms a BH as a result of the LK dynamics, which we have not modelled here. To estimate ζ , we conservatively consider that all stellar triples whose initial LK time-scale is less than the lifetime of the primary star (~ 7 Myr; Iben 1991; Hurley et al. 2000; Maeder 2009) in the inner binary merge as MS stars (Rodríguez & Antonini 2018). We find that the fraction of these triples is $\zeta \sim 0.60$ on average, except for model A3 and model A4 where we find $\zeta \sim 0.35$. Furthermore, we check the fraction of systems that produce a stellar mean sequence TDE instead of a WD–TDE, i.e. before the secondary star in the inner binary forms a WD. We estimate this fraction to be $\kappa \sim 0.15$ from the results of Fragione et al. (2019b).

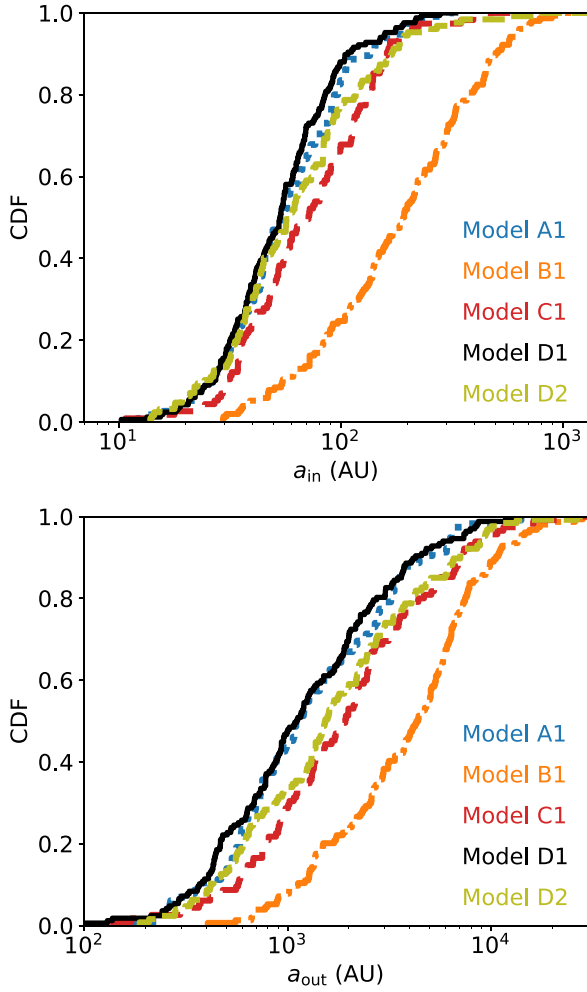


Figure 4. Cumulative distribution function of the inner (left) and outer (right) semimajor axes (top) and eccentricities (bottom) of BH–WD binaries in triples that lead to a WD–TDE for different initial distributions of semimajor axes and eccentricities.

In our calculations, we adopt for the triple fraction $f_3 = 0.25$ and $f_{\text{WD-TDE}} \sim 0.21$ on average (see Table 1). The fraction of stable systems after the SNe depends on the value of σ_{BH} and σ_{WD} and on the details of the distributions of initial parameters. We report f_{stable} for all our models in Table 1. Using the minimum and maximum values of f_{stable} in Table 1, our final estimated WD–TDE rate is in the range,

$$\mathcal{R}_{\text{WD-TDE}} = (4.1 \times 10^{-3} - 4.8) \text{ Gpc}^{-3} \text{ yr}^{-1}. \quad (10)$$

For a log-uniform distribution of mass ratios, we estimate a rate ~ 1.5 times larger. Considering the signal up to $z = 0.1$, the WD–TDE rate becomes,

$$\Gamma_{\text{WD-TDE}}(z \leq 0.1) = (1.2 \times 10^{-3} - 1.4) \text{ yr}^{-1}. \quad (11)$$

We can also estimate the WD–TDE rate in triples for a Milky Way-like galaxy. Assuming momentum-conserving natal kicks and a star formation rate of $1 \text{ M}_{\odot} \text{ yr}^{-1}$ (Licquia & Newman 2015), we obtain

$$\Gamma_{\text{WD-TDE}}^{\text{MW}} = (4.8 \times 10^{-11} - 5.7 \times 10^{-8}) \text{ yr}^{-1}. \quad (12)$$

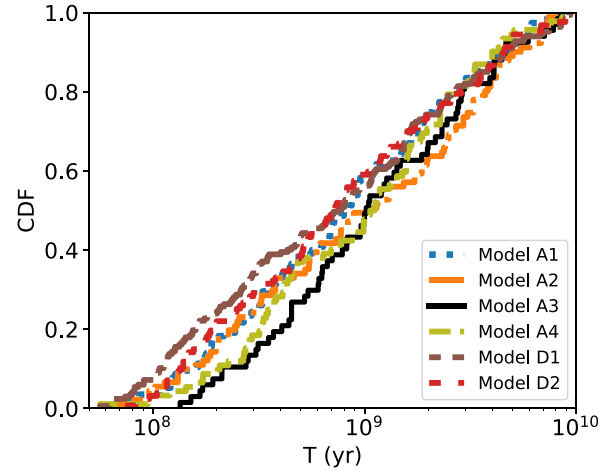


Figure 5. WD–TDE time distribution (after the SN event) of BH–WD binaries in triples that lead to a WD–TDE for all models (see Table 1).

Finally, we note that we are not taking into consideration fallback in our calculations, whose effect would be to increase the WD–TDE rates for large σ_{BHs} since it would give smaller natal kick velocities.

3.5 The role of the mass loss prior to supernovae

In our simulations, we assume that the SN events take place instantaneously and do not simulate the systems during the MS lifetime of the progenitors and the eventual mass loss prior to the SN explosion. Mass loss prior to SN events could change not only the binding energy of the triples but also the effective mass ratios of the inner and outer components, semimajor axes, and eccentricities. This, along with kicks (taking place in wider systems), could affect the evolution of the triples consisting of an inner BH–WD binary.

