

Tidal disruption events on to stellar black holes in triples

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ABSTRACT

Stars passing too close to a black hole can produce tidal disruption events (TDEs), when the tidal force across the star exceeds the gravitational force that binds it. TDEs have usually been discussed in relation to massive black holes that reside in the centres of galaxies or lurk in star clusters. We investigate the possibility that triple stars hosting a stellar black hole (SBH) may be sources of TDEs. We start from a triple system made up of three main-sequence stars and model the supernova (SN) kick event that led to the production of an inner binary comprised of an SBH. We evolve these triples with a high-precision N -body code and study their TDEs as a result of Kozai–Lidov oscillations. We explore a variety of distributions of natal kicks imparted during the SN event, various maximum initial separations for the triples, and different distributions of eccentricities. We show that the main parameter that governs the properties of the SBH–MS binaries that produce a TDE in triples is the mean velocity of the natal kick distribution. Smaller σ 's lead to larger inner and outer semimajor axes of the systems that undergo a TDE, smaller SBH masses, and longer time-scales. We find that the fraction of systems that produce a TDE is roughly independent of the initial conditions, while estimate a TDE rate of 2.1×10^{-4} – 4.7 yr^{-1} , depending on the prescriptions for the SBH natal kicks. This rate is almost comparable to the expected TDE rate for massive black holes.

Key words: stars: black holes – stars: kinematics and dynamics – Galaxies: kinematics and dynamics – galaxy: kinematics and dynamics.

1 INTRODUCTION

Stars passing too close to a black hole can produce tidal disruption events (TDEs) when the tidal force across the star exceeds the gravitational force that binds it [see e.g. Stone et al. (2019a) for a recent review]. The resulting stellar debris can produce an electromagnetic flare and can be used as a powerful instrument to probe the presence of quiescent massive black holes, which would otherwise remain dark (D’Orazio, Loeb & Guillochon 2019). TDEs are usually discussed in the context of galactic nuclei, where the numerous two-body interactions of stars surrounding a supermassive black hole (SMBH) drive some of them on to plunging orbits, which result in TDE events (Alexander 2017). The rate of TDEs due to SMBHs in galactic nuclei is highly uncertain, and could be enhanced by a secondary black hole (Fragione & Leigh 2018).

Both observational and theoretical estimates are within the range 10^{-5} – 10^{-4} yr^{-1} per galaxy (Stone & Metzger 2016; Alexander 2017; van Velzen 2018).

TDEs have also been studied in relation to the elusive intermediate-mass black holes (IMBHs) (Baumgardt, Makino & Ebisuzaki 2004; Rosswog, Ramirez-Ruiz & Hix 2008, 2009). The discovery of the tidal consumption of a star passing in the vicinity of an IMBH may provide a definitive proof for their existence. TDEs on to IMBHs can take place in galactic nuclei, where the rate of TDEs can be as high as $\sim 10^{-4}$ – 10^{-2} yr^{-1} on \sim few Myr time-scales. Another source of IMBH TDEs are globular clusters. Recent calculations by Fragione et al. (2018) have computed a typical rate $\sim 10^{-5}$ – 10^{-3} yr^{-1} . Lin et al. (2018) recently observed a TDE-like event consistent with an IMBH in an off-centre star cluster, at a distance of $\sim 12.5 \text{ kpc}$ from the centre of the host galaxy.

Recently, TDEs have also been discussed in the context of stellar black holes (SBHs). Rastello et al. (2019) showed that binary SBHs can trigger TDEs in open clusters and estimated a typical rate of

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$\sim 0.3\text{--}3 \times 10^{-6} \text{ yr}^{-1}$. Lopez Martin et al. (2019) showed that the tidal disruption of a star by an SBH binary in a star cluster can alter the intrinsic spins of the two SBHs. Samsing et al. (2019) proposed that the same events can be used to constrain the orbital period distribution and, as a consequence, the dynamical mechanisms that eventually drive these binaries to merge. Recently, Kremer et al. (2019) used a wide range of N -body simulations of globular clusters and estimated a rate of $3 \times 10^{-6} \text{ Gpc}^{-3} \text{ yr}^{-1}$ for these events.

Bound stellar multiples are not rare. Both massive (O, B, A types) and near solar mass stars (F, G, K types) have been shown to reside in triples or higher order multiplicities, with a relative fraction that can be as high as $\sim 20\text{--}30$ per cent (Duquennoy & Mayor 1991; Raghavan et al. 2010; Sana et al. 2013a; Dunstall et al. 2015; Sana 2017; Jiménez-Esteban, Solano & Rodrigo 2019). Most recent studies of transient events associated with bound multiple systems focused on determining the SBH and neutron star (NS) merger rates (Antonini, Toonen & Hamers 2017; Silsbee & Tremaine 2017; Fragione & Kocsis 2019; Fragione & Loeb 2019; Liu & Lai 2019; Fragione, Leigh & Perna 2019b) and the double white dwarf merger rate (Katz & Dong 2012; Fang, Thompson & Hirata 2018; Hamers 2018; Toonen, Perets & Hamers 2018).

In this paper, we investigate the possibility that isolated triple stars in galaxies are sources of TDEs, some of which can take place off-centre from the nucleus of the host galaxy. We consider triples comprised of an inner binary consisting of an SBH and a main-sequence (MS) star, which eventually produce a TDE as a result of Kozai–Lidov (KL) oscillations. We start from the MS progenitors of the SBH and model the supernova (SN) event that leads to the formation of these triples under study. We adopt different prescriptions for the natal kick velocities that are imparted by SN events. We quantify how the probability of a TDE depends on the initial conditions, and determine the parameter distributions of merging systems relative to the initial distributions.

The paper is organized as follows. In Section 2, we discuss the SN mechanism in the context of triple stars, and the KL mechanism. In Section 3, we present our numerical methods to determine the rate of SBH TDEs in triples and discuss the parameters of the merging systems. The implications for possible electromagnetic counterparts are presented in Section 4. Finally, in Section 5, we discuss the implications of our findings for the current state of the literature and draw our conclusions.

2 SUPERNOVAE IN TRIPLES AND THE KOZAI-LIDOV MECHANISM

We consider a hierarchical triple system that consists of an inner binary of mass $m_{\text{in}} = m_1 + m_2$ and a third body of mass m_3 that orbits the inner binary (for details see Pijloo, Caputo & Portegies Zwart 2012). The triple can be described in terms of Keplerian orbital elements for both the inner orbit (i.e. the relative motion of m_1 and m_2) and the outer orbit (i.e. the relative motion of m_3 around the centre of mass of the inner binary). The semimajor axis and eccentricity of the inner orbit are a_{in} and e_{in} , respectively, while the semimajor axis and eccentricity of the outer orbit are a_{out} and e_{out} , respectively. The inner and outer orbital planes have initial mutual inclination i_0 .

When a star undergoes an SN event, we assume that it takes place instantaneously, i.e. on a time-scale much shorter than the orbital period (Toonen, Hamers & Portegies Zwart 2016; Lu & Naoz 2019). At the time of detonation, the star instantaneously loses mass. Under this assumption, the position of the body that undergoes an SN event

is assumed not to change.¹ However, due to asymmetric mass-loss, the exploding star is imparted a kick to its centre of mass (Blaauw 1961). We assume that the velocity kick is drawn from a Maxwellian distribution:

$$p(v_k) \propto v_k^2 e^{-v_k^2/\sigma^2}, \quad (1)$$

where σ is the root-mean-square kick velocity that characterizes the distribution.²

We assume that the SN event happens first in the primary star of the inner binary. Before the SN takes place, for the inner binary consisting of two stars with masses m_1 and m_2 , a relative velocity $v = |\mathbf{v}| = |\mathbf{v}_1 - \mathbf{v}_2|$, and separation distance $r = |\mathbf{r}| = |\mathbf{r}_1 - \mathbf{r}_2|$, energy conservation implies

$$|\mathbf{v}|^2 = \mu \left(\frac{2}{r} - \frac{1}{a_{\text{in}}} \right), \quad (2)$$

where $\mu = G(m_1 + m_2)$. The angular momentum integral \mathbf{h} is related to the orbital parameters by

$$|\mathbf{h}|^2 = |\mathbf{r} \times \mathbf{v}|^2 = \mu a_{\text{in}} (1 - e_{\text{in}}^2). \quad (3)$$

