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INTERRUPTION OF TIDAL-DISRUPTION FLARES BY SUPERMASSIVE BLACK HOLE BINARIES

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ABSTRACT

Supermassive black hole binaries (SMBHBs) are products of galaxy mergers, and are important in testing Λ cold dark matter cosmology and locating gravitational-wave-radiation sources. A unique electromagnetic signature of SMBHBs in galactic nuclei is essential in identifying the binaries in observations from the IR band through optical to X-ray. Recently, the flares in optical, UV, and X-ray caused by supermassive black holes (SMBHs) tidally disrupting nearby stars have been successfully used to observationally probe single SMBHs in normal galaxies. In this Letter, we investigate the accretion of the gaseous debris of a tidally disrupted star by a SMBHB. Using both stability analysis of three-body systems and numerical scattering experiments, we show that the accretion of stellar debris gas, which initially decays with time $\propto t^{-5/3}$, would stop at a time $T_{\rm tr} \simeq \eta T_{\rm b}$. Here, $\eta \sim 0.25$ and $T_{\rm b}$ is the orbital period of the SMBHB. After a period of interruption, the accretion recurs discretely at time $T_{\rm r} \simeq \xi T_{\rm b}$, where $\xi \sim 1$. Both η and ξ sensitively depend on the orbital parameters of the tidally disrupted star at the tidal radius and the orbit eccentricity of SMBHB. The interrupted accretion of the stellar debris gas gives rise to an interrupted tidal flare, which could be used to identify SMBHBs in non-active galaxies in the upcoming transient surveys.

Key words: accretion, accretion disks – black hole physics – galaxies: active – galaxies: evolution – galaxies: nuclei – gravitational waves

1. INTRODUCTION

Supermassive black hole binaries (SMBHBs) are predicted by the hierarchical galaxy formation model in Λ cold dark matter (ΛCDM) cosmology (Begelman et al. 1980; Volonteri et al. 2003). After a SMBHB at the center of merging systems become hard, it would stall at the hard radius for a timescale even longer than the Hubble time if spherical two-body relaxation dominates (Begelman et al. 1980). However, recent investigations suggested that the hardening rates of SMBHBs can be boosted and SMBHBs may coalesce within a Hubble time either due to various stellar dynamical processes other than the spherical two-body relaxation (Yu 2002; Chatterjee et al. 2003; Merritt & Poon 2004; Berczik et al. 2006; Sesana et al. 2008), or due to gas dynamics (Gould & Rix 2000; Liu et al. 2003; Colpi & Dotti 2009, and references therein).

The strong gravitational wave (GW) radiation generated by coalescing supermassive black holes (SMBHs) is the main target of the GW detector the Laser Interferometer Space Antenna (LISA) and of the Pulsar Timing Array (PTA) program. Because of the poor accuracy of both LISA and PTA in locating GW radiation sources, it is of key importance to detect electromagnetic counterparts (EMCs) of GW radiation sources. Identifying SMBHBs by their EMCs is also essential to constraining the poorly understood galaxy-merger history. Several EMCs have been suggested in the literature to probe SMBHBs and their coalescence: (1) precession of jet orientation and its acceleration in radio galaxies during the in-spiraling of SMBHBs (Begelman et al. 1980; Liu & Chen 2007), (2) optical periodic outbursts in blazars due to the interaction between SMBHB and accretion disk (Sillanpaa et al. 1988; Liu et al. 1995, 2006; Liu & Wu 2002; Valtonen et al. 2008; Haiman et al. 2009), (3) jet reorientation in X-shaped radio galaxies due to the exchange of angular momentum between SMBHB and accretion disk (Liu 2004), (4) two systems of broad emission lines (BELs) in quasars (Boroson & Lauer 2009), (5) intermittent activity in double–double radio galaxies at binary coalescence (Liu et al. 2003), (6) X-ray, UV, optical, and IR afterglow following binary coalescence (Milosavljević & Phinney 2005; Shields & Bonning 2008; Lippai et al. 2008; Schnittman & Krolik 2008), and (7) systematically shifted BELs relative to narrow emission lines (Merritt et al. 2006; Komossa et al. 2008) and off-center active galactic nuclei (AGNs; Madau & Quataert 2004; Loeb 2007) because of SMBH GW radiation recoil.