To quantify the role of mass loss prior to SN, we now consider the impact of slow (adiabatic) and isotropic mass loss. Adiabatic mass loss drives the orbits of two objects to larger semimajor axes (e.g. Perets & Kratter 2012)

$$a_{\text{new}} = \frac{m_{\text{old}}}{m_{\text{new}}} a_{\text{old}}, \quad (13)$$

where a_{new} and a_{old} are the new and old semimajor axis, respectively, and m_{new} and m_{old} are the system mass after mass loss and before mass loss, respectively. In this approximation, the orbital eccentricity remains roughly constant. Since we assume in our calculations that all the mass loss takes place at the moment of SN, to bracket the uncertainties of our method, we apply the above prescription assuming that all the mass loss happens adiabatically for the three stars in our triple systems, with no mass loss at the moment of SN. In reality, mass loss will happen partially prior to the SN event and partially during the SN event itself.

We show in Fig. 6 the comparison of the distributions of masses, semimajor axes, eccentricities, inclinations, and LK time-scales of stable systems obtained for the case where only kick prescriptions are applied (blue histograms) and for the case where only adiabatic mass loss is applied for model A1 (see Table 1), using 1000 realizations. We performed a two-sample KS test to assess quantitatively the statistical difference between the two populations. We find that the D-values of the parameters shown

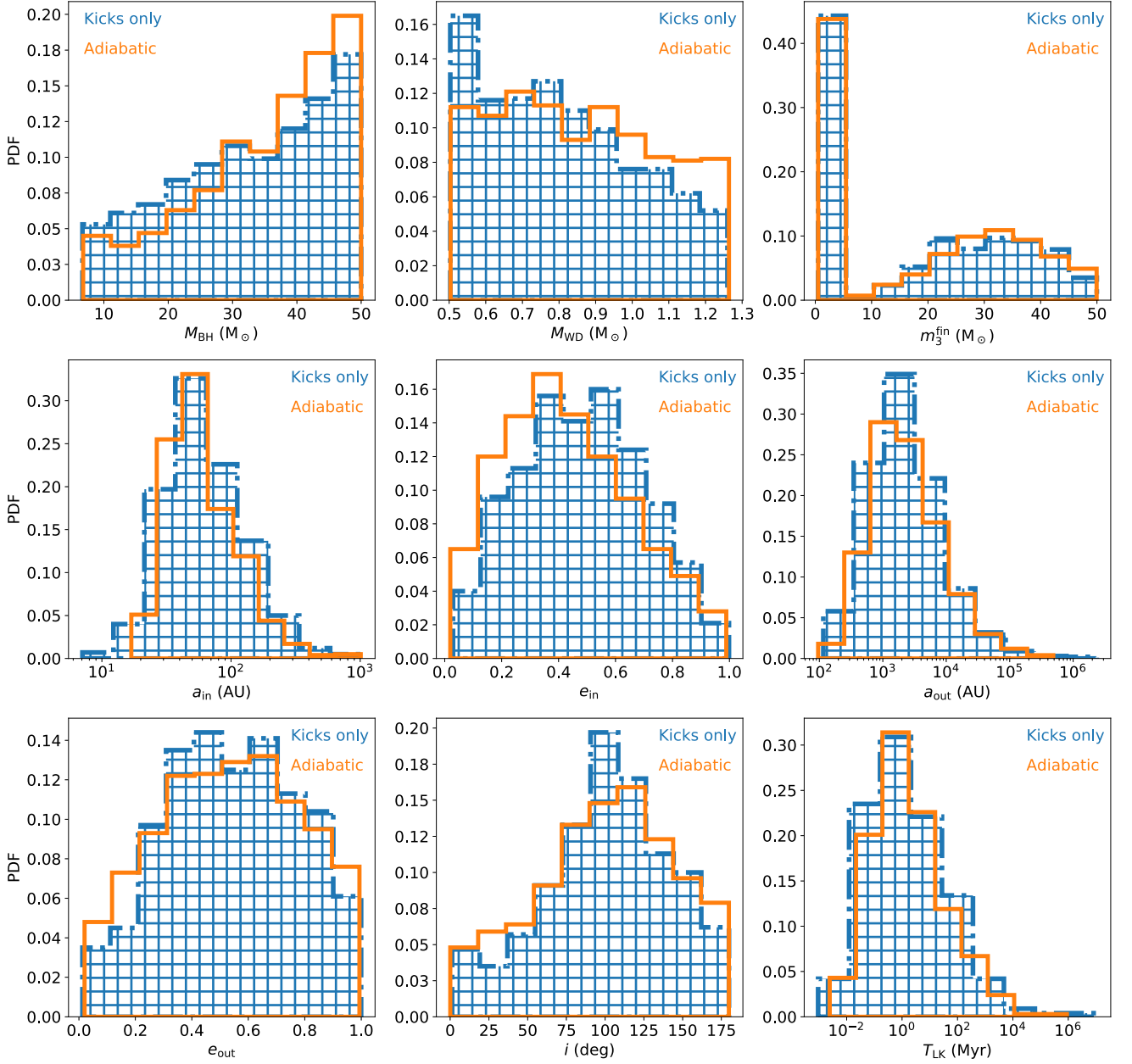


Figure 6. Comparison of the distributions of masses, semimajor axes, eccentricities, inclinations, and LK time-scales of stable systems, obtained in the case that only kick prescriptions are applied (blue histograms) and in the case that only adiabatic mass loss is applied (orange histograms) for model A1 (see Table 1).

in Fig. 6 for the two populations are $\lesssim 0.043$, which corresponds to a 95 per cent confidence level, thus statistically consistent, except for M_{BH} , M_{WD} , and e_{in} . We find that the adiabatic case favours higher BH and WD masses. We find similar results for the other models in Table 1.

We report in Table 1 the fraction of stable systems assuming adiabatic mass loss. Compared to the fraction of stable systems assuming kicks only, we find that the fraction of stable triples that can lead to a BH–WD merger is increased by a factor of ~ 3 – 20 in the case that the mass loss is adiabatic only. Assuming a similar merger fraction as found in our simulations, this would even imply a slightly larger number of BH–WD mergers. We caution that both approaches are only approximate and a final answer is left to future studies (see Conclusions). However, this definitively shows that

adiabatic mass loss prior to SNe can have a relevant effect on the stability and merger rates of BH–WD systems in triples.