After the SN event, the orbital semimajor axis and eccentricity change due to the mass-loss Δm in the primary star and the natal kick v_k (which is assumed to be isotropic). The total mass of the binary decreases to $m_{\text{in},n} = m_{1,n} + m_2$, where $m_{1,n} = m_1 - \Delta m$. The relative velocity becomes $\mathbf{v}_n = \mathbf{v} + \mathbf{v}_k$, while $\mathbf{r}_n = \mathbf{r}$. We assume that the SN takes place instantaneously. The new semimajor axis can be computed from equation (2),

$$a_{\text{in},n} = \left(\frac{2}{r} - \frac{v_n^2}{\mu_{\text{in},n}} \right)^{-1}, \quad (4)$$

where $\mu_{\text{in},n} = G(m_{1,n} + m_2)$, and the new eccentricity can be computed from equation (3):

$$e_{\text{in},n} = \left(1 - \frac{|\mathbf{r} \times \mathbf{v}_n|^2}{\mu_{\text{in},n} a_{\text{in},n}} \right)^{1/2}. \quad (5)$$

Since the primary in the inner binary undergoes an SN event, an effective kick \mathbf{V}_{cm} is imparted to its centre of mass (Pijloo et al. 2012). As a consequence of the mass-loss in the primary, the centre of mass position of the inner binary

$$\mathbf{r}_{\text{cm}} = \left(1 - \frac{m_2}{m_{\text{in}}} \right) \mathbf{r}_1 + \frac{m_2}{m_{\text{in}}} \mathbf{r}_2 \quad (6)$$

changes due to an instantaneous translation to $\mathbf{r}_{\text{cm},n} = \mathbf{r}_{\text{cm}} + \Delta \mathbf{r}_{\text{cm}}$, where

$$\Delta \mathbf{r}_{\text{cm}} = \left(\frac{m_2}{m_{\text{in},n}} - \frac{m_2}{m_{\text{in}}} \right) \mathbf{r}. \quad (7)$$

Thus, the separation distance \mathbf{R}_3 between the centre of mass of the inner binary and the tertiary star becomes

$$\mathbf{R}_{3,n} = \mathbf{R}_3 + \Delta \mathbf{r}_{\text{cm}}, \quad (8)$$

while the relative velocity \mathbf{V}_3 changes into

$$\mathbf{V}_{3,n} = \mathbf{V}_3 + \mathbf{V}_{\text{cm}}, \quad (9)$$

where

$$\mathbf{V}_{\text{cm}} = \left(1 - \frac{m_2}{m_{\text{in},n}} \right) (\mathbf{v}_1 + \mathbf{v}_k) + \frac{m_2}{m_{\text{in},n}} \mathbf{v}_2. \quad (10)$$

¹We assume the SN shell has no impact on the companion stars.

²Here, we do not take into account the fact that natal kicks for BHs can be reduced by the amount of fallback as $v_{k,\text{BH}} = v_k(1 - f_{\text{fb}})$, where f_{fb} is the fallback parameter.

The outer semimajor axis a_{out} and eccentricity e_{out} change accordingly. To compute the relative change with respect to the pre-SN values, the strategy is to use again equations (2) and (3) for the outer orbit,

$$a_{\text{out},n} = \left(\frac{2}{R_{3,n}} - \frac{V_{3,n}^2}{\mu_{\text{out},n}} \right)^{-1}, \quad (11)$$

where $\mu_{\text{out},n} = G(m_{1,n} + m_2 + m_3)$,

$$e_{\text{out},n} = \left(1 - \frac{|\mathbf{R}_{3,n} \times \mathbf{V}_{3,n}|^2}{\mu_{\text{out},n} a_{\text{out},n}} \right)^{1/2}. \quad (12)$$

Finally, the inclination of the outer binary orbital plane with respect to the inner binary orbital plane is tilted due to the kick. The new relative inclination i_n is computed from

$$i_n = \arccos \left(\frac{\mathbf{L}_n \cdot \mathbf{L}_{3,n}}{L_n L_{3,n}} \right), \quad (13)$$

where \mathbf{L}_n and $\mathbf{L}_{3,n}$ are the post-SN angular-momentum vectors of the inner and outer orbits, respectively.

In the event that either of the other two stars in the triple explode, or both of them, the same prescriptions described above can be applied to compute the post-SN orbital parameters. After every SN event, if either $a_{\text{in}} \leq 0$ or $a_{\text{out}} \leq 0$ the triple becomes unbound.

In this paper, we consider triple systems that survive the SN events and where the inner binary is made up of an SBH and an MS star of masses m_{SBH} and m_{MS} , respectively. A triple system undergoes KL oscillations in eccentricity whenever the initial mutual orbital inclination of the inner and outer orbits is in the window $i \sim 40^\circ$ – 140° (Kozai 1962; Lidov 1962). At the quadrupole order of approximation, the KL oscillations occur on a time-scale (Naoz 2016),

$$T_{\text{KL}} = \frac{8}{15\pi} \frac{m_{\text{tot}}}{m_3} \frac{P_{\text{out},n}^2}{P_{\text{SBHMS}}} (1 - e_{\text{out},n}^2)^{3/2}, \quad (14)$$

where m_3 is the mass of the outer body orbiting the inner SBH–MS binary, m_{tot} is the total mass of the triple system, and $P_{\text{SBHMS}} \propto a_{\text{in},n}^{3/2}$ and $P_{\text{out},n} \propto a_{\text{out},n}^{3/2}$ are the orbital periods of the inner SBH–MS binary and of the outer binary, respectively. In the quadrupole interaction approximation, the maximal eccentricity is a function of the initial mutual inclination,

$$e_{\text{in},n}^{\text{max}} = \sqrt{1 - \frac{5}{3} \cos^2 i_n}. \quad (15)$$

Whenever $i_n \sim 90^\circ$, the inner binary eccentricity approaches almost unity. If the octupole corrections are taken into account and the outer orbit is eccentric, the inner eccentricity can reach almost unity even if the initial inclination is outside of the $i_n \sim 40^\circ$ – 140° KL range (Naoz et al. 2013a; Li et al. 2014). However, KL oscillations can be suppressed by additional sources of precession, such as tidal bulges or relativistic precession (Naoz et al. 2013b; Naoz 2016).

We note that these analytical relations are useful to give a qualitative understanding of the evolution of triple systems, but we are not limited to these secular prescriptions since we use N -body simulations, as discussed in the next section. Moreover, the system may become non-hierarchical in some cases and the above secular equations lose validity (e.g. Antognini et al. 2014; Fragione et al. 2019c).

If the inner SBH–MS binary reaches sufficiently high eccentricity, the star can be tidally disrupted by the SBH. This occurs whenever their relative distance is smaller than the tidal disruption

Table 1. Models: name, mean of SBH kick-velocity distribution (σ), eccentricity distribution ($f(e)$), maximum outer semimajor axis of the triple ($a_{3,\text{max}}$), fraction of TDEs from the N -body simulations (f_{TDE}).

Name	σ (km s $^{-1}$)	$f(e)$	$a_{3,\text{max}}$ (au)	f_{TDE}
A1	34	Uniform	2000	0.14
A2	0	Uniform	2000	0.14
A3	13	Uniform	2000	0.14
B1	34	Uniform	5000	0.12
B2	34	Uniform	7000	0.13
C1	34	Thermal	2000	0.11

radius,

$$R_T = R_* \left(\frac{m_{\text{SBH}}}{m_{\text{MS}}} \right)^{1/3}, \quad (16)$$

where R_* is the radius of the star that we compute from Demircan & Kahraman (1991),

$$R_* = \begin{cases} 1.06(m_{\text{MS}}/M_\odot)^{0.945} R_\odot & m_{\text{MS}} < 1.66 M_\odot, \\ 1.33 (m_{\text{MS}}/M_\odot)^{0.555} R_\odot & m_{\text{MS}} > 1.66 M_\odot. \end{cases} \quad (17)$$

We note that the exact value of equation (16) could depend on the properties of the star (Guillochon & Ramirez-Ruiz 2013). Moreover, the effective tidal radius could be substantially larger owing to the fact that the stellar spin would increase at any close passages to the SBH (Golightly, Coughlin & Nixon 2019), if the merger happens after several KL cycles.