All the above observational signatures require gas accretion disks around SMBHBs. The SMBHBs in gas-poor galactic nuclei are difficult to detect, because the SMBHs are dormant. However, a dormant SMBH could be temporarily activated by tidally disrupting a star passing by and accreting the disrupted stellar debris (Hills 1975). A tidal flare decays typically as a power law $t^{-5/3}$ (Rees 1988; Phinney 1989), which has been observed in several non-active galaxies (Komossa & Bade 1999; Komossa 2002; Halpern et al. 2004; Esquej et al. 2008; Gezari et al. 2008, 2009). Recently, Chen et al. (2008) and Chen et al. (2009) calculated the tidal-disruption rate in SMBHB systems at different evolutionary stages, and found that it is significantly different from the typical rate for single SMBHs by orders of magnitude. This great difference of the flaring rates enables one to statistically constrain the SMBHB population in normal galaxies (Chen et al. 2008), but identifying SMBHBs individually is still difficult at present. In this Letter, we investigate the influence of a SMBHB on the accretion of tidally disrupted stellar plasma and on the tidal flare. We show that the accretion of the stellar debris is interrupted by the SMBHB and this interruption can be taken as a key distinguishable observational signature for SMBHBs in gas-poor galactic nuclei.

2. TIDAL DISRUPTION IN A SMBHB SYSTEM

A star with mass m_* and radius r_* will be tidally disrupted by a SMBH with mass $M_\bullet$ if it approaches the black hole (BH) within the tidal radius

$$r_t \simeq \mu r_* (M_\bullet / m_*)^{1/3} \quad (1)$$

(Hills 1975; Rees 1988; Phinney 1989), where μ is a dimensionless parameter of order unity. We focus on tidal disruptions of solar-type stars with solar radius $r_\odot$ and solar mass $M_\odot$ by SMBHs with $M_\bullet \lesssim 10^8\ M_\odot$, which are detected in the tidal-flare surveys (Komossa & Bade 1999; Komossa 2002; Esquej et al. 2008; Gezari et al. 2008, 2009). For more massive BHs, the tidal radii become smaller than the event horizon (Ivanov & Chernyakova 2006). After tidal disruption at the tidal radius, the specific energy E across the star ranges from $-E_b - \Delta E$ to $-E_b + \Delta E$, where E_b is the orbital binding energy of the star, $\Delta E = kGM_\bullet r_*/r_t^2$ is the spread in specific energy across the stellar radius, and $k = 1$ if the tidal spin-up of the star is negligible or $k = 3$ if the star is spun-up to the breakup angular velocity (Rees 1988; Lacy et al. 1982; Li et al. 2002). Since ΔE is $(M_\bullet/M_*)^{1/3}$ times larger than the internal binding energy of the star and the interaction between the stellar debris is negligible after the tidal disruption (Evans & Kochanek 1989), each fluid element moves ballistically.

If we neglect the influence of the companion SMBH, the bound debris with $E < 0$ should move in Keplerian orbits with eccentricity of about unity and fall back to the tidal radius after one Keplerian period, $T = 2\pi GM_\bullet/(-2E)^{3/2}$. The debris continuously returning to the tidal radius generates a falling-back rate $\dot{m} = (dm/dE)(dE/dt)$. For Keplerian orbits, $dE/dt = dE/dT \propto t^{-5/3}$. If we assume dm/dE following a constant distribution in the energy range $-E_b - \Delta E$ to $-E_b + \Delta E$ (see, e.g., Rees 1988; Evans & Kochanek 1989; Lodato et al. 2009), the falling-back rate evolves as

$$\dot{m} \simeq \frac{m_*}{3T_{\rm min}} \left(\frac{t - T_D}{T_{\rm min}} \right)^{-5/3} \quad (2)$$

for $t \geqslant T_D + T_{\rm min}$, where T_D is the disruption time and

$$T_{\rm min} \simeq 2\pi GM_\bullet (2\Delta E)^{-3/2} \simeq 0.355\ {\rm yr}\ k^{-3/2} \left(\frac{R_*}{r_\odot} \right)^{3/2} \left(\frac{m_*}{M_\odot} \right)^{-1} \left(\frac{M_\bullet}{10^7\ M_\odot} \right)^{1/2} \quad (3)$$

is the returning time for the most bound debris (typically $|E_b| \ll \Delta E$). It is assumed that once the bound material comes back to the tidal-disruption radius, it loses kinetic energy due to strong shocks because of the interaction between fluid elements and is circularized on a timescale much shorter than T to form an orbiting torus at a radius about $r_c = 2r_t$ around the SMBH (e.g., Rees 1988; Phinney 1989; Ulmer 1999; Li et al. 2002). Both the radiative dissipation of the shock energy and the accretion of the gas torus onto the BH will give rise to an X-ray/UV flare, decaying with $(t - t_D)^{-5/3}$.