4 ELECTROMAGNETIC COUNTERPARTS OF BLACK HOLE–WHITE DWARF TIDAL DISRUPTION EVENTS

Previous works have considered possible EM signatures of the tidal disruption of a WD by a stellar-mass compact object, such as a NS or a BH (Fryer et al. 1999; King et al. 2007; Metzger 2012; Fernández & Metzger 2013; Margalit & Metzger 2016; Fernández et al. 2019; Zenati et al. 2019). As discussed, the WD is tidally disrupted once its orbital pericentre radius, R_p , decreases below the tidal radius R_T [see equation (6)]. The disruption of stars and planets

was first discussed by Perets et al. (2016), who termed these events micro-TDEs. More recently, these events have been discussed by Fragione et al. (2019b) in triple systems and Kremer et al. (2019) in star clusters.

Tidal pinching of the WD and/or tidal tail intersection can in principle result in thermonuclear burning during the WD disruption process (Luminet & Pichon 1989; Rosswog, Ramirez-Ruiz & Hix 2009; MacLeod et al. 2016; Kawana, Tanikawa & Yoshida 2018), particularly for high penetration factors

$$\beta \equiv \frac{R_t}{R_p} = \left(\frac{R_p}{R_{WD}} \right)^{-1} \left(\frac{M_{BH}}{M_{WD}} \right)^{1/3}. \quad (14)$$

However, unlike the focus of the present paper, most of these works consider massive $\gtrsim 100 M_\odot$ BHs for which high $\beta \gg 1$ and thus strong tidal compression is possible.⁴ We do not generally expect significant nuclear burning during the disruption by lower mass BHs.

The tidal disruption imparts a specific energy spread to the WD debris (Rees 1988),

$$\Delta E_t \sim \frac{GM_{BH}R_{WD}}{R_t^2}. \quad (15)$$

This greatly exceeds the initial orbital binding energy of the WD, $E_{orb} \sim GM_{BH}/a$, for initial WD semimajor axes obeying

$$a \gg a_t = \frac{R_t^2}{R_{WD}} = R_{WD} \left(\frac{M_{BH}}{M_{WD}} \right)^{2/3}. \quad (16)$$

The condition $\Delta E_t \gg E_{orb}$ is easily satisfied by the WD–TDEs in our population. In this case, the half of the disrupted WD furthest from the BH at the time of disruption receives positive energy and is ejected promptly from the system. The other half of the WD is tightly bound to the BH and returns to the tidal radius over a characteristic fallback time corresponding to the orbital period of matter with binding energy $\Delta E_t = GM_{BH}/a_t$ (e.g. Stone, Sari & Loeb 2013)

$$\begin{aligned} t_{fb} &\sim 2\pi \left(\frac{a_t^3}{GM_{BH}} \right)^{1/2} \approx 2\pi \left(\frac{R_{WD}^3 M_{BH}}{GM_{WD}^2} \right)^{1/2} \\ &\approx 100 \text{ s} \left(\frac{M_{BH}}{10 M_\odot} \right)^{1/2} \left(\frac{M_{WD}}{0.6 M_\odot} \right)^{-1} \left(\frac{R_{WD}}{10^4 \text{ km}} \right)^{3/2}. \end{aligned} \quad (17)$$

In the top panel of Fig. 7, we illustrate t_{fb} for models A1–A4.

Also note that we are justified in neglecting the influence of a binary companion on the dynamics of the mass fallback (Coughlin et al. 2017; Liu & Lai 2019). This is because the apocentre radii $\sim a$ of the bound debris $a \simeq 0.41(M/10M_\odot)^{1/3}(T/1 \text{ month})^{2/3} \text{ AU}$, where T is the elapsed time since the disruption, is much smaller than the separations of the outer companion of the systems considered here (Fig. 3).

For the bound fallback material to circularize and hence form an accretion disc, it must lose a significant amount of energy. Circularization is believed to be aided by relativistic effects, since apsidal precession causes highly eccentric debris streams to self-intersect (e.g. Hayasaki, Stone & Loeb 2016; Sadowski et al. 2016; Stone et al. 2019). However, whether circularization can be fully realized before the end of the actual TDE still remains an issue of discussion (see e.g. Piran et al. 2015); in the case of stellar mass BHs, it is aided by the fact that the bound debris are not highly

⁴One exception is Kawana et al. (2018), who in some cases obtain explosions with BHs of mass $10 M_\odot$.

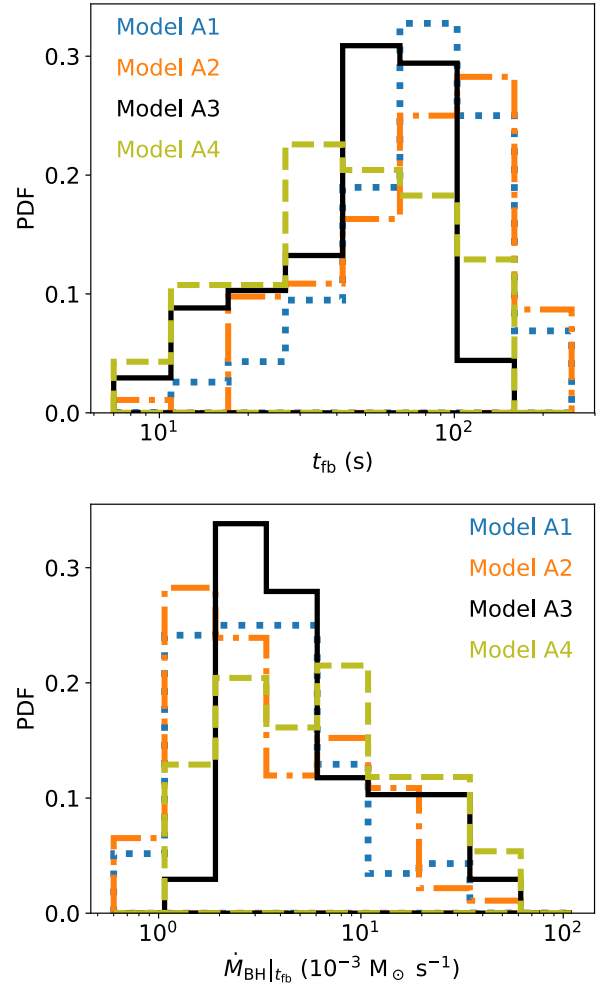


Figure 7. Distributions of fallback times (top) and accretion rates (bottom) for stellar BH–WD systems that lead to a merger for models A1–A4.

eccentric (Kremer et al. 2019). Additionally, a large fraction of the tidally disrupted material is expected to be flung out and become unbound as a result of heating associated with inter-stream shocks (Ayal, Livio & Piran 2000).