3 N-BODY SIMULATIONS

3.1 Initial conditions

The stellar triples in our simulations are initialized as follows. In total, we consider six different sets of initial conditions (see Table 1).

For simplicity, we assume that stars in the mass range of 20–150 M_\odot collapse to an SBH. In all our models, we adopt the Kroupa (2001) initial mass function

$$f(m) = 0.0795 M_\odot^{-1} (m/M_\odot)^{-2.3} \quad \text{if } m \geq 0.5 M_\odot \quad (18)$$

in the relevant mass range.³ We sample the mass m_1 of the most massive star in the inner binary in the mass range of 20–150 M_\odot , reflecting the progenitor of the SBH. We assume that the primary produces an SBH of mass $m_{\text{SBH}} = m_1/3$. We adopt a flat mass ratio distribution for both the inner orbit, $q_{12} = m_2/m_1$, and the outer orbit, $q_{123} = m_3/(m_1 + m_2)$ (Sana et al. 2012; Duchêne & Kraus 2013; Sana 2017).⁴ We sample q_{12} in the range of 0.5–8 M_\odot/m_1 so that the mass of the secondary ($m_{\text{MS}} = q_{12}m_1$) in the inner binary is in the range of 0.5–8 M_\odot , and sample q_{123} in the range of 0.5–150 $M_\odot/(m_1 + m_2)$ so that the mass of the third companion ($m_3 = q_{123}(m_1 + m_2)$) is in the range of 0.5–150 M_\odot . If the initial mass of the tertiary m_3 is in the range of 8–20 M_\odot , we assume it will form an NS of mass 1.3 M_\odot . For higher masses, we assume that it collapses to an SBH of mass $m_3/3$. For comparison, we also

³The constant coefficient accounts for the fraction of stars with $m < 0.5 M_\odot$ such that the integral of $\int_0^\infty f(m) dm = 1$.

⁴From observations, Duchêne & Kraus (2013) found 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 $10^{5.5}$ d, respectively, while Sana et al. (2013b) found $f(q) \propto q^{-1.0 \pm 0.4}$ for massive O-type stars.

estimate how the final TDE rate in triples changes if the mass ratio distribution is assumed to be log-uniform (Sana et al. 2013b).

The exact values of the NS and SBH masses vary with the specific evolutionary path (i.e. single and binary) followed by the progenitor star, and depend on a number of variables, such as metallicity, stellar winds, rotation, and possible common envelope phases. For example, stellar winds could be important since they may change the orbital parameters of binaries before an SBH or an NS is formed, as well as contribute to the mass-loss of a star during the MS; their strength depends on the progenitor metallicity, and hence these variables all contribute to determine the final mass of the NSs and SBHs. Here, we are not modelling these effects, which could reduce the available parameter space (Shappee & Thompson 2013). The previous picture can become even more complicated if mass-loss during possible episodes of Roche lobe overflows and common evolution phases in the triple are taken into account. While these processes are relatively well understood in binaries, they are not modelled in a self-consistent way in triple systems because of the possible interplay with the KL cycles (Di Stefano 2019; Hamers & Dosopoulou 2019). Therefore, we prefer to adopt a simple procedure to derive the final SBH and NS masses, where the maximum SBH mass is consistent with recent theoretical results on pulsational pair instabilities that limit the maximum BH mass to $\sim 50 M_\odot$ (Belczynski et al. 2016).

The distributions of the inner and outer semimajor axes, a_{in} and a_{out} (respectively), are assumed to be flat in log-space (Öpik's law), consistent with the results of Kobulnicky et al. (2014). We set as a minimum separation 10 au, and adopt different values for the maximum separation $a_{3,\text{max}} = 2000\text{--}5000\text{--}7000$ au (Sana et al. 2014). For the orbital eccentricities of the inner and outer binaries, or e_{in} and e_{out} (respectively), we assume flat distributions. For comparison, we run one additional model where we consider a thermal eccentricity distribution.

The initial mutual inclination i_0 between the inner and outer orbits is drawn from an isotropic distribution (i.e. uniform in $\cos i_0$). The other relevant angles are drawn from uniform distributions.

After sampling the relevant parameters, we check that the initial configuration satisfies the stability criterion for stable hierarchical triples (Mardling & Aarseth 2001),

$$\frac{R_p}{a_{\text{in}}} \geq 2.8 \left[\left(1 + \frac{m_3}{m_1 + m_2} \right) \frac{1 + e_{\text{out}}}{\sqrt{1 - e_{\text{out}}}} \right]^{2/5} \left(1.0 - 0.3 \frac{i_0}{\pi} \right), \quad (19)$$

where $R_p = a_{\text{out}}(1 - e_{\text{out}})$ is the pericentre distance of the outer orbit.

If the systems are stable according to the previous criterion, we let the primary star in the inner binary undergo an SN explosion and instantaneously convert it to an SBH. The orbital elements of the inner and outer orbits are updated following the procedure discussed in Section 2, to account both for mass-loss and the natal kick.

The distribution of natal kick velocities of SBHs and NSs is unknown. To be conservative, we implement momentum-conserving kicks. As a consequence, the mean kick velocities for SBHs are lower relative to those of NSs by a factor $m_{\text{SBH}}/m_{\text{NS}}$. In our fiducial model, we consider a non-zero natal kick velocity for the newly formed SBHs, by adopting equation (1) with $\sigma = 34 \text{ km s}^{-1}$ for $m_{\text{SBH}} = 10 M_\odot$. This corresponds to a mean velocity $\sim 34 \text{ km s}^{-1} \times m_{\text{SBH}}/m_{\text{NS}} \approx 260 \text{ km s}^{-1}$ for NSs, consistent with the distribution deduced by Hobbs et al. (2005). We run an additional model where we adopt $\sigma = 13 \text{ km s}^{-1}$, which translates into a mean velocity $\sim 13 \text{ km s}^{-1} \times m_{\text{SBH}}/m_{\text{NS}} \approx 100 \text{ km s}^{-1}$ for NSs, consistent with the

distribution of natal kicks found by Arzoumanian, Chernoff & Cordes (2002). Finally, we adopt a model where no natal kick is imparted during SBH formation (which we label $\sigma = 0 \text{ km s}^{-1}$). We note that even in this case, the triple experiences a kick to its centre of mass at the time of SBH formation, because one of the massive components suddenly loses mass (Blaauw 1961).

If the third companion is more massive than $8 M_\odot$, we let it undergo an SN event and convert to a compact object, either an NS with $m_{3,n} = 1.3 M_\odot$ or an SBH with $m_{3,n} = m_3/3$.⁵ If the triple remains bound, we check again the triple stability criterion of Mardling & Aarseth (2001) with the updated masses and orbital parameters for the inner and outer orbits. Fig. 1 shows the distributions of inner and outer semimajor axes of stable SBH–MS binaries in triples before (a_{in} and a_{out}) and after ($a_{\text{in},n}$ and $a_{\text{out},n}$) the SN events, for $\sigma = 0 \text{ km s}^{-1}$ and $\sigma = 34 \text{ km s}^{-1}$.

Given the above set of initial parameters, we integrate the equations of motion of the three-bodies:

$$\ddot{\mathbf{r}}_i = -G \sum_{j \neq i} \frac{m_j (\mathbf{r}_i - \mathbf{r}_j)}{|\mathbf{r}_i - \mathbf{r}_j|^3}, \quad (20)$$

with $i = 1, 2, 3$, by means of the ARCHAIN code (Mikkola & Merritt 2006, 2008), a fully regularized code able to model the evolution of binaries of arbitrary mass ratios and eccentricities with high accuracy, thanks to a transformed leapfrog method combined with the Bulirsch–Stoer extrapolation. ARCHAIN includes PN corrections up to order PN2.5 and a treatment of equilibrium dissipative and non-dissipative tides (Hut 1981; Fragione & Antonini 2019). For MS stars, we fix the apsidal motion constant to $k = 0.014$ and the time-lag factor to $\tau_{\text{lag}} = 0.66 \text{ s}$ (Fragione & Antonini 2019). We perform 1000 simulations for each model, for the initial conditions provided in Table 1. If the MS star is tidally disrupted (see equation 16), we stop the integration. Otherwise, for the secondary star in the inner binary m_2 and the third companion m_3 (assuming it does not evolve to form a compact object, or $m_3 < 8 M_\odot$), we compute an MS lifetime. This is simply parametrized as (e.g. Iben 1991; Hurley, Pols & Tout 2000; Maeder 2009)

$$\tau_{\text{MS}} = \max(10 (m/M_\odot)^{-2.5} \text{ Gyr}, 7 \text{ Myr}). \quad (21)$$

We fix the maximum integration time,

$$T = [\min(\tau_{\text{MS},1}, \tau_{\text{MS},3}), \min(10^3 \times T_{\text{KL}}, 10 \text{ Gyr})], \quad (22)$$

where T_{KL} is the triple KL time-scale. We also check if the secondary star in the inner binary or the third star (if it does not collapse to a compact object) overflow their Roche lobe using the formulae provided in Eggleton (1983). In this case, we stop the integration.