For a SMBHB system, the stellar-disrupting BH could be either the primary (with mass M_1) or the secondary (with mass M_2). Since the probability of stellar disruption by the secondary is relatively low if the two BHs are very unequal (Chen et al. 2008, 2009), here we assume the primary BH to be the stellar-disrupting one. Because the interaction between the fluid elements is negligible before they come back to the tidal-disruption radius, the SMBHB and each bound fluid element constitute a restricted three-body system. When the orbit of a bound fluid element is inside the SMBHB orbit, the system is called S-type. An S-type three-body system could be stable for a long time only when the system is hierarchical, namely, the system consists of an inner binary (the bound fluid element and the primary BH) on a nearly Keplerian orbit with semimajor axis $a_{\rm f}$ and eccentricity of near unit, and an outer binary with eccentricity e and semimajor axis $a_{\rm b} \gg a_{\rm f}$ in which the secondary BH orbits the mass center of the inner binary. The orbital change of a stable S-type system is negligible on the fluid-element dynamical timescale, so the falling-back stellar debris may interact with one another at the tidal-disruption radius and finally be accreted with accretion rate given in Equation (2). However, for those less bound fluid elements with $a_{\rm f}$ larger than a critical radius $a_{\rm cr}$, the orbit of the triple system becomes chaotic. For a triple system with an angle θ between the angular momenta of the inner and outer binaries, $a_{\rm cr}$ can be semiempirically given by

$$a_{\rm b}/a_{\rm cr} = 2.8\,(1+q)^{2/5}\,(1+e)^{2/5} \times (1-e)^{-6/5}\,(1 - 0.3\theta/180^\circ) \quad (4)$$

(Mardling & Aarseth 2001), where $q = M_2/M_1 < 1$ is the BH mass ratio.

Because of the nonlinear overlap of the multiple resonances (Mardling 2007) in the chaotic triple systems, the fluid elements significantly exchange angular momentum and energy with the SMBHB and change their orbit dramatically on the dynamical timescale of the triple system, therefore would not return to the tidal radius to fuel the accreting torus and to form continuous accretion. Although a fraction of the fluid elements with chaotic orbits may return to the tidal radius on a timescale much longer than its Keplerian period, others would escape the system during the three-body interactions (see our numerical simulations in Section 3). Therefore, Equation (4) implies that the continuous accretion of tidally disrupted stellar plasma stops with the accretion of the last fluid element with $a < a_{\rm cr}$, this occurring at a time

$$T_{\rm tr} \approx \frac{T_{\rm b}}{4.7}\,(1+q)^{-1/10}\,(1+e)^{-3/5} \times (1-e)^{9/5}\,(1 - 0.3\theta/180^\circ)^{-3/2}\,, \quad (5)$$

where $T_{\rm b}$ is the SMBHB orbital period. The eccentricity of hard SMBHBs is moderate (Milosavljević & Merritt 2001) and minor mergers with $q \ll 1$are the most common in the hierarchical galaxy formation model (Volonteri et al. 2003). We re-write Equation (5) as $T_{\rm tr} = \eta T_{\rm b}$, where η is in the range (0.21, 0.36) for $e \sim 0$ and $q \ll 1$, and independent of $a_{\rm b}$. For a SMBHB with semimajor axis $a_{\rm b} = a_h/\beta$ residing in a stellar cluster with velocity dispersion σ_*, where

$$a_h = \frac{GM_1M_2}{4(M_1+M_2)\sigma_*^2} \quad (6)$$

is the hard radius and β is the hardness, the accretion is interrupted at

$$T_{\rm tr} = \eta T_{\rm b} \simeq 6.2\ {\rm yr}\ \sigma_{110}^{-3} M_7 q_{-1}^{3/2} (1+q)^{-2} \left(\frac{\eta}{0.25} \right) \left(\frac{\beta}{10} \right)^{-3/2}, \quad (7)$$

where $\sigma_{110} = \sigma_*/110\ {\rm km\ s^{-1}}$, $M_7 = M_1/10^7\ M_\odot$, and $q_{-1} = q/0.1$.