For the debris that remains bound, at times $t \gg t_{fb}$, the fallback rate obeys

$$\dot{M}_{fb} \approx \dot{M}_{fb}|_{t_{fb}} \left(\frac{t}{t_{fb}} \right)^{-5/3}, \quad (18)$$

where

$$\begin{aligned} \dot{M}_{fb}|_{t_{fb}} &\approx \frac{M_{WD}}{3t_{fb}} \approx 2 \times 10^{-3} M_\odot \text{ s}^{-1} \left(\frac{M_{BH}}{10 M_\odot} \right)^{-1/2} \\ &\times \left(\frac{M_{WD}}{0.6 M_\odot} \right)^2 \left(\frac{R_{WD}}{10^4 \text{ km}} \right)^{-3/2} \end{aligned} \quad (19)$$

is the peak fallback rate. Once in a circular disc at $R_{out} \sim 2R_t$, matter is fed on to the BH on the viscous time-scale,

$$t_{visc} \approx \frac{1}{\alpha} \left(\frac{R_{out}^3}{GM_{BH}} \right)^{1/2} \left(\frac{H}{R_{out}} \right)^{-2}, \quad (20)$$

where $H/R_{\text{out}} \sim 1$ is the aspect ratio of the disc and α its effective viscosity. To the extent that $(M_{\text{BH}}/M_{\text{WD}})^{1/2} \lesssim \alpha^{-1}$, the viscous time-scale is generally longer than the fallback time. However, for simplicity we adopt equation (19) for the BH accretion rate hereafter (though note that the true accretion rate could be smaller if $t_{\text{visc}} \gg t_{\text{fb}}$).

As matter accretes deeper into the potential well approaching the BH, the increasingly high densities and temperatures of the accretion flow will burn the WD material into increasingly heavy elements at sequentially smaller radii, generating an onion skin-like radial structure to the disc composition (Metzger 2012).

Given the very high accretion rates, photons are trapped in the accretion flow and radiative cooling is inefficient. Under these conditions, powerful disc winds driven by the released accretion energy are likely to carry away most of the accreting material before it reaches the central BH (e.g. Narayan & Yi 1995; Blandford & Begelman 1999). Axisymmetric hydrodynamical α -viscosity simulations by Fernández et al. (2019) find that the accretion rate \dot{M}_{BH} , which ultimately reaches the innermost stable circular orbit of the central BH ($R_{\text{BH}} = 6R_g$, where $R_g = GM_{\text{BH}}/c^2$) is reduced from the outer feeding rate \dot{M}_{fb} according to

$$\dot{M}_{\text{BH}}|_{t_{\text{fb}}} \approx \dot{M}_{\text{fb}}|_{t_{\text{fb}}} \left(\frac{R_{\text{BH}}}{2R_t} \right)^p \approx 2.6 \times 10^{-5} M_{\odot} \text{ s}^{-1} \times \left(\frac{M_{\text{BH}}}{10 M_{\odot}} \right)^{-0.03} \left(\frac{M_{\text{WD}}}{0.6 M_{\odot}} \right)^{2.23} \left(\frac{R_{\text{WD}}}{10^4 \text{ km}} \right)^{-2.2}, \quad (21)$$

where $p \approx 0.7$. The ~ 99 per cent of the matter not accreted by the BH is ejected in a wind (e.g. Margalit & Metzger 2016; Fernández et al. 2019). In the bottom panel of Fig. 7, we illustrate $\dot{M}_{\text{BH}}|_{t_{\text{fb}}}$ for models A1–A4. The inner parts of the accretion flow (near the central BH) could generate a relativistic jet similar to those that give rise to GRBs (e.g. Fryer et al. 1999; King et al. 2007). From Fig. 7, we predict peak accretion rates of $\sim 10^{-3} - 10^{-2} M_{\odot} \text{ s}^{-1}$, with a typical time-scale varying between a few tens and a few hundreds of seconds (models A1 and A2 have especially long time-scales). Assuming a jet launching efficiency of $\epsilon_j \lesssim 0.1$, the peak jet power could therefore be $\epsilon_j \dot{M} c^2 \lesssim 10^{50} - 10^{51} \text{ erg s}^{-1}$. Internal dissipation (e.g. shocks or magnetic reconnection) within such a jet could plausibly give rise to a short-lived (approximately several tens to several hundreds of seconds) gamma-ray or X-ray transient with a luminosity $10^{49} - 10^{50} \text{ erg s}^{-1}$.

Have such events already been observed? The distribution of accretion rates and durations largely falls within the range observed for the canonical long GRBs, with the tail of the distribution approaching the time-scales of a sub-class with similar characteristics, but longer duration, known as the ‘ultra-long’ GRBs (ULGRBs) (Levan et al. 2014). It remains debated whether ULGRBs are simply the longest lasting members of a single, continuous LGRB population (Zhang et al. 2014) or whether they represent a distinct class with potentially different progenitors (Levan et al. 2014). Either way, an important observational feature of the TD events discussed here would be the lack of signatures of a core-collapse supernova in association with a GRB-like type event. Wolf-Rayet stars are believed to be the progenitor stars of the canonical LGRBs (Woosley & Bloom 2006), while a working model for the ULGRBs is the collapse of a blue supergiant star (Perna, Lazzati & Cantiello 2018; though competing models exist involving millisecond magnetar engines, e.g. Greiner et al. 2015; Metzger et al. 2015). Among the events observed so far, an interesting one is GRB060614, with a duration of 102 s. At a redshift of $z = 0.125$, its

associated core-collapse SN should have been detected, but it was not, calling for the possibility of a new γ -ray burst classification (Gehrels et al. 2006), which King et al. (2007) suggested might be indicative of a WD–NS merger. Future events of this kind will hence deserve special attention.

