Stellar Binaries Incident on Supermassive Black Hole Binaries: Implications for Double Tidal Disruption Events, Calcium-rich Transients, and Hypervelocity Stars

Eric R. Coughlin1,4, Siva Darbha2, Daniel Kasen1,3, and Eliot Quataert1

1 Astronomy Department and Theoretical Astrophysics Center, University of California, Berkeley, Berkeley, CA 94720, USA; eric_coughlin@berkeley.edu
2 Department of Physics, University of California, Berkeley, Berkeley, CA 94720, USA
3 Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA

Received 2018 February 21; revised 2018 August 2; accepted 2018 August 2; published 2018 August 16

Abstract

We analyze the outcome of the interaction between a stellar binary and a supermassive black hole binary (SMBHB) by performing a large number of gravitational scattering experiments. Most of the encounters result in either the ejection of an intact binary or the ejection of two individual stars following the tidal breakup of the binary. However, tidal disruption events (TDEs) and mergers constitute a few percent of the outcomes, and double temporally distinct TDEs (i.e., separated by at least one orbit of the SMBHB) occur at the percent level. We also demonstrate that the properties of the ejected binaries are significantly altered through the interaction with the SMBHB, and their large eccentricities increase the merger rate and could lead to gravitational-wave inspirals far from the nucleus of the host galaxy. We discuss our results in the context of observed tidal disruption events, hypervelocity stars, and remote supernovae, such as calcium-rich transients.

Key words: binaries: general – black hole physics – galaxies: nuclei

1. Introduction

Discerning the presence of a supermassive black hole binary (SMBHB; Begelman et al. 1980) in the center of a galaxy is challenging (e.g., Comerford et al. 2015; Liu et al. 2016), and this is especially true when neither hole is active and the separation is small. One possible tool for probing such quiescent, near-merger SMBHBs is the tidal disruption of stars (Rees 1988), as the accretion of the disrupted material onto the disrupting SMBH can be modulated on timescales comparable to the binary orbital period (Liu et al. 2009; Ricarte et al. 2016; Coughlin et al. 2017). Furthermore, depending on the mechanism responsible for injecting stars into the loss cone (Frank & Rees 1976; Lightman & Shapiro 1977; Magorrian & Tremaine 1999; Stone & Metzger 2016) and the stage of the binary inspiral, the rate of disruption can be greatly enhanced (Chen et al. 2009; Wegg & Nate Bode 2011). Thus, especially with current wide-field surveys (and the upcoming era of the Large Synoptic Survey Telescope (LSST); Ivezić et al. 2008), our inevitable detection of multiple tidal disruption events (TDEs) in the same galaxy could be highly indicative of a SMBHB at its center.

The studies of the dynamical effects of an SMBHB on a stellar population, which ultimately lead to TDEs or stellar ejections, have largely focused on the outcome of single stars encountering the binary (e.g., Quinlan 1996; Yu & Tremaine 2003; Bromley et al. 2006; Sesana et al. 2008; Darbha et al. 2018). However, a large fraction of stars—especially those toward the massive end—are known to occur in binaries (e.g., Eggleton & Tokovinin 2008; Yuan et al. 2015). Owing to its internal degrees of freedom, a stellar binary interacting with an SMBHB can yield many more outcomes, including not just the ejection of a hypervelocity binary (Lu et al. 2007; Sesana et al. 2009; Guillochon & Loeb 2015) or the disruption of one star (Wang et al. 2018), but the ejection of one star at the expense of capturing the other (the Hills mechanism; Hills 1988), the merger of the stellar binary owing to repeated perturbations to its orbit (Bradnick et al. 2017; Liu et al. 2017), and the tidal disruption of both stars at temporally distinct times.

By performing a large number of numerical gravitational scattering experiments between a stellar binary and an SMBHB, in this Letter we attempt to gain an understanding of the relative likelihood of these outcomes. In Section 2 we describe the setup of the problem and the parameters chosen for our study. Section 3 presents the results, and we demonstrate that two temporally separated TDEs can occur, albeit infrequently (≪1% of the time), from these interactions; we also discuss the properties of the ejected stellar binaries, and we give the probabilities of the various outcomes (e.g., stellar mergers, captures) as a function of stellar separation. Our conclusions are given in Section 4.