3.2 Results

A SBH–MS 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). According to equation (15), the SBH–MS eccentricity reaches almost unity when $i_n \sim 90^\circ$. Fig. 2 shows the inclination probability distribution function (PDF) of merging SBH–MS binaries in triples. The distributions are shown for $a_{3,\text{max}} = 2000$ au and different values of σ . Independently of the mean of the natal kick

⁵We do not model the process that leads to the formation of a white dwarf. We note that in the case the third companion becomes a white dwarf, and the system remains bound according to equation (19), some of the systems could still produce a TDE.

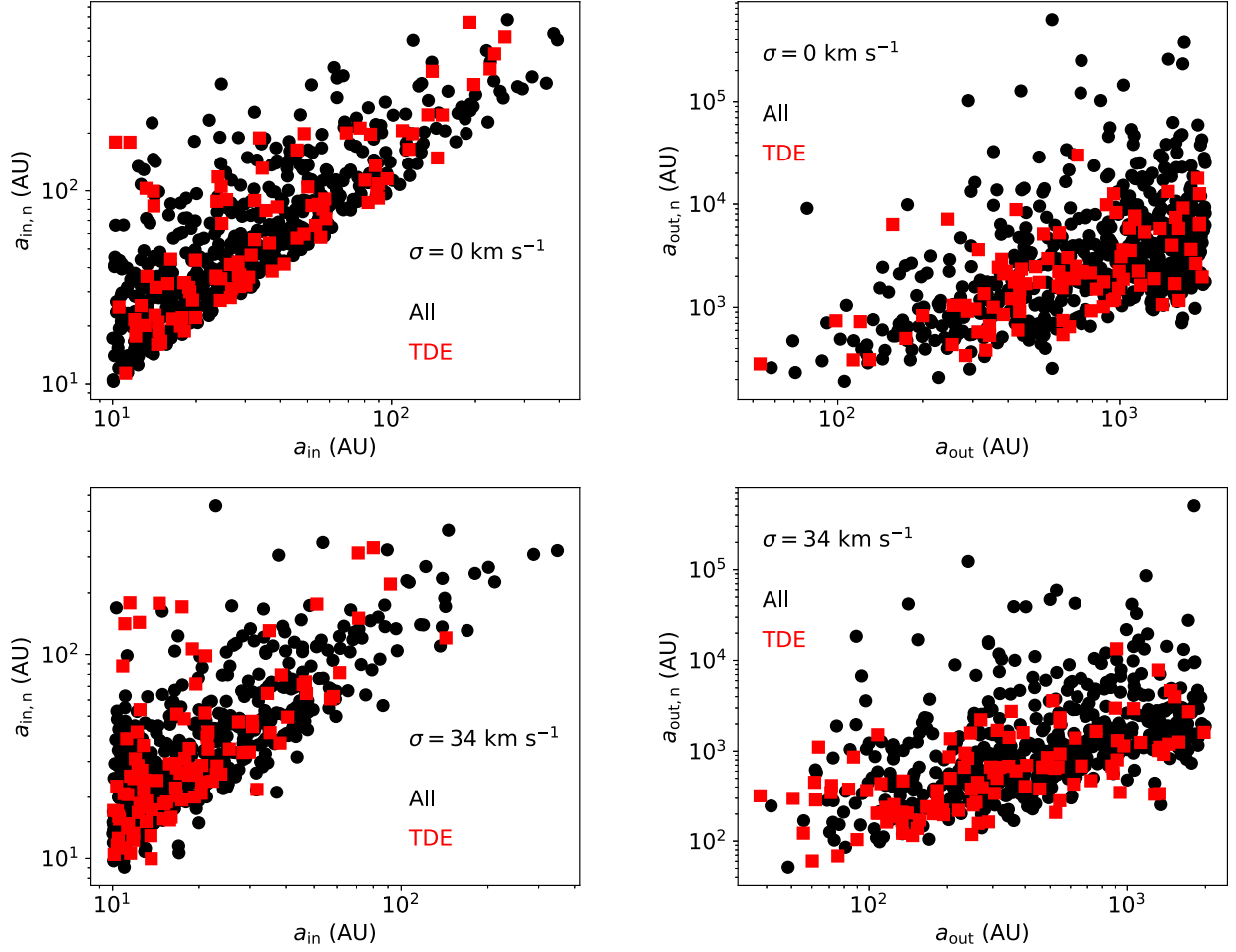


Figure 1. Distributions of inner and outer semimajor axes of SBH–MS binaries in triples before (a_{in} and a_{out}) and after ($a_{\text{in},n}$ and $a_{\text{out},n}$) the SN events for $\sigma = 0 \text{ km s}^{-1}$ and $\sigma = 34 \text{ km s}^{-1}$ kicks. Systems that lead to a TDE are marked in red.

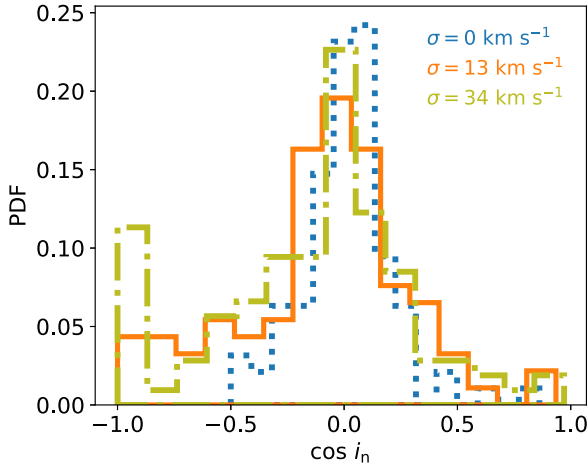


Figure 2. Inclination PDF of merging SBH–MS binaries in triples, for $a_{3,\text{max}} = 2000 \text{ au}$ and different values of the mean kick velocity σ .

velocity, the majority of SBH–MS TDEs in triples occur when the inclination approaches $\sim 90^\circ$. In this case, the KL effect is maximal, leading to eccentricity oscillations up to unity. SBH–MS systems that undergo a TDE with low relative inclinations typically have

large initial eccentricities. We also identify a possible second peak at $i_n \sim 180^\circ$ for high natal kicks, which corresponds to a coplanar counterrotating configuration. We note that an enhancement of GW-driven mergers in SBH triples at $\sim 180^\circ$ was also seen previously in non-hierarchical three-body simulations by Arca-Sedda, Li & Kocsis (2018) that may be related to the coplanar flip phenomenon (Li et al. 2014).

In Fig. 3, we show the PDF distribution of the eccentricity e_{TDE} (top) and penetration factor β (bottom) of MS stars that produce a TDE in triples, for $a_{3,\text{max}} = 2000 \text{ au}$ and different values of the mean kick velocity σ . The penetration factor

$$\beta \equiv \frac{R_{\text{T}}}{R_{\text{p}}} = \left(\frac{R_{\text{p}}}{R_{\text{*}}} \right)^{-1} \left(\frac{m_{\text{SBH}}}{m_{\text{MS}}} \right)^{1/3}, \quad (23)$$

where R_{p} is the pericentre of the MS star, gives an indication of how extreme some of these encounters could be. For all the σ 's, the distribution of e_{TDE} is peaked at ~ 1 , similarly to the case of a TDE by an SMBH. The distribution of penetration factors is peaked at ~ 1 , with non-negligible tails in the range ~ 0.02 – 10 . This is different than the case of SMBHs and IMBHs, for which $\beta \gg 1$ and strong tidal compression is possible.