However, while not accompanied by canonical core-collapse SNe, WD–BH mergers may be accompanied by fast-evolving supernova-like transients. As mentioned above, half of the WD is unbound promptly during the tidal disruption process at a characteristic velocity $v_t \sim (GM_{\text{BH}}^{1/3} M_{\text{WD}}^{2/3} / R_{\text{WD}})^{1/2} \approx 4.4 \times 10^3 \text{ km s}^{-1}$. Due to outflows from the accretion disc, the majority of the bound half of the WD will also be ejected, with a range of velocities $\sim 10^4 - 10^5 \text{ km s}^{-1}$ (Metzger 2012; Margalit & Metzger 2016; Fernández et al. 2019). Due to the low ejecta mass $\sim M_{\text{WD}} \lesssim 1 M_{\odot}$, any thermal transient would be expected to peak much faster than normal supernovae, e.g. on a time-scale of $t_{\text{sn}} \sim \text{days}$ instead of weeks.

What source of luminosity would power the supernova-like emission? Although little radioactive ^{56}Ni is likely to be produced during the tidal compression, a small quantity of ^{56}Ni is produced by the inner regions of the accretion flow (Metzger 2012). Fernández et al. (2019) predict that the accretion flows generated by the merger of quasi-circular BH–WD systems will generate $\sim 10^{-3} - 10^{-2} M_{\odot}$ in ejected ^{56}Ni (see their table 2), in which case the resulting thermonuclear supernovae would peak at a luminosity $\sim 10^{40} - 10^{41} \text{ erg s}^{-1}$, i.e. 10–100 times less luminous than normal Type Ia supernovae.

The luminosity of the thermonuclear supernova could be substantially boosted if the ejecta is heated by ongoing outflows from the central engine (e.g. Dexter & Kasen 2013). In particular, if 10 per cent of the accretion power reaching the BH goes into powering the supernova luminosity through accretion-disc winds, then from equations (19) and (21), we see that the peak luminosity could reach

$$L_{\text{pk}} \approx 0.1 \dot{M}_{\text{BH}}|_{t_{\text{fb}}} c^2 \left(\frac{t_{\text{sn}}}{t_{\text{fb}}} \right)^{-5/3} \sim 10^{43} - 10^{44} \text{ erg s}^{-1} \quad (22)$$

for characteristic parameters, e.g. $t_{\text{sn}} \sim 1 \text{ d}$. Consistent with this, numerical simulations of the radiation–hydrodynamic evolution of disc winds by Kremer et al. (2019) showed that it can produce optical transients with luminosities $\sim 10^{41} - 10^{44} \text{ erg s}^{-1}$ on time-scales varying from about a day to about a month.

A number of fast-evolving blue supernovae with luminosities in this range have been discovered in recent years (Drout et al. 2014). However, the total estimated rate of this (highly heterogeneous) population of transients $\approx 4800 - 8000 \text{ Gpc}^{-3} \text{ yr}^{-1}$ exceeds the rate of BH–WD mergers found in this paper, hence suggesting another progenitor origin for the bulk of this population. Furthermore, the closest example yet discovered (AT2018cow; e.g. Prentice et al. 2018) showed evidence for hydrogen in the spectrum, ruling out a BH–WD origin.

5 GRAVITATION WAVE COUNTERPARTS

It is well known that the extreme mass ratio inspiral of a WD into an IMBH is a target for multimessenger observations including GW detections with *LISA* (e.g. Hils & Bender 1995; Kobayashi et al. 2004; Dai & Blandford 2013; Eracleous et al. 2019). Stellar-mass BH–WD and NS–WD inspirals could also be observed coincidentally in GWs with *LISA* up to the point of disruption.

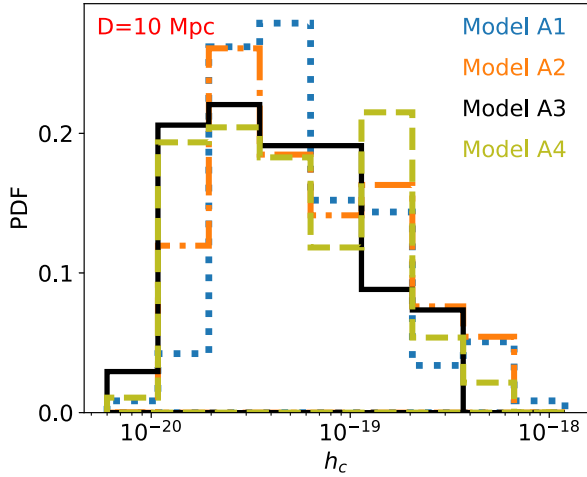


Figure 8. Distributions of the total characteristic GW strain h_c for stellar-mass BH–WD systems that lead to a merger at a distance of 10 Mpc for models A1–A4. For comparison, note that the characteristic *LISA* noise amplitude is approximately 8×10^{-21} at 0.09 Hz corresponding to the TDE.

The GW frequency at disruption is⁵

$$f_{\text{GW}} = \frac{G^{1/2}(M_{\text{BH}} + M_{\text{WD}})^{1/2}}{\pi R_t^{3/2}} \\ = 0.09 \text{ Hz} \left(1 + \frac{M_{\text{WD}}}{M_{\text{BH}}} \right) M_{\text{WD},0.6 M_\odot}^{1/2} R_{\text{WD},10^4 \text{ km}}^{-3/2}, \quad (23)$$

where we introduced the abbreviated notation $X_a = X/a$. Note that for $R_{\text{WD}} \propto M_{\text{WD}}^{-1/3}$ and $M_{\text{WD}} \ll 1.44 M_\odot$ [see equation (3)], the GW frequency at disruption follows $f_{\text{GW}} \propto M_{\text{WD}}$ and is independent of M_{BH} to leading order.