2. Problem Setup

A stellar binary, with individual masses $m_1$ and $m_2$, total mass $m = m_1 + m_2$, and semimajor axis $a_\star$ (we assume here that the stellar binary and SMBHB are circular for simplicity), incident on an SMBHB, with individual masses $M_1$ and $M_2$, total mass $M = M_1 + M_2$, and separation $a_\star$, can be described by its initial center of mass (COM) position, its COM orbit, and the orientation of the stellar semimajor axis with respect to the COM orbit. Here we will assume that the stellar binary is approaching the SMBHB from a large distance, and hence we will let the COM orbit be parabolic. We will also presuppose that the COM is in the “pinhole” regime, meaning that the square of its specific angular momentum, $\ell^2$, is uniformly distributed; to ensure that the stellar binary interacts strongly with the SMBHB, we will let this range be $0 \leq \ell^2 \leq 4 \, G M_\star$, corresponding to a stellar COM pericenter between 0 and $2a_\star$. If there are a large number of “massive perturbers” in the vicinity of the SMBHB, it is possible for the stellar binary to be captured, resulting in a near-instantaneous merger.

5 This is a reasonable assumption if each stellar binary undergoes a number of “collisions” over its lifetime that randomize its COM properties and cause it to enter the loss cone from a large distance (≪ the SMBHB sphere of influence).
galaxy (e.g., giant molecular clouds or stellar clusters, the presence of which may be enhanced following a gas-rich merger), one can further enhance the influx of stellar binaries from the pinhole regime (Perets et al. 2007; Perets & Alexander 2008). Furthermore, for tight SMBHBs that are within the gravitational-wave inspiral regime, which is the scenario upon which we focus here, one expects only a handful of bound stars to be capable of diffusing into the empty loss cone within the inspiral time of the binary (Coughlin et al. 2017); we caution, however, that the merger that gave rise to the binary may also have generated a stronger cusp of stars, which could greatly enhance the rate of disruption from the empty loss cone; Stone & van Velzen 2016). We therefore neglect the contribution of bound stars to the disruption rate. We further let the initial COM position be uniformly distributed over a sphere at a large distance from the binary (≫a∗), and let the orientation of the binary be uniform over a sphere of radius a∗ from the position of the COM.

The stellar binary is, in all circumstances considered here, much less massive than the SMBHB, and hence we will let the motion of the SMBHB be fixed. In this case, the four additional variables that enter the equations are M1/M, m1/M, m2/M, and a∗/a. While the masses themselves play a role in the outcome of the encounters, we suspect that the quantity that has most influence on the survivability of the stellar binary is the ratio a∗/a, as the binary tidal disruption radius scales linearly with the separation (and only as the mass ratio to the one-third power). Therefore, in our study we will let the masses be fixed at M1/M = 0.5 (equal-mass SMBH binary), m1/M = m2/M = 0.5 × 10⁻⁶—corresponding to Solar-like stars for 10⁶M⊙ SMBHs—and investigate the consequences of letting a∗/a vary between 0.1 and 0.0005.

We simulated ~10⁵ encounters for each choice of a∗/a, using an eighth-order explicit Runge–Kutta scheme for ~1600 binary orbits, with ejections occurring whenever a star exited a sphere of radius 50a. Even though they do not enter into the equations, the tidal radius rₜ must be specified in order to “count” disruptions. We chose rₜ/a = 10⁻², which corresponds to a∗ ≃ 1 pc for Solar-like stars and 10⁶M⊙ SMBHs. Stellar collisions were counted when stars came within some minimum separation rₘᵢₙ for which we chose rₘᵢₙ = 5 × 10⁻⁵a, which corresponds to ~0.5 R⊙ for Solar-like progenitors. The integration was stopped if a collision occurred, while a disruption resulted in the disrupted star being removed from the simulation. We therefore do not take into account the gravitational field of the disrupted debris on the evolution of the intact star. Finally, if neither star was ejected or disrupted after ~1600 SMBHB orbits, the outcome was deemed “inconclusive,” which comprised ≲0.1% of the outcomes.