Fig. 4 reports the cumulative distribution function (CDF) of the inner (top) and outer (bottom) semimajor axes of SBH–MS binaries in triples that lead to a TDE, for different values of σ . The larger the

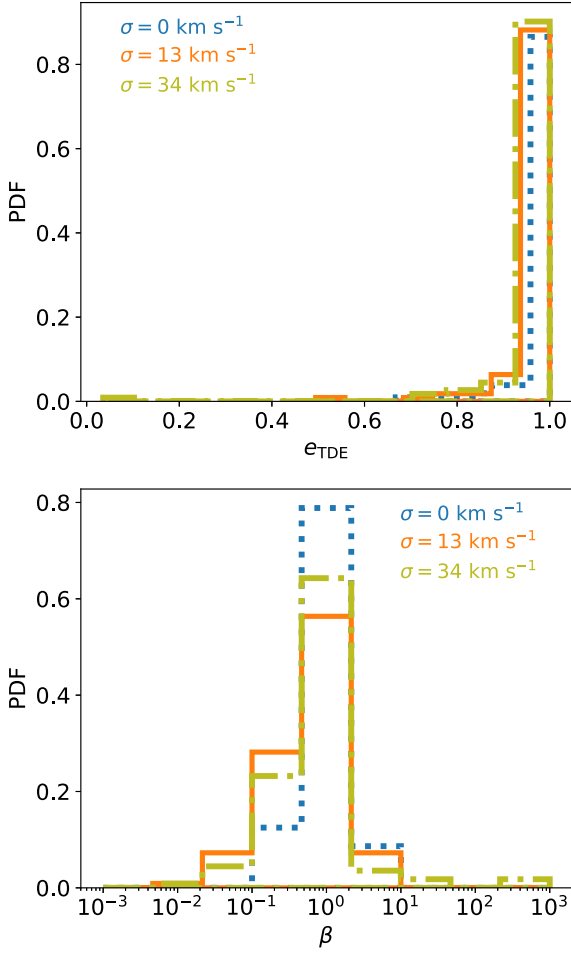


Figure 3. PDF distribution of the eccentricity (top) and penetration factor (bottom) of MS stars that produce a TDE in triples, for $a_{3,\text{max}} = 2000$ au and different values of the mean kick velocity σ .

mean natal kick, the smaller the typical inner and outer semimajor axes. This can be understood by considering that triples with wide orbits are generally left unbound by large kick velocities, while they stay bound if the natal kick is not too intense. We find similar CDFs for $\sigma = 13 \text{ km s}^{-1}$ and $\sigma = 34 \text{ km s}^{-1}$, but significant differences for $\sigma = 0 \text{ km s}^{-1}$. For the inner orbit, we find that ~ 50 per cent of the systems that produce a TDE have $a_{\text{in},n} \lesssim 60 \text{ au}$ and $\lesssim 30 \text{ au}$ for $\sigma = 0 \text{ km s}^{-1}$ and 34 km s^{-1} , respectively. For the outer orbit, we find that ~ 50 per cent of the systems have $a_{\text{out},n} \lesssim 2000 \text{ au}$ and $\lesssim 500 \text{ au}$ for $\sigma = 0 \text{ km s}^{-1}$ and 34 km s^{-1} , respectively.

The typical mean natal kick velocity affects also the distribution of SBH masses in SBH–MS binaries that lead to a TDE in triple systems. We illustrate this in Fig. 5, where we plot the CDF and PDF of m_{SBH} of SBH–MS binaries in triples that lead to a TDE, for different values of σ . In the case of $\sigma = 0 \text{ km s}^{-1}$, we find that merging SBHs have typically lower masses compared to the models with $\sigma = 13 \text{ km s}^{-1}$ and $\sigma = 34 \text{ km s}^{-1}$. In the former case, ~ 50 per cent of the SBHs that produce a TDE have masses $\lesssim 10 M_{\odot}$, while for non-zero kick velocities we find that ~ 50 per cent of the SBHs have masses $\lesssim 25 M_{\odot}$ and $\lesssim 35 M_{\odot}$ for $\sigma = 13 \text{ km s}^{-1}$ and $\sigma = 34 \text{ km s}^{-1}$, respectively. This is justified by our assumption of momentum-conserving kicks, where higher mass SBHs receive, on average, lower velocity kicks and, as a consequence, are more likely to be retained in triples and eventually produce a TDE.

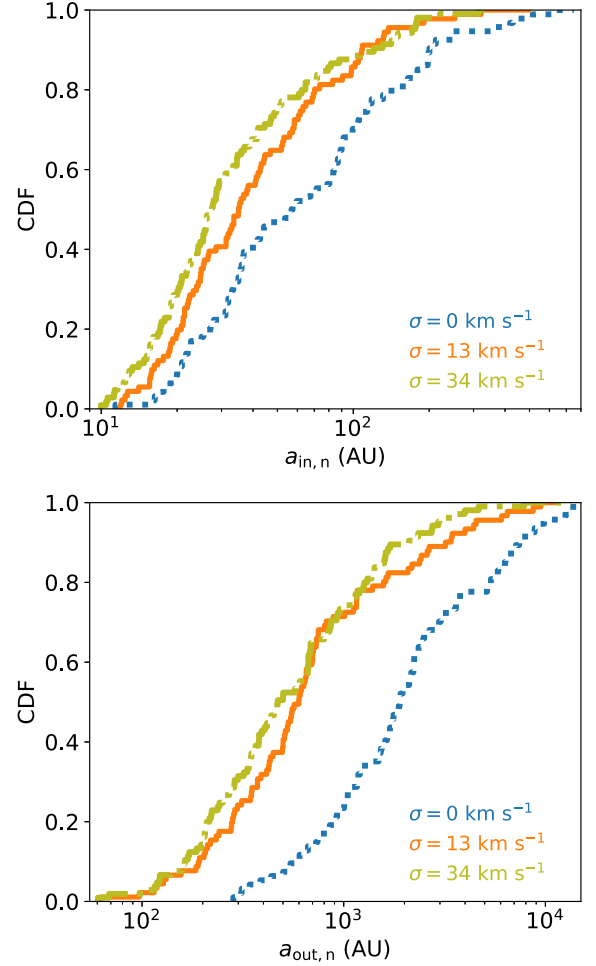


Figure 4. CDF of inner (top) and outer (bottom) semi-major axes of SBH–MS binaries in triples that lead to a TDE, for different values of σ .

The mean velocity σ has an effect also in determining the typical mass of the third companion in triples that lead to a TDE. We show this in Fig. 6, where we plot the progenitor mass m_3 of the third companion of SBH–MS binaries in triples that lead to a TDE for $\sigma = 0 \text{ km s}^{-1}$ (top) and $\sigma = 34 \text{ km s}^{-1}$ (bottom). Note that $m_{3,n} = m_3$, if $m_3 \lesssim 8 M_{\odot}$. In the case of no natal kick velocity, the third companion in triples that lead to a TDE can be an MS star, an NS, or an SBH. If $\sigma = 34 \text{ km s}^{-1}$, which corresponds to a mean velocity of $\sim 260 \text{ km s}^{-1}$ for NSs, none of the third companions is an NS because the large v_k typically unbinds the triple. Moreover, if the third companion is an SBH (i.e. given two SN events that lead to the formation of an SBH in the inner binary and an SBH as tertiary), its typical mass $m_{3,n}$ is smaller in the case $\sigma = 0 \text{ km s}^{-1}$ than the case $\sigma = 34 \text{ km s}^{-1}$, as explained above (for the SBH in the inner binary).