The total characteristic GW strain for observing the GWs for a duration T averaged over binary and detector orientation is approximately [see equation (27) in Robson, Cornish & Liu 2019]

$$h_c = \frac{8}{\sqrt{5}} \frac{G^2}{c^4} \frac{M_{\text{BH}} M_{\text{WD}}}{R_t D} (T f_{\text{GW}})^{1/2} = 2.0 \times 10^{-20} \\ \times T_{4\text{yr}}^{0.5} D_{10\text{Mpc}}^{-1} M_{\text{BH},10 M_\odot}^{0.66} M_{\text{WD},0.6 M_\odot}^{1.58} R_{\text{WD},10^4 \text{ km}}^{-1.75}. \quad (24)$$

In Fig. 8, we show the distributions of the total characteristic GW strain for stellar-mass BH–WD systems that lead to a merger in models A1–A4 at a distance of $D = 10$ Mpc. Note that the characteristic noise amplitude for *LISA* is 8×10^{-21} at 0.09 Hz (see fig. 6 in Robson et al. 2019). We follow Robson et al. (2019) to calculate the signal-to-noise ratio (SNR) of detecting the GWs for a WD–BH inspiral using the current design of *LISA* with arm length of 2.5×10^6 km. For a 4-yr observation, we find that the binary orientation averaged SNR is higher than 8 up to 10 Mpc for $M_{\text{BH}} = 40 M_\odot$, $M_{\text{WD}} = 1.0 M_\odot$. For optimal (face-on) binary orientation, the detection distance is a factor of 2.5 larger. We conclude that the GW observations of WD mergers with stellar-mass BHs or NSs will be limited to the local Universe within ~ 25 Mpc.

⁵This expression corresponds to circular orbits, but the peak GW frequency at disruption is similar for arbitrary eccentricities $0 \leq e \leq 1$ to within 20 per cent.

The detection volume is $V_{\text{GW}} \propto h_c^3 / [f S_n(f)]^{1/2}$, where S_n is the noise power spectral density, which scales as $S_n(f) \propto f^2$ for $f \gtrsim 0.02$ Hz. Thus, $V_{\text{GW}} \propto h_c^3 f_{\text{GW}}^{-3/2} \propto M_{\text{BH}}^2 M_{\text{WD}}^4 R_{\text{WD}}^{-3} T^{1.5}$. The GW-observed TDE rate is strongly biased towards higher BH mass and higher WD masses.

If an NS–WD, BH–WD, or IMBH–WD TDE happens within the detectable *LISA* volume, the GW measurements can be used to determine the parameters f_{GW} given by equation (23), the chirp mass of the binary $\mathcal{M} = M_{\text{BH}}^{3/5} M_{\text{WD}}^{3/5} / (M_{\text{BH}} + M_{\text{WD}})^{1/5}$, and the distance to the source D independently of EM observations. Coincident GW detections may help to secure the identification of the EM counterpart. The joint multimessenger analysis of the merger of a WD with a stellar BH, NS, or IMBH offers to gain a more accurate understanding of these astrophysical sources. Our predicted rate implies that the chance of coincident EM/GW detections of TDEs in stellar triple systems is very small as the rate is $\sim 10^{-6} - 10^{-9} \text{ yr}^{-1}$ within 10 Mpc. Most WD/BH binaries detectable with *LISA* are expected to be far from merger.

Note that BH–WD and NS–WD binaries typically emit GWs in the *LISA* band for thousands of years before merger. We find that the peak SNR corresponds to $f \sim 0.03$ Hz and the SNR decreases slowly for higher f . For a fixed observation time, the SNR varies by less than a factor of 2.5 between 0.005 Hz and the point of tidal disruption. For circular BH–WD binaries, the GW frequency arrives at 0.005 Hz at $10^4 \text{ yr} M_{\text{WD},0.6 M_\odot}^{-1} M_{\text{BH},10 M_\odot}^{-5/3}$ before tidal disruption. Since the number of systems at a given frequency f scales with the residence time $N \propto t_{\text{res}} = f / \dot{f} \propto f^{-8/3}$, most WD/BH binaries detected through GWs will be far from disruption. Furthermore, LK oscillation induced by a triple companion leaves a time-dependent imprint on the GW spectrum of the inner binary (Hoang et al. 2019; Randall & Xianyu 2019). Thus, *LISA* observations of GWs emitted by binaries in the Galaxy may be used directly to constrain the expected TDE rate from BH–WD and NS–WD TDE systems in the Universe.

6 CONCLUSIONS

The mergers of binaries comprising two compact objects can produce diverse explosive transient events, such as GW chirps, Type Ia, and GRBs. Though they have received comparatively less attention in the literature, the mergers of NS–WD and BH–WD binaries are expected to generate transients if the WD approaches the NS or BH close enough to be disrupted in a WD–TDE.

This paper explores a new triple channel for WD–BH mergers driven by the joint effect of GW emission and the LK mechanism. We explore the sensitivity of our results to different assumptions for the distributions of natal kick velocities imparted to the BH and the WD, the semimajor axes and eccentricities of the triple and the initial stellar masses. We estimate the rate of WD–TDEs in triples to be in the range $1.2 \times 10^{-3} - 1.4 \text{ Gpc}^{-3} \text{ yr}^{-1}$ for $z \leq 0.1$, under the assumption of momentum-conserving natal kicks. Compared to stellar TDEs in triples, WD–TDEs are therefore a factor of ~ 3 – 30 rarer. Moreover, we have found that the fraction of stable triples that can lead to a BH–WD merger is enhanced by a factor of ~ 3 – 20 in the case that the mass loss is adiabatic only. Assuming a similar merger fraction as found in our simulations, this would even imply a slightly larger number of BH–WD mergers, assessing the relevance of adiabatic mass loss prior to SNe in triples.

In our simulations, we check that the triple systems remain stable after each SN event. Systems that become unstable may still merge, but they are not taken into account in our results. Moreover, we

are assuming that the SN events take place instantaneously and do not simulate the systems during the MS lifetime of the progenitors. This and the details of the specific evolutionary paths, which depend on stellar winds, metallicity, and rotation, of the stellar progenitors could reduce the available parameter space for BH–WD mergers (Shappee & Thompson 2013). Systems that experience significant LK oscillations on the MS will frequently be driven to merge prematurely during this phase, assuming that the LK process is not damped by GR or tidal precession in the inner binary. Such systems will typically be those triples with high birth inclinations, even though this is not a necessary requirement in cases where the octupole term or chaotic non-secular dynamics become important.