### 3. Results

Table 1 gives the percentage of the various outcomes of the scattering experiments. The last row gives the average probability of each outcome integrated over the lifetime of the SMBHB as it shrinks due to gravitational wave emission, assuming M₁ = M₂ = 10⁶M⊙, a = 10⁴R⊙ initially, and the probability distribution function of the stellar binaries follows f(a∗) ∝ 1/a for the range 5R⊙ ≤ a ≤ 10⁴R⊙ (Poveda et al. 2007; we also included a factor ∝ a in the rate calculation to account for the SMBHB cross section, though this does not affect the results much). We see that the vast majority of the interactions result in either the ejection of an intact binary (binary ejection) or the ejection of both stars following the dissolution of the binary (double ejection), and the sum of these two outcomes typically totals ~95% of the total number of events.

The number in parentheses in column 1 of Table 1 gives the percentage of intact binaries with an escape velocity in excess of 1000 km s⁻¹, while that in column 2 is the fraction of double ejections with at least one star that has a velocity greater than 10⁶ km s⁻¹; to calculate these numbers, we let the binary satisfy M₁ = M₂ = 10⁶M⊙ and a = 10⁴R⊙ initially. These statistics are a more direct measure of the true rate of hypervelocity ejection, as these binaries or stars would not only escape from the potential of the SMBHB, but from the galactic potential as well.

Hills capture—where one star is ejected at the expense of capturing the other in a bound orbit around one of the SMBHs—accounts for at most ~1% of the outcomes, and is far less likely when a∗/a ≲ 0.005. Interestingly, stellar mergers reach a peak likelihood of ~1% at a separation of a∗/a ≃ 0.0025, which is likely due to the fact that tighter binaries are more difficult to perturb and wider binaries are more easily ripped apart.

### Table 1

| Outcome a∗/a | Binary Ejection | Double Ejection | Hills Capture | Single TDE | Prompt Double TDE | Delayed Double TDE | Merger |
|--------------|-----------------|-----------------|---------------|------------|-------------------|-------------------|--------|
| 0.0005       | 92.8% (73.8%)   | 4.11% (4.05%)   | 0.0111%       | 0.770%     | 1.36%             | 0.0952%           | 0.838% |
| 0.001        | 87.9% (69.1%)   | 4.34% (8.24%)   | 0.00502%      | 1.07%      | 2.13%             | 0.932%            | 0.899% |
| 0.0025       | 76.4% (57.8%)   | 19.14% (19.05%) | 0.0171%       | 1.58%      | 0.925%            | 0.153%            | 1.49%  |
| 0.005        | 60.9% (43.6%)   | 34.3% (34.2%)   | 0.195%        | 1.94%      | 0.791%            | 0.173%            | 1.31%  |
| 0.01         | 35.6% (23.7%)   | 60.5% (58.7%)   | 0.794%        | 2.11%      | 0.661%            | 0.186%            | 0.621% |
| 0.05         | 3.09% (1.61%)   | 92.6% (80.8%)   | 0.959%        | 2.57%      | 0.490%            | 0.166%            | 0.0240%|
| 0.1          | 0.936% (0.451%) | 94.6% (82.2%)   | 0.973%        | 2.88%      | 0.334%            | 0.179%            | 0.0050%|
| Integrated   | 45.1% (37.7%)   | 50.6% (49.1%)   | 0.508%        | 1.97%      | 0.661%            | 0.165%            | 0.726% |

Note. Each number was calculated out of ~10⁵ interactions between a stellar binary and the SMBHB. The last row is the time-integrated probability over the lifetime of the binary, assuming that M₁ = M₂ = 10⁶M⊙, the initial SMBHB separation is a = 10⁴R⊙, and a∗ follows an ∝1/a distribution. The number in parentheses in column 1 is the percentage of ejected binaries with velocity greater than 10⁶ km s⁻¹ at the time of ejection (assuming the same set of SMBHB properties), while the number in parentheses in column 2 is the percentage of double ejections with at least one star that has a velocity greater than 10⁶ km s⁻¹.

6 This upper limit may be somewhat optimistic for velocity dispersions appropriate to Milky Way-type galaxies owing to their reduced survivability (Hills 1988), but we emphasize that this specific assumption about the distribution of stellar semimajor axes only enters into the calculation of the integrated rate; all other numbers in Table 1 only depend on the ratio a∗/a. If one reduces the upper limit to 100 R⊙, one changes the integrated percentage of ejections to ~60%, the integrated percentage of double ejections to ~35%, and all other integrated quantities are roughly unaltered.
In addition, roughly 1%–3% of the scattering experiments result in the tidal disruption of one of the stars, and \(~0.5%–1.5\%\) of the encounters yield double TDEs. Of these double TDEs, a large fraction occur one after the other, or “promptly,” which we define as when the temporal difference between disruptions is less than \(1/(2\pi)\) of a binary orbit. As was found by Mandel & Levin (2015), who analyzed the deep encounter of a binary star system and a single SMBH, these prompt double TDEs occur when the pericenter of the stellar binary is within the tidal disruption radii of the stars themselves. Thus, the vast majority of these double TDEs are nearly contemporaneous.