Fig. 7 reports the CDF and PDF of the TDE time (after the SN event) of SBH–MS binaries in triples that lead to a TDE for all models (see Table 1). The shape of these CDFs depends only on the value of σ , where Model A2 has a distribution shifted by about one order of magnitude compared to other models with non-zero natal kicks. In order to compute the TDE rate of SBH–MS in triples, we assume that the local star formation rate is $0.025 M_{\odot} \text{ Mpc}^{-3} \text{ yr}^{-1}$ (Bothwell et al. 2011), thus the number of stars formed per unit

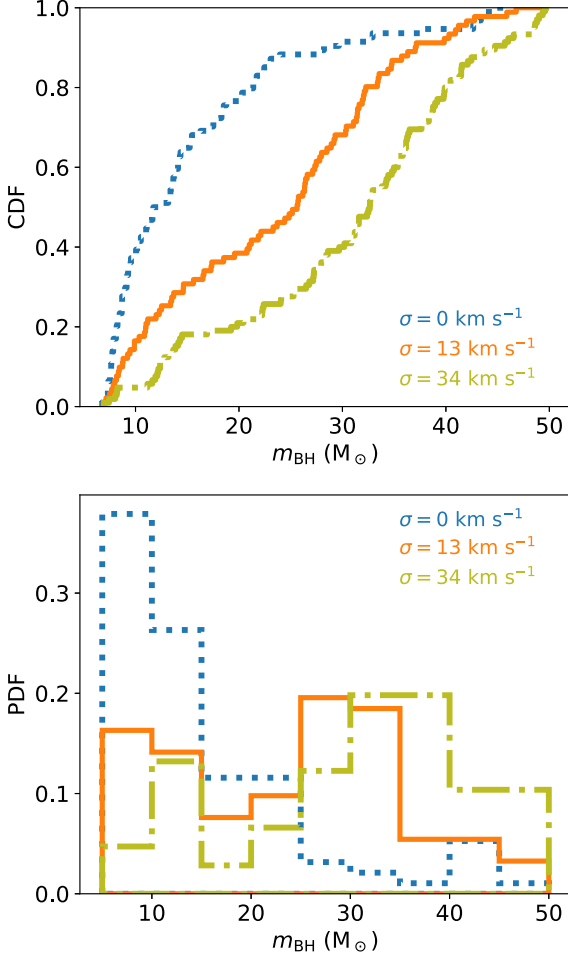


Figure 5. CDF (top) and PDF (bottom) of the mass of SBHs in SBH-MS binaries in triples that lead to a TDE, for different values of σ .

mass, volume, and time is given by

$$\begin{aligned} \dot{n}(m) &= \frac{\eta_{\text{SFR}} f(m)}{\langle m \rangle} \\ &= 5.2 \times 10^6 \left(\frac{m}{M_\odot} \right)^{-2.3} M_\odot^{-1} \text{Gpc}^{-3} \text{yr}^{-1}, \end{aligned} \quad (24)$$

where $\langle m \rangle = 0.38 M_\odot$ is the average stellar mass. Assuming a constant star formation rate, the TDE rate in triple systems is then

$$\begin{aligned} R_{\text{TDE}} &= \eta(1 - \zeta) f_3 f_{\text{stable}} f_{\text{TDE}} \int_{20 M_\odot}^{150 M_\odot} \dot{n}(m_1) dm_1 \\ &= 7.4 \times 10^4 \eta(1 - \zeta) f_3 f_{\text{stable}} f_{\text{TDE}} \text{Gpc}^{-3} \text{yr}^{-1}, \end{aligned} \quad (25)$$

where f_3 is the fraction of stars in triples, f_{stable} is the fraction of systems that remain stable after the SN events take place, and f_{TDE} is the fraction of systems that lead to a TDE (see Table 1). The factor η comes from assumptions that the secondary mass satisfies $1 M_\odot \leq m_2 = q_{12} m_1 \leq 8 M_\odot$, when sampling the mass ratio q_{12} ,

$$\eta = \frac{\int_{0.01 M_\odot}^{150 M_\odot} dm_1 f_{\text{IMF}}(m_1) \int_{1 M_\odot/m_1}^{8 M_\odot/m_1} dq f_q(q)}{\int_{20 M_\odot}^{150 M_\odot} dm_1 f_{\text{IMF}}(m_1)}. \quad (26)$$

Here, $f_q(q)$ is the mass ratio distribution. We find $\eta = 0.21$ and $\eta = 0.25$, for an uniform and log-uniform mass ratio distributions,

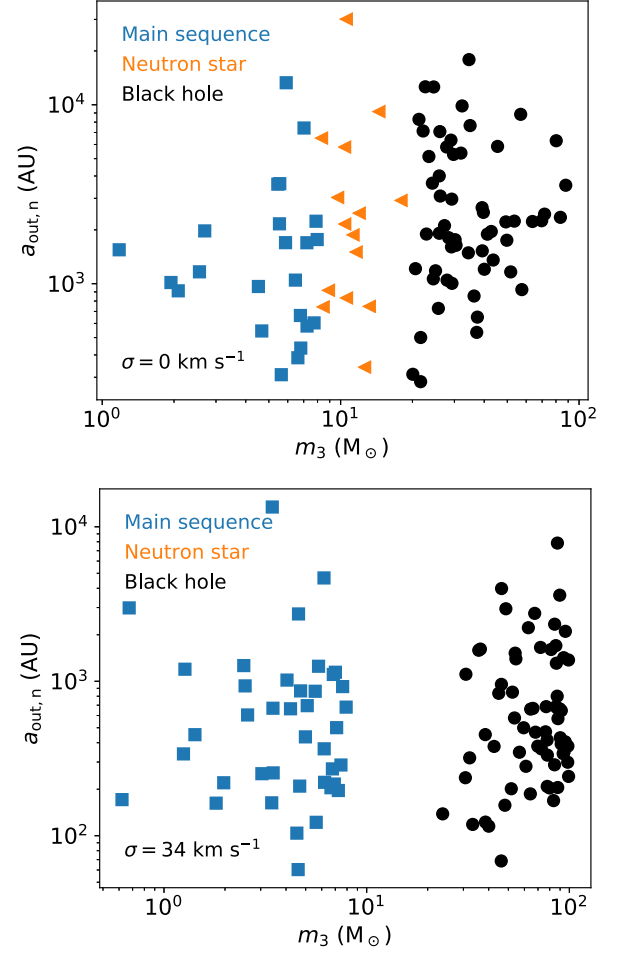


Figure 6. Progenitor mass of the third companion of SBH-MS binaries in triples that lead to a TDE for $\sigma = 0 \text{ km s}^{-1}$ (top) and $\sigma = 34 \text{ km s}^{-1}$ (bottom).

respectively. A factor of uncertainty is the possible KL dynamics during the evolution of the stellar triples before they form an SBH-MS system in the inner binary, which we have not modelled here. Some fraction of the parameter space can be removed by the earlier evolution of the system (Shappee & Thompson 2013). To estimate this uncertainty, we consider very conservatively that any stellar triple whose initial KL time-scale is less than the lifetime of the primary star ($\sim 7 \text{ Myr}$; Iben 1991; Hurley et al. 2000; Maeder 2009) in the inner binary merges in the MS phase, and, as a consequence, will not form a triple system with an inner SBH-MS binary (Rodríguez & Antonini 2018). We find that the fraction of these triples is $\zeta \sim 0.8$ on average, except for Model A2 where we find $\zeta \sim 0.7$.

In our calculations, we adopt $f_3 = 0.25$. The fraction of stable systems after SNe depends mainly on the value of σ for the natal velocity kick distribution. We find $f_{\text{stable}} \approx 9.2 \times 10^{-2}$, 8.1×10^{-3} , 1.6×10^{-3} for $\sigma = 0 \text{ km s}^{-1}$, 13 km s^{-1} , 34 km s^{-1} , respectively, when $a_{3,\text{max}} = 2000 \text{ au}$, and $f_{\text{stable}} \approx 1.6 \times 10^{-3}$, 1.1×10^{-3} , 1.0×10^{-3} for $a_{3,\text{max}} = 2000, 5000, 7000 \text{ au}$, respectively, when $\sigma = 260 \text{ km s}^{-1}$. The typical fraction of systems that produce a TDE is $f_{\text{TDE}} = 0.13$ (see Table 1). Here, we include also systems that result in crossing of the Roche limit. This can produce phases of accretion as X-ray binaries and may drive the two stars into merging (e.g. Naoz & Fabrycky 2014). We find that typically these