Therefore, to avoid counting systems that would undergo MS mergers prior to the start of our simulations, we have conservatively neglected the contribution of stable triple systems that have LK time-scales shorter than the lifetime of the progenitor stars in the inner binary (hence, our inferred merger rates should be interpreted as lower limits on the true rate). The systems that we account for, which can possibly lead to a merger, are therefore the triples that were born typically with moderate inclinations, which become highly inclined only due to the BH kick. Moreover, we also tried to correct for mergers that occur before the inner binary secondary evolves to the WD phase by accounting for the progenitors that could lead to a stellar TDE, rather than a WD–TDE, thus removing another portion of triples (Shappee & Thompson 2013; Toonen et al. 2016, 2018a; Fragione et al. 2019b).

The situation becomes even more complicated if episodic mass loss occurs due to eccentric Roche lobe overflow and/or if common evolutionary phases in the triple are taken into account. However, these are not modelled in a self-consistent way in triple systems. This is because of a possibly complex interplay between these effects and LK evolution during the MS lifetime of the progenitors (Leigh et al. 2016; Di Stefano 2019; Hamers & Dosopoulou 2019).

Accretion of the bound debris on to the BH following a BH–WD TDE could power a relativistic jet, generating a burst of high-energy X-ray or gamma-ray emission with a duration similar to a long GRB. The heating of WD debris (unbound during the TDE or in outflows from the accretion disc) by radioactivity or winds from the accretion disc could generate a rapidly evolving supernova-like optical transient. Such peculiar transients from BH–NS mergers might be observable by high-energy satellites or upcoming time-domain optical surveys, such as LSST. The characterization of WD–TDE events and their distributions is therefore a fundamental step in ultimately being able to identify them among the myriad of other cataclysmic events.

Stellar mass BH–WD, NS–WD, and IMBH–WD binaries may also be detected in GWs using *LISA* up to the point of TDE. *LISA* may also provide an accurate determination of the TDE rates from triples by observing systems thousands of years before merger in the Galaxy. Multimessenger studies of WD–TDEs by stellar-mass BHs or NSs will be limited by the *LISA* detection range of ~ 10 Mpc.

The future discovery of a population of WD–TDE could be used to study the demographics of BHs in nearby galaxies and to place constraints on the distributions of natal kicks at BH birth in a complementary way to what now probed by LIGO from BH–BH mergers.

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REFERENCES

- Abbott B. P. et al., 2017, *ApJ*, 848, L13
 Antonini F., Perets H. B., 2012, *ApJ*, 757, 27
 Antonini F., Toonen S., Hamers A. S., 2017, *ApJ*, 841, 77
 Arzoumanian Z., Chernoff D. F., Cordes J. M., 2002, *ApJ*, 568, 289
 Ayal S., Livio M., Piran T., 2000, *ApJ*, 545, 772
 Bahramian A. et al., 2017, *MNRAS*, 467, 2199
 Blaauw A., 1961, *B. Astron. I. Neth.*, 15, 265
 Blandford R. D., Begelman M. C., 1999, *MNRAS*, 303, L1
 Bobrick A., Davies M. B., Church R. P., 2017, *MNRAS*, 467, 3556
 Bothwell M. S. et al., 2011, *MNRAS*, 415, 1815
 Coughlin E. R., Armitage P. J., Nixon C., Begelman M. C., 2017, *MNRAS*, 465, 3840
 Dai L., Blandford R., 2013, *MNRAS*, 434, 2948
 Dexter J., Kasen D., 2013, *ApJ*, 772, 30
 Di Stefano R., 2019, *MNRAS*, 491, 495
 Drout M. R. et al., 2014, *ApJ*, 794, 23
 Duchêne G., Kraus A., 2013, *Annu. Rev. Astron. Astr.*, 51, 269
 El-Badry K., Rix H.-W., 2018, *MNRAS*, 480, 4884
 Eracleous M., Gezari S., Sesana A., Bogdanovic T., MacLeod M., Roth N., Dai L., 2019, *BAAS*, 51, 10
 Fernández R., Metzger B. D., 2013, *ApJ*, 763, 108
 Fernández R., Margalit B., Metzger B. D., 2019, *MNRAS*, 488, 259
 Foucart F., Hinderer T., Nissanke S., 2018, *Phys Rev*, 98, 081501
 Fragione G., Leigh N. W. C., Ginsburg I., Kocsis B., 2018, *ApJ*, 867, 119
 Fragione G., Grishin E., Leigh N. W. C., Perets H. B., Perna R., 2019a, *MNRAS*, 488, 47
 Fragione G., Leigh N. W. C., Perna R., Kocsis B., 2019b, *MNRAS*, 489, 727
 Fryer C. L., Kalogera V., 2001, *ApJ*, 554, 548
 Fryer C. L., Woosley S. E., Herant M., Davies M. B., 1999, *ApJ*, 520, 650
 Gehrels N. et al., 2006, *Nature*, 444, 1044
 Geller A. M., Leigh N. W. C., Giersz M., Kremer K., Rasio F. A., 2019, *ApJ*, 872, 165
 Greiner J. et al., 2015, *Nature*, 523, 189
 Hamers A. S., 2018, *MNRAS*, 478, 620
 Hamers A. S., Dosopoulou F., 2019, *ApJ*, 872, 119
 Hayasaki K., Stone N., Loeb A., 2016, *MNRAS*, 461, 3760
 Hils D., Bender P. L., 1995, *ApJ*, 445, L7
 Hoang B.-M., Naoz S., Kocsis B., Farr W. M., McIver J., 2019, *ApJ*, 875, L31
 Hobbs G., Lorimer D. R., Lyne A. G., Kramer M., 2005, *MNRAS*, 360, 974
 Hurley J. R., Pols O. R., Tout C. A., 2000, *MNRAS*, 315, 543
 Iben I., Jr, 1991, *ApJS*, 76, 55
 Igoshev A. P., Perets H. B., Michael E., 2019, *MNRAS*, 494, 1448
 Katz B., Dong S., 2012, preprint (arXiv:1211.4584)
 Kawana K., Tanikawa A., Yoshida N., 2018, *MNRAS*, 477, 3449
 King A., Olsson E., Davies M. B., 2007, *MNRAS*, 374, L34
 Kobayashi S., Laguna P., Phinney E. S., Mészáros P., 2004, *ApJ*, 615, 855
 Kobulnicky H. A. et al., 2014, *ApJS*, 213, 34