However, a comparable number of double TDEs occur at “delayed” times from one another, defined as when the temporal offset between successive TDEs is greater than \(1/(2\pi)\) of an SMBHB orbit. In these instances, the stellar binary is tidally destroyed, but both stars are temporarily captured by the binary and eventually pass through the tidal radius of one or the other SMBH. Figure 1 shows the distributions of the temporal offset between disruptions for the prompt disruptions (left panel) and the delayed disruptions (right panel) when \(a_s/a_\ast = 0.001\) (other values of \(a_s/a_\ast\) give very similar distributions). This figure confirms that there are two distinct classes of double disruptions: the prompt class that peaks on timescales of \(~0.001\) stellar binary orbits, and the delayed class that peaks on timescales of a few SMBHB orbits.

Figure 2 gives the properties of the binaries ejected from the SMBHB: their eccentricities (top-left panel), pericenters normalized by the initial semimajor axis (top-right panel), COM velocities with \(a_\ast = 10^4 R_\odot\) and \(M_1 = M_2 = 10^9 M_\odot\) (bottom-left panel), and gravitational wave inspiral times calculated from Equations (5.6) and (5.7) of Peters (1964) with \(m_1 = m_2 = 1 M_\odot\) and \(a_\ast = 10^3 R_\odot\) (bottom-right panel). From the top-left and top-right panels we see that most binaries are perturbed from their initial states by the SMBHB, which is partially due to our requirement that the pericenter of the stellar COM be less than \(2a_\ast\) from the SMBHB COM (i.e., if we had permitted larger pericenter distances in our study, then the number of unaffected binaries for \(a_s/a_\ast > 0.001\) would have been larger). It is also apparent that the distribution of stellar COM velocities is peaked around \(1000\,\text{km}\,\text{s}^{-1}\), which is comparable to the speed of the binary \(\sqrt{GM/a_\ast} \approx 6000\,\text{km}\,\text{s}^{-1}\), but the maximum attainable velocity can be more than an order of magnitude larger than this. Finally, while the inspiral distribution still peaks at a time comparable to the inspiral time of the initial binary, there are large wings induced by the relatively small number of heavily modified orbits; for these cases, the inspiral time can be well within the age of the universe even if that of the unperturbed orbit is not. Furthermore, this only takes into account inspirals assisted by gravitational waves, which is most relevant for compact objects; for more extended stars, the tidal dissipation timescale could be comparable or shorter (e.g., Ogilvie 2014).

Figure 3 gives the time between ejections (left panel); ejection occurs when a star reaches \(50a_\ast\) from the SMBHB COM and the cosine of the polar angle between ejected stars (right panel) for experiments yielding double ejections (i.e., when the binary is ripped apart and both stars are subsequently ejected). This figure demonstrates that, while there is a wide range of temporal offsets between individual stellar ejections, the angular distribution is still peaked near \(\Delta \theta_{\text{ejection}} = 0\) (an isotropic distribution has a flat distribution of \(\cos \Delta \theta_{\text{ejection}}\)). Also, although we did not plot the ejection angles, the ejected stars and binaries with the highest velocities stars are preferentially confined to the orbital plane of the SMBHB, which is consistent with previous findings (e.g., Sesana et al. 2006).

The orbit-integrated probability distribution functions for these quantities—obtained by following an analogous weighting procedure that yielded the integrated probabilities in Table 1—appear similar to those corresponding to \(a_s/a_\ast = 0.01\). However, there are small contributions from stellar binaries with \(a_s/a_\ast < 0.01\) that widen the distributions.