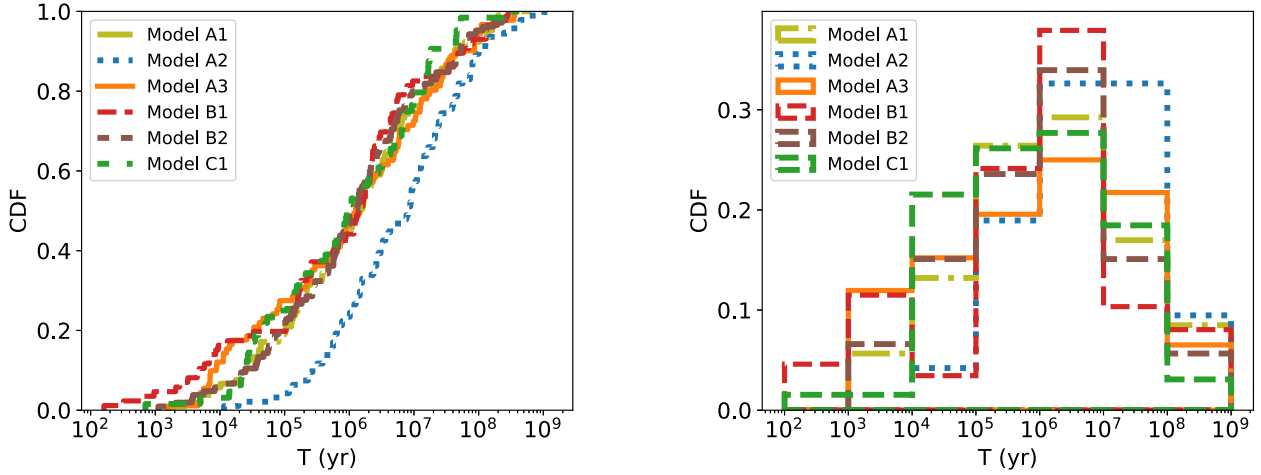


Figure 7. CDF (left) and PDF (right) of the TDE time (after the SN event) of SBH-MS binaries in triples that lead to a TDE for all models (see Table 1).

systems constitute ~ 30 – 50 per cent of the merging systems. Using the minimum and maximum values of f_{stable} in Table 1, our final estimated rate is in the range of

$$R_{\text{TDE}} = 0.11\text{--}16 \text{ Gpc}^{-3} \text{ yr}^{-1}. \quad (27)$$

For a log-uniform distribution of mass ratios, we estimate a rate ~ 2 times larger. Considering the signal up to $z = 0.1$, the TDE rate becomes

$$\Gamma_{\text{TDE}}(z \leq 0.1) = 3.4 \times 10^{-2} \text{--} 4.7 \text{ yr}^{-1}. \quad (28)$$

We have also computed the values of f_{stable} in the case of non-momentum-conserving kicks, i.e. all the SBHs (and NSs) receive a kick independent of their mass (see e.g. Perna et al. 2018a). We have found that $f_{\text{stable}} \sim 9.2 \times 10^{-2}$, 2.2×10^{-4} , 2.6×10^{-5} , 1.7×10^{-6} for $\sigma = 0 \text{ km s}^{-1}$, $\sigma = 50 \text{ km s}^{-1}$, 100 km s^{-1} , 260 km s^{-1} , respectively. Thus, assuming an average $f_{\text{TDE}} = 0.15$, the predicted local TDE rate is for non-momentum-conserving kicks,

$$\Gamma_{\text{TDE},3}^{\text{NC}}(z \leq 0.1) = 2.1 \times 10^{-4} \text{--} 4.7 \text{ yr}^{-1}. \quad (29)$$

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

$$\Gamma_{\text{TDE}}^{\text{MW}} = 1.3 \times 10^{-9} \text{--} 1.9 \times 10^{-7} \text{ yr}^{-1}. \quad (30)$$

For comparison, the rates for SMBHs and IMBHs are estimated to be 10^{-5} – 10^{-4} yr^{-1} (van Velzen 2018) and 10^{-5} – 10^{-3} yr^{-1} (Fragione et al. 2018), respectively.

We note that we are not taking into consideration fallback, whose effect would likely increase the TDE rates for large σ_{SBH} 's.

4 ELECTROMAGNETIC SIGNATURES OF STELLAR TDES

How can these events be recognized among the variety of transient sources on the sky? TDEs on to massive BHs (MBHs) ubiquitous in galactic centres have long been studied in the literature, partly motivated by actual detections of TDEs by MBHs. However, the basic physics of the phenomenon is expected to be similar across different scales, with the mass of the disrupting BH mostly dictating the characteristic accretion rate (and hence luminosity) and the duration of the event.

Before discussing the above, we need to assess whether the presence of the outer companion is expected to be influential on the TDE event. In fact, it has been discussed in the context of MBHs that binarity can impact the rate of mass fallback and the formation of an accretion flow following the disruption event (Liu, Li & Komossa 2014; Coughlin et al. 2017). In particular, fallback dynamics will be drastically perturbed if the apocenter distance a_{apo} of fallback orbits is such that $a_{\text{apo}} > a_{\text{out}}$. This translates into $a_{\text{out}} < 3 \times 10^{-6} (m_{\text{MS}}/M_{\odot})^{1/3} (T/1 \text{ month})^{2/3} \text{ pc}$, where T is the time after disruption. Comparing this distance with the distribution of separations of the outer companion of the (former) triple studied here (cf. Fig. 4), we see that $a_{\text{out}} \gg a_{\text{apo}}$, and hence the presence of the outer companion is not expected to affect the fallback dynamics.

Once the star (of mass m_{MS} and radius R_{*}) has been disrupted, elements of the tidal debris move on nearly geodesic orbits around the BH. In order to circularize, i.e. to form an accretion disc, the bound matter must lose a significant amount of energy. Circularization is believed to be possible thanks to general relativistic effects, as apsidal precession forces highly eccentric debris streams to self-intersect (i.e. Stone et al. 2019a). However, whether circularization can be completed before the end of the actual event still remains an issue of debate (Piran et al. 2015); albeit, in the case of SBHs, it is aided by the fact that the bound debris are not highly eccentric (Kremer et al. 2019). A large fraction of the debris 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 material that remains bound, the fallback rate after an initial rapid increase follows roughly the decay (Phinney 1989)

$$\dot{m}_{\text{MS}} \sim \frac{m_{\text{MS}}}{t_0} \left(\frac{t}{t_0} \right)^{-5/3}, \quad (31)$$

where t_0 represents the time after which the first bound material returns to pericenter (R_p), with $R_p \sim R_T$, (see e.g. Guillochon & Ramirez-Ruiz 2013; Stone, Sari & Loeb 2013; Stone et al. 2019b), i.e.

$$\begin{aligned} t_0 &= \frac{\pi R_T^3}{\sqrt{2Gm_{\text{SBH}}R_*^3}} \\ &\approx 9 \times 10^3 \text{ s} \left(\frac{R_T}{R_{\odot}} \right)^3 \left(\frac{R_{\odot}}{R_*} \right)^{3/2} \left(\frac{10 \text{ M}_{\odot}}{m_{\text{SBH}}} \right)^{1/2} \\ &= 9 \times 10^3 \text{ s} \left(\frac{R_*}{R_{\odot}} \right)^{3/2} \left(\frac{m_{\text{MS}}}{M_{\odot}} \right)^{-1} \left(\frac{m_{\text{SBH}}}{10 \text{ M}_{\odot}} \right)^{1/2}. \end{aligned} \quad (32)$$

The late-time fallback light curve is often observed to be shallower than t^{-1} (Auchettl, Guillochon & Ramirez-Ruiz 2017), which may be due to general relativistic corrections to viscous diffusion and finite stress at the last stable orbit (Balbus & Mummery 2018). Note however that, in the cases for which only partial disruption of the star is achieved, then the fallback rate is found to be steeper than $t^{-5/3}$ (e.g. Guillochon & Ramirez-Ruiz 2013). Recently, Coughlin & Nixon (2019) showed that the fallback rate from a partial TDE follows a universal scaling of $t^{-9/4}$.

In our calculations, we are assuming that a star is disrupted whenever its closest passage to the SBH is smaller than R_T (Equation 16). We note that R_T is only the leading order term in the ratio $R_*/r_{\text{CM},*}$, where $r_{\text{CM},*}$ is the position of the centre of mass of the star. Higher order terms in the gravitational potential (as the binding energy of the disrupted star itself) could remain important if comparable to the spread induced by the SBH tidal potential, and this will further modify the energy distribution of the disrupted debris. As a consequence, a larger fraction of the debris produced by the TDE may be bound to the SBH, resulting in a larger peak accretion rate and corresponding luminosity.