- Kozai Y., 1962, *AJ*, 67, 591
- Kremer K., Lu W., Rodriguez C. L., Lachat M., Rasio F., 2019, *ApJ*, 881, 75
- Kroupa P., 2001, *MNRAS*, 322, 231
- Leigh N. W. C., Geller A. M., 2013, *MNRAS*, 432, 2474
- Leigh N. W. C., Lützgendorf N., Geller A. M., Maccarone T. J., Heinke C., Sesana A., 2014, *MNRAS*, 444, 29
- Leigh N. W. C., Antonini F., Stone N. C., Shara M. M., Merritt D., 2016, *MNRAS*, 463, 1605
- Levan A. J. et al., 2014, *ApJ*, 781, 13
- Licquia T. C., Newman J. A., 2015, *ApJ*, 806, 96
- Lidov M. L., 1962, *Planet. Space Sci.*, 9, 719
- Liu B., Lai D., 2019, *MNRAS*, 483, 4060
- Livio M., Mazzali P., 2018, *Phys. Rep.*, 736, 1
- Luminet J. P., Pichon B., 1989, *A&A*, 209, 103
- Lu C. X., Naoz S., 2019, *MNRAS*, 484, 1506
- MacLeod M., Guillochon J., Ramirez-Ruiz E., Kasen D., Rosswog S., 2016, *ApJ*, 819, 3
- Maeder A., 2009, *Physics, Formation and Evolution of Rotating Stars*. Springer, Berlin Heidelberg
- Maoz D., Mannucci F., Nelemans G., 2014, *ARA&A*, 52, 107
- Mardling R. A., Aarseth S. J., 2001, *MNRAS*, 321, 398
- Margalit B., Metzger B. D., 2016, *MNRAS*, 461, 1154
- Metzger B. D., 2012, *MNRAS*, 419, 827
- Metzger B. D., Margalit B., Kasen D., Quataert E., 2015, *MNRAS*, 454, 3311
- Michael E., Perets H. B., 2014, *ApJ*, 794, 122
- Michael E., Perets H. B., 2019, *MNRAS*, 484, 4711
- Mikkola S., Merritt D., 2006, *MNRAS*, 372, 219
- Mikkola S., Merritt D., 2008, *AJ*, 135, 2398
- Moe M., Di Stefano R., 2017, *ApJS*, 230, 15
- Narayan R., Yi I., 1995, *ApJ*, 444, 231
- Perets H. B., Kratter K. M., 2012, *ApJ*, 760, 99
- Perets H. B., Li Z., Lombardi J. C., Jr, Milcarek S. R., Jr, 2016, *ApJ*, 823, 113
- Perna R., Lazzati D., Cantiello M., 2018, *ApJ*, 859, 48
- Pijlloo J. T., Caputo D. P., Portegies Zwart S. F., 2012, *MNRAS*, 424, 2914
- Piran T., Svirski G., Krolik J., Cheng R. M., Shiokawa H., 2015, *ApJ*, 806, 164
- Prentice S. J. et al., 2018, *ApJ*, 865, L3
- Randall L., Xianyu Z.-Z., 2019, preprint ([arXiv:1902.08604](https://arxiv.org/abs/1902.08604))
- Rees M. J., 1988, *Nature*, 333, 523
- Robson T., Cornish N. J., Liu C., 2019, *Classical. Quant. Grav.*, 36, 105011
- Rodriguez C. L., Antonini F., 2018, *ApJ*, 863, 7
- Rosswog S., Ramirez-Ruiz E., Hix W. R., 2008, *ApJ*, 679, 1385
- Rosswog S., Ramirez-Ruiz E., Hix W. R., 2009, *ApJ*, 695, 404
- Sadowski A., Tejeda E., Gafton E., Rosswog S., Abarca D., 2016, *MNRAS*, 458, 4250
- Sana H. et al., 2012, *Science*, 337, 444
- Sana H. et al., 2013, *A&A*, 550, A107
- Sana H. et al., 2014, *ApJS*, 215, 15
- Shappee B. J., Thompson T. A., 2013, *ApJ*, 766, 64
- Silber K., Tremaine S., 2017, *ApJ*, 836, 39
- Stone N., Sari R., Loeb A., 2013, *MNRAS*, 435, 1809
- Stone N. C., Kesden M., Cheng R. M., van Velzen S., 2019, *Gen. Relat. Gravit.*, 51, 30
- The LIGO Scientific Collaboration, the Virgo Collaboration, 2019, *Phys Rev X*, 9, 031040
- Tokovinin A., 2017, *ApJ*, 844, 103
- Toonen S., Hamers A., Portegies Zwart S., 2016, *Comput. Astrophys. Cosmology*, 3, 6
- Toonen S., Perets H. B., Hamers A. S., 2018a, *A&A*, 610, A22
- Toonen S., Perets H. B., Hamers A. S., 2018b, *A&A*, 610, A22
- Toonen S., Perets H. B., Igoshev A. P., Michael E., Zenati Y., 2018c, *A&A*, 619, A53
- van Kerkwijk M. H., Bassa C. G., Jacoby B. A., Jonker P. G., 2005, in Rasio F. A., Stairs I. H., eds, *ASP Conf. Ser. Vol. 328, Binary Radio Pulsars*. Astron. Soc. Pac., San Francisco, p. 357
- Woosley S. E., Bloom J. S., 2006, *ARA&A*, 44, 507
- Zenati Y., Perets H. B., Toonen S., 2019, *MNRAS*, 486, 1805
- Zhang B.-B., Zhang B., Murase K., Connaughton V., Briggs M. S., 2014, *ApJ*, 787, 66

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