To reduce the parameter space, here we primarily focused on circular binaries (both for the stars and SMBHs) with equal mass ratios. We did, however, assess the importance of the initial eccentricity of the stellar binary, \(e_\ast\), by running \(10^5\) encounters between a stellar binary with \(e_\ast = 2/3\), \(a_s/a_\ast = 0.01\), and otherwise the same set of fiducial parameters. We found that the majority of the statistics were only slightly modified from those in Table 1 for \(a_s/a_\ast = 0.01\), with the one significant difference being the percentage of mergers, which increased from \(\sim 0.62\%\) to \(\sim 4.5\%\). Because our merger rate for circular binaries peaks at a separation of \(a_s/a_\ast \sim 0.001\), a modest increase to \(\sim 1\%\) might be expected from the smaller stellar pericenter separation, being \(a_s(1-e_\ast)/a_\ast \approx 0.003\). The additional increase by a factor of \(\sim 4\), however, suggests that mergers are primarily driven by extreme, eccentric-Kozai-like oscillations, which increase the eccentricity to the point where the stars merge; this finding is also consistent with that of Mandel & Levin (2015), who found

---

**Figure 1.** Left panel: the distribution of time between disruptions, in units of stellar binary orbits, for prompt TDEs that occur with temporal offsets satisfying \(\Delta T < 1/(2\pi)\) SMBHB orbits. Right panel: the distribution of time between disruptions, in units of SMBHB orbits, for delayed TDEs that occur with temporal offsets satisfying \(\Delta T > 1/(2\pi)\) SMBHB orbits.
that stellar binaries approaching isolated SMBHs merged under this mechanism.

We also investigated the influence of the stellar mass ratio by simulating $10^5$ encounters between a circular, stellar binary with the mass of the secondary reduced by a factor of 5 compared to the fiducial value, a stellar separation of $a_*/a_{\text{fid}} = 0.01$, and otherwise the same fiducial parameters. As was true for the eccentricity, the majority of the statistics are very similar to those in Table 1 with $a_*/a_{\text{fid}} = 0.01$, with the most significant differences being a reduction in the binary escape fraction to $\sim 9.3\%$ and an increase in the double escape fraction to $\sim 86\%$. These differences are likely due to the fact that the total energy of the stellar binary, $E_* = Gm_1m_2/(2a_*)$, scales in proportion to the mass ratio, and hence the binary is more easily ripped apart in this case.

4. Discussion and Conclusions

Owing to the chaotic gravitational interactions between the stars in a stellar binary and the black holes in an SMBHB, we have shown that scattering events between the two can generate a variety of dynamical outcomes. In particular, while ejections of an intact stellar binary and individual stellar ejections following the tidal separation of the binary dominate the statistics, more exotic end states—including stellar mergers, single and double tidal disruptions—can occur, albeit with reduced likelihoods. Table 1 summarizes the relative probabilities of these occurrences as a function of $a_*/a_\ast$, the ratio of the stellar binary semimajor axis to that of the SMBHB.

In addition to double TDEs that occur when the stellar COM pericenter comes within the tidal disruption radius of the individual stars, which result in “prompt,” or nearly contemporaneous disruptions by one SMBH (Mandel & Levin 2015), we also found that a comparable fraction of double TDEs occur after the stellar binary is dissociated and with large temporal offsets ($\gtrsim 1/(2\pi)$ SMBHB orbits). From Table 1, we see that the fraction of delayed double TDEs is approximately independent of the ratio $a_*/a_\ast$, which likely results from a competition between tidal stripping (easier for wider binaries) and capture (harder for wider binaries). Figure 1 shows the distribution of the time between disruptions, indicating that the delay can be between a fraction and hundreds of SMBHB orbits. Two such delayed TDEs resulting from the disruption of a binary could explain the extremely luminous, double-peaked transient ASASSN-15lh (Brown et al. 2016; Dong et al. 2016; Godoy-Rivera et al. 2017); while a TDE interpretation has already been investigated for this event, both in the single-star-SMBH (Leloudas et al. 2016) and single-star-SMBHB (Coughlin & Armitage 2018) scenarios (an extremely energetic and exotic supernova could have also powered the emission; Chatzopoulos et al. 2016), two temporally offset TDEs following the separation of a stellar binary naturally explains therebrightening (the lack of hydrogen and helium emission lines is an additional puzzling aspect of this event, but may tentatively be explained by optical depth effects; Roth et al. 2016).