Once a disc is formed, the time-scale for the tidally disrupted debris to accrete is set by the viscous time-scale. For a geometrically thick disc (i.e. with a scale height $H/R \sim 1$), as expected at high accretion rates, this is given by

$$t_{\text{acc}} \sim \frac{1}{\alpha \Omega_K(R_{\text{in}})} = 4 \times 10^4 \text{ s} \left(\frac{\alpha}{0.1} \right)^{-1} \left(\frac{R_{\text{in}}}{2 R_\odot} \right)^{3/2} \left(\frac{10 M_\odot}{m_{\text{SBH}}} \right)^{1/2}, \quad (33)$$

where $\Omega_K(R_{\text{in}})$ is the Keplerian angular speed at the radius of closest approach $R_{\text{in}} = R_p$, and α the viscosity constant (Shakura & Sunyaev 1973). The maximum accretion rate, $\dot{M}_{\text{acc}} \sim \dot{M}_{\text{fb}}/t_{\text{acc}}$, with \dot{M}_{fb} being the fraction of m_{MS} that remains bound and falls back, is found to be in the range of $\sim \text{few} \times 10^{-6} - \text{few} \times 10^{-5} M_\odot \text{ s}^{-1}$ (Perets et al. 2016; Kremer et al. 2019), and it declines at later times as a power law, as discussed above. These accretion rates are somewhat lower, but still relatively comparable, to the fallback rates found in numerical simulations of the collapse of blue supergiant stars (Perna, Lazzati & Cantiello 2018b), which have been invoked as possible progenitors of the small but interesting sub-class of ultra-long GRBs (Gendre et al. 2013). If a jet is driven as observed in TDEs from MBHs, then the phenomenology may indeed appear similar to that of the ultra-long GRBs, as pointed out by Perets et al. (2016), i.e. a bright and energetic flare in γ -rays and X-rays, with durations on the order of $10^3 - 10^4$ s. These events would be distinguishable from the ultra-long GRBs, in that they would not have a supernova associated with them. Furthermore, the TDEs formed in stellar-mass triples are expected to have different spectra, since they are not limited to any particular stellar type such as Wolf-Rayet or blue supergiants that produce long- and ultra-long GRBs, respectively.

The above scenario assumes that a jet is successfully launched. However, this may not necessarily be the case: the physics of hyper-Eddington accretion is still not fully understood (see e.g. Abramowicz & Fragile 2013), and neither are the conditions required for the production of a relativistic, ‘GRB-like’ jet. Several studies (i.e. Narayan & Yi 1994; Blandford & Begelman 1999) have shown that strong winds can blow away a significant fraction of the disc mass. The radiation-hydrodynamic evolution of such a wind was recently calculated by Kremer et al. (2019); they found that it can give rise to optical transients with luminosities $\sim 10^{41} - 10^{44} \text{ erg s}^{-1}$, lasting from a day to about a month. An event with a typical luminosity of $10^{42} \text{ erg s}^{-1}$ would be observable with the

Zwicky Transient Facility up to a distance of ~ 150 Mpc. The higher sensitivity of the upcoming LSST survey ($r < 24.5$ for 15 s of integration time during the routine sky scans) would allow detection up to about 0.5 Gpc for a luminosity of $\sim 10^{41} \text{ erg s}^{-1}$.

In the most pessimistic scenario, in which a jet is not launched and the unbound material is not strongly emitting, the dominant source of luminosity would be provided by the accretion disc (such as in advection-dominated accretion discs with super-Eddington accretion and low radiative efficiency, e.g. Popham, Woosley & Fryer 1999; Narayan, Piran & Kumar 2001; Janiuk et al. 2004) and it would be Eddington-limited, hence not expected to exceed $\sim 10^{40} \text{ erg}$. These events, mostly brighter in X-rays, would constitute the high-end of the high-mass X-ray binary luminosity function, but would be transient.

Additional emission could arise even *prior* to the TDE event as the gas liberated by the SN could accrete on to the SBH, initiating X-ray emission. These systems would look like high-mass X-ray binaries with a steady increase in X-rays, which have a sudden jump in brightness in X-rays, and/or at other wavelengths as a consequence of the TDE, if the latter takes place not too long after the SN explosion.

5 DISCUSSION AND CONCLUSIONS

In this paper, we have investigated the possibility that triple stars are sources of TDEs, some of which can take place off-centre from the nucleus of the host galaxy. We started from a triple system made up of three MS stars and modelled the SN event that leads to the production of an inner binary comprised of an SBH. We evolved these triples with a high-precision N -body code and studied their TDEs as a result of KL oscillations. We adopted different distributions of natal kicks imparted during the SN event, different maximum initial separations for the triples, and different distributions of eccentricities. Most of the systems produce a TDE when the relative inclination of the inner and outer orbits is $\sim 90^\circ$ after the SN event takes place. We showed that the main parameter that governs the properties of the SBH–MS binaries that produce a TDE in triples is the mean natal velocity kick. Smaller values lead to larger inner and outer semimajor axes of the systems that undergo a TDE, smaller SBH masses, and larger merging time-scales.

While the fraction of systems that remain in a stable triple f_{stable} depends critically on the prescriptions adopted for natal kicks, we found that the fraction of these systems that produce a TDE, f_{TDE} , is not significantly affected by the initial conditions considered in this work and is typically ~ 15 per cent (see Table 1). Therefore, the future observed TDE rates of stars on to SBHs could be used to constrain the underlying kick distribution. We have estimated the rate of TDEs in triples in the range of $3.4 \times 10^{-2} - 4.7 \text{ yr}^{-1}$ for $z \leq 0.1$, assuming momentum-conserving natal kicks, consistent with the recent rate inferred for star clusters by Kremer et al. (2019). For a Milky Way-like galaxy, we found a rate in the range $1.3 \times 10^{-9} - 1.9 \times 10^{-7} \text{ yr}^{-1}$. As a comparative reference, the rates for SMBHs and IMBHs are estimated to be $10^{-5} - 10^{-4} \text{ yr}^{-1}$ (van Velzen 2018) and $10^{-5} - 10^{-3} \text{ yr}^{-1}$ (Fragione et al. 2018), respectively. If the MS stars evolve to form a WD, SBH–WD binaries can merge under the influence of the third companion via KL cycles and are expected to generate other kinds of transients (Fragione et al. 2019a).

We used simple prescriptions to determine the final NS and SBH masses, without entering into the details of the single and binary stellar evolution, and hence the dependence of the compact remnants on metallicity, stellar winds, rotation, Roche lobe overflows, and possible common envelope phases. These effects could reduce

the parameter space (Shappee & Thompson 2013) studied here; however, they still lack a full, self-consistent description in triple systems, due to the possible interplay with the KL cycles (Di Stefano 2019; Hamers & Dosopoulou 2019). This could have an effect on the final rates estimated in this work. We leave it to a future study to quantify the importance of these effects in the context of triple stellar evolution.

A triple system comprised of an inner SBH–MS binary orbiting an SMBH could similarly produce TDEs on to SBHs. The triple dynamics would be similar, but would take place on a shorter time-scale owing to the large SMBH mass. The typical rate of TDEs coming from this channel would then depend on the supply rate of binaries that produce an SBH–MS binary. This could be due to a slow segregation of binaries from the outermost regions of the SMBH sphere of influence or local star formation (Fragione et al. 2019c). Thus, if there is a nuclear starburst that would populate the innermost regions of the galaxy with these kind of binaries, a burst of TDEs on to SBHs is expected coming from the centre of the galaxy. Therefore, these TDEs would come from the galactic nucleus as the usual TDEs on to SMBH.

Detectability of these events will depend on the dominant emission mechanism. If a jet is successfully launched, then the observable phenomenology is going to resemble that of an ultra-long GRB. So far, only a handful of these has been observed. Hence the upper bound of our predicted rates is already starting to be probed by the rates of these events, at least for jets with a wide angular size. Additional (or alternative emission of no jet is successfully launched) could come from a disc wind (Kremer et al. 2019), and would be peaking in the optical; for typical luminosities it would be detectable by LSST with up to a few events per year. In the most pessimistic scenario in which neither jets nor winds are launched, these systems would populate the tail of the high-mass X-ray binaries, but would be transient; some X-ray emission could be seen even preceding the TDE.

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