Figure 2. Top-left panel: the eccentricity distribution of the ejected binaries, with different colors corresponding to the ratios $a_*/a_\ast$ indicated in the legend. Top-right panel: the distribution of the ejected stellar binary pericenters normalized by the initial binary separation. Bottom-left panel: the velocity distribution of the center of mass of the ejected binaries with $a_\ast = 10^9 R_\odot$ and $M_1 = M_2 = 10^6 M_\odot$. Bottom-right panel: the gravitational-wave inspiral time of the ejected binaries in years, assuming $m_1 = m_2 = 1 M_\odot$ and $a_\ast = 10^9 R_\odot$. 

The Astrophysical Journal Letters, 863:L24 (7pp), 2018 August 20 Coughlin et al.
Ejected intact binaries constitute the vast majority of the outcomes for $a_e/a_\ast \lesssim 0.01$. Investigating Figure 2, a fraction ($\sim$ few $\times 0.1\%–1\%$) of ejected binaries merge in significantly less time than the original gravitational-wave inspiral time of the binary and within the age of the universe. Also, given the relatively large velocities imparted to the binaries, their nuclear separation from the host galaxy at the time of merger is substantial; the left-hand panel of Figure 4 shows the distribution of distances from the nucleus, calculated by taking the product of the ejected velocity and the inspiral time, for $a_e/a_\ast = 0.001$, $a_\ast = 10^5 R_\odot$, and $M_\odot = 10^6 M_\odot$. If we demand that the gravitational-wave merger time be less than 10 Gyr. The vertical dashed lines at $10^4$ ($10^3$) show the maximum achievable distance if we restrict the inspiral time to less than 1 (1) Gyr.

It has recently been suggested (Foley 2015) that calcium-rich transients (Filippenko et al. 2003; Perets et al. 2010; Kasliwal et al. 2012; Lyman et al. 2014) could be the product of gravitational-wave inspirals of white dwarf (WD)–WD binaries, their large galactic offsets caused by the ejection of the stellar binary following its interaction with an SMBHB. Our inferred distances at the time of inspiral, while likely overestimates of the true distances owing to our small SMBHB separation (the ejected velocity scales as $\propto a_\ast^{-1/2}$, so the same range of $a_\ast$ and larger $a_\ast$ would significantly reduce the distances) and our neglect of the galactic potential and tidal dissipation within the stellar binary itself, confirm that this aspect of Ca-rich supernovae can be reproduced with this mechanism.

The theoretical rate at which these inspirals take place is uncertain from our analysis alone, as we only explored a restricted range of parameter space and we are not accounting for a number of priors. However, if the binary is already composed of WDs when it reaches the SMBHB, then the rate of inspirals is $\sim 10^{-4} \times a_\ast/a_\ast \times F_{\text{SMBHB}} \times F_{\text{merger}} \times F_{\text{WDWD}} \sim 10^{-4} - 10^{-2} \text{gal}^{-1} \text{yr}^{-1}$, where $F_{\text{SMBHB}} \lesssim 1$ is the fraction of SMBHBs in binaries, $F_{\text{merger}} \sim 10^{-1} - 10^{-2}$ is the fraction of ejected systems that merge in a Hubble time, and $F_{\text{WDWD}} \lesssim 10^{-1}$ (Brown et al. 2011) is the fraction of WD–WD binaries encountering the SMBHB. If the binary is still in the main sequence phase at the time of ejection, then the total number of ejected binaries is likely higher, but those that survive intact through the common envelope phase are uncertain. Regardless, our findings indicate that the rate of mergers from such systems is probably only $10^{-3} - 10^{-1}$ the type-Ia rate of $0.001–0.01 \text{gal}^{-1} \text{yr}^{-1}$ (e.g., Scannapieco & Bildsten 2005; Li et al. 2011; Maoz & Mannucci 2012), which is toward the low end of the

\[ \frac{a}{a_\ast} = 0.001 \]

\[ \frac{a}{a_\ast} = 0.01 \]
estimated rate of calcium-rich transients (e.g., Perets et al. 2010; Kasliwal et al. 2012; Foley 2015; more recent work, however, indicates that the rate could be as high as the type-Ia rate; Frohmaier et al. 2018). We note, however, that the theoretical and observational rates could be brought closer to agreement if wider SMBHBs boost the rate geometrically, Calcium-rich transients repeat (which could occur, e.g., if a phase of mass transfer ignites a more mild explosion near the pericenter of the orbit), or the rate of injection of stars into the SMBHB loss cone is intrinsically higher.

Potentially discrepant rates aside, there are other aspects of calcium-rich transients that seem to defy the explanation that they exclusively originate from WD–WD binaries kicked from the centers of galaxies. For example, the event iPTF15adv displayed a mixture of properties appropriate to calcium-rich transients and core-collapse supernovae (Milisavljevic et al. 2017). This source also lacked significantly Doppler-shifted lines, a feature that must necessarily be present in the spectrum if the large velocity imparted to the binary from the SMBHB (see Figure 2) explains the nuclear offset of the source (though there could be line-of-sight effects that complicate this trend). Furthermore, Ca-rich transients seem to trace an older population of stars, and type-Ia supernovae from such an older population can be located in the outskirts of galaxies and are therefore consistent with the lack of any inferred kick velocity (Perets 2014).

There is therefore evidence—not only from our lower-than-observed rate calculations here—that not all calcium-rich transients arise from this avenue of WD–WD binary ejection.

The binaries that undergo mergers within a Hubble time have very high eccentricities at the time of ejection—especially those with larger initial separations—as shown in the right-hand panel of Figure 4. In these highly eccentric orbits, resonances between the orbital timescale and the stellar Eigenmodes could be strong enough to tidally detonate the stars before the gravitational-wave inspiral time (e.g., Rathore et al. 2005; Fuller & Lai 2011, 2012; Burkart et al. 2013). Finally, if the system is initially composed of two main sequence stars that then evolve through a phase of common envelope evolution, the passage of the compact object through the envelope of the companion on such a highly eccentric orbit could produce another avenue of reducing the separation more rapidly. Although the outcome and observational appearance of tidally induced mergers are unclear, this should be a source of some variety of transient well-separated from any host.

Finally, the ejection of two stars following the disruption of the binary (double ejections) has interesting implications for the detection of hypervelocity stars (e.g., Brown 2015). From Figure 3, we see that >60% of double ejections yield angular separations >0.99 rad ~ 8°, corresponding to ~few kpc-scale separations between the stars once they recede to ~100 kpc from the galaxy. If the two ejected stars formed from the same protostellar cloud, so that the original stellar binary was preserved from the site of star formation, two such hypervelocity stars could look very similar spectroscopically but would have spatial offsets on the order of kpc. The detection of such spatially distinct and spectroscopically similar hypervelocity stars would then be a strong indication of the presence of an SMBHB in the center of the host galaxy.

E.R.C. acknowledges support from NASA through the Einstein Fellowship Program, grant PF6-170150. This work was supported in part by a Simons Investigator award from the Simons Foundation (E.Q.) and the Gordon and Betty Moore Foundation through grant GBMF5076. This work was supported by the National Science Foundation under grant No. 1616754. We thank the referee for constructive comments and suggestions.

ORCID iDs
Eric R. Coughlin @ https://orcid.org/0000-0003-3765-6401
Eliot Quataert @ https://orcid.org/0000-0001-9185-5044

References
Begelman, M. C., Blandford, R. D., & Rees, M. J. 1980, Natur, 287, 307
Bromley, B. C., Kenyon, S. J., Geller, M. J., et al. 2006, ApJ, 653, 1194
Brown, J. M., Kilic, M., Brown, W. R., & Kenyon, S. J. 2011, ApJ, 730, 67
Brown, P. J., Yang, Y., Cooke, J., et al. 2016, ApJ, 828, 3
Brown, W. R. 2015, ARA&A, 53, 15
Burkart, J., Quataert, E., Arras, P., & Weinberg, N. N. 2013, MNRAS, 433, 332
Chatzopoulos, E., Wheeler, J. C., Vinko, J., et al. 2016, ApJ, 828, 94
Chen, X., Madan, P., Sesana, A., & Liu, F. K. 2009, ApJ, 697, L149
Comerford, J. M., Pooley, D., Barrows, R. S., et al. 2015, ApJ, 806, 219
Coughlin, E. R., & Armitage, P. J. 2018, MNRAS, 474, 3857
Coughlin, E. R., Armitage, P. J., Nixon, C., & Begelman, M. C. 2017, MNRAS, 465, 3840
Darbha, S., Coughlin, E. R., Kasen, D., & Quataert, E. 2018, ApJL, 877, 4009
Dong, S., Shappee, B. J., Prieto, J. L., et al. 2016, Sci, 351, 257
Eggleton, P. P., & Tokovinin, A. A. 2008, MNRAS, 389, 869
Filippenko, A. V., Chornock, R., Swift, B., et al. 2003, IAUC, 8159, 2
Foley, R. J. 2015, MNRAS, 452, 2463
Frank, J., & Rees, M. J. 1976, MNRAS, 176, 633
Frohmaier, C., Sullivan, M., Macquarie, K., & Nugent, P. 2018, ApJ, 858, 50
Fuller, J., & Lai, D. 2011, MNRAS, 412, 1331
Fuller, J., & Lai, D. 2012, ApJL, 756, L17
Godoy-Rivera, D., Stanek, K. Z., Kochanek, C. S., et al. 2017, MNRAS, 466, 1428
Guillochon, J., & Loeb, A. 2015, ApJ, 806, 124
Hills, J. G. 1988, Natur, 331, 687
Ivezic, Z., Tyson, J. A., Abel, B., et al. 2008, arXiv:0805.2366
Kasliwal, M. M., Kulkarni, S. R., Gal-Yam, A., et al. 2012, ApJ, 755, 161
Leloudas, G., Fraser, M., Stone, N. C., et al. 2016, NatAs, 1, 0002
Li, W., Chornock, R., Leaman, J., et al. 2011, MNRAS, 412, 1473
Lightman, A. P., & Shapiro, S. L. 1977, ApJ, 211, 244
Liu, B., Wang, Y.-H., & Yuan, Y.-F. 2017, MNRAS, 466, 3376
Liu, F. K., Li, S., & Chen, X. 2009, ApJL, 706, L133
Liu, J., Eraeelous, M., & Halpern, J. P. 2016, ApJ, 817, 42
Lu, Y., Yu, Q., & Lin, D. N. C. 2007, ApJL, 666, L89
Lyman, J. D., Levan, A. J., Church, R. P., Davies, M. B., & Tanvir, N. R. 2014, MNRAS, 444, 2157
Margorion, J., & Tremaine, S. 1999, MNRAS, 309, 447
Mandel, I., & Levin, Y. 2015, ApJ, 805, L4
Maoz, D., & Mannucci, F. 2012, PASA, 29, 447
Milisavljevic, D., Patnaude, D. J., Raymond, J. C., et al. 2017, ApJ, 846, 50
Ogilvie, G. I. 2014, ARA&A, 52, 171
Perets, H. B. 2014, arXiv:1407.2254
Perets, H. B., & Alexander, T. 2008, ApJ, 677, 146
Perets, H. B., Hopman, C., & Alexander, T. 2007, ApJ, 656, 709
Perets, H. B., Gal-Yam, A., Mazzali, P. A., et al. 2010, Natur, 465, 322
Peters, P. C. 1964, PhRv, 136, 1224
Poveda, A., Allen, C., & Hernández-Alcántara, A. 2007, in IAU Symp. 240, Binary Stars as Critical Tools Tests in Contemporary Astrophysics, ed. W. I. Hartkopf, P. Harmanec, & E. F. Guinan (Cambridge: Cambridge Univ. Press), 417
Quinlan, G. D. 1996, NewA, 1, 35
Rathore, Y., Blandford, R. D., & Broderick, A. E. 2005, MNRAS, 357, 834
Rees, M. J. 1988, Natur, 333, 523
Ricarte, A., Natarajan, P., Dai, L., & Coppi, P. 2016, MNRAS, 458, 1712
Roth, N., Kasen, D., Guillochon, J., & Ramirez-Ruiz, E. 2016, ApJ, 827, 3
Scannapieco, E., & Bildsten, L. 2005, ApJL, 629, L85
Sesana, A., Haardt, F., & Madau, P. 2006, ApJ, 651, 392

Coughlin et al.
Sesana, A., Haardt, F., & Madau, P. 2008, ApJ, 686, 432
Sesana, A., Madau, P., & Haardt, F. 2009, MNRAS Letters, 392, L31
Stone, N. C., & Metzger, B. D. 2016, MNRAS, 455, 859
Stone, N. C., & van Velzen, S. 2016, ApJL, 825, L14

Wang, Y.-H., Leigh, N., Yuan, Y.-F., & Perna, R. 2018, MNRAS, 475, 4595
Wegg, C., & Nate Bode, J. 2011, ApJL, 738, L8
Yu, Q., & Tremaine, S. 2003, ApJ, 599, 1129
Yuan, H., Liu, X., Xiang, M., et al. 2015, ApJ, 799, 135