3. NUMERICAL SIMULATIONS AND RESULTS

Because the fluid elements of a tidally disrupted star move like test particles before falling back to the tidal radius, their evolution could be correctly simulated with scattering experiments. We use $N = 10^6$ particles to resolve the stellar debris of a disrupted star and integrate their trajectories in restricted three-body systems. The particles are logarithmically sampled in the binding-energy range $[E_{\rm thd}, \Delta E]$, where $E_{\rm thd} = G(M_1 + M_2)/2.5a_{\rm b}$ is a binding energy corresponding to an orbital period of $4T_{\rm b}$ and $\Delta E = GM_1 r_*/r_t^2$ is the spread in specific energy for a non-spinning star. For a typical tidal-disruption event with $|E_b| \ll \Delta E$, the ith particle has a binding energy $E_i = \Delta E(E_{\rm thd}/\Delta E)^{(i-0.5)/N}$, pericenter velocity $V_i = (2E_i + 2GM_1/r_t)^{1/2}$, and mass $m_i = 0.5m_*\Delta E_i/\Delta E$, where $\Delta E_i = E_i \ln(0.5E_{\rm thd}/\Delta E)/N$ is the size of the ith energy bin.

The evolution of the three-body systems is computed in a frame centered on the mass center of the SMBHB with X–Y plane aligned with the SMBHB orbital plane. We assume $e = 0$ in this work for simplicity, and that the secondary BH initially lies on the positive X-axis and moves in the direction of positive Y. In each experiment, a test particle starts with velocity V_i from the pericenter at tidal radius r_t about the primary BH, and the orbit is determined by three initial parameters (determined by the orbital parameters of the disrupted star at tidal radius) (1) the inclination angle θ between the orbital planes of the particle and the SMBHB, (2) the longitude of ascending node Ω, and (3) the argument of pericenter ω. With the initial parameters, we integrate the equations of motion in the pseudo-Newtonian potential $\phi = GM_\bullet/(r - r_{\rm g})$ (Paczyński & Wiita 1980), where $r_{\rm g}$ is the Schwarzschild radius of BHs, using an explicit Runge–Kutta method of order 8 (Hairer et al. 1987). Stellar debris which falls back to within $2r_t$ from the primary BH is assumed to be circularized via shocks and be accreted instantaneously. Therefore, if a particle with id i passes by the primary BH within a distance $r_{\rm acc} = 2r_t$,[4] the integration is stopped and the time t_i is recorded. Otherwise, the integration continues until time $4T_{\rm b}$. The accretion rate of the stellar debris is calculated using the recorded m_i and t_i.

Figure 1 shows the accretion rate of stellar debris in our fiducial simulations with $q = 0.1$, $M_7 = 1$, $\beta = 10$, $\sigma_{110} = 0.9545$, $r_* = r_\odot$, $m_* = M_\odot$, $\Omega = 90°$, and $\omega = 90°$. Our results suggest that the interruption of accretion occurs at $(0.15–0.5)T_{\rm b}$, depending on θ. In Figure 1, a better agreement between the numerical value $t_{\rm tr}$ and the analytical estimate $T_{\rm tr}$ for $\theta = 0°$ and $180°$ is by coincidence, because η not only depends on θ but also on Ω and ω. To illustrate this, we did 100 numerical simulations with random $\cos\theta$, Ω, and ω. The results show that η ranges from 0.15 to 0.5 with a mean value 0.25, consistent with the analytical mean value 0.27 given by Equation (5). Figure 1 also shows that after being interrupted for about $(1 - \eta)T_{\rm b}$, accretion recurs and "accretion islands" emerge discretely. The accretion rate at the islands is variable and can be larger than the corresponding value for single BH. The duration of interruption and the periods of the accretion islands decrease with θ, the shortest occurring at $\theta = 180°$.

To investigate the effect of different $a_{\rm b}$ on the results, we ran a scattering experiment for $\beta = 1$ and $\theta = 0$, keeping the other parameters as in Figure 1. The result is given in Figure 2. Figure 2 shows that the interruption occurs at a slightly earlier time $t_{\rm tr}/T_{\rm b}$ as hardness β decreases, which seems inconsistent with the analytical prediction given by Equation (5). However, we should note that Equation (5) is obtained statistically by averaging over different Ω and ω. When we did the simulations with different Ω and ω, the averaged interruption time for different β resides in the predicted range. Accordingly, in the scattering experiments with different BH mass M_1 ($M_7 = 0.1$) and mass ratios q ($q = 1, 0.02$), we find that η weakly depends on q and M_1. Our numerical results are consistent with the analytical estimate given by Equation (5), implying that the dependence of η on β, q, and M_1 is much weaker than on θ, Ω, and ω.

[4] We test our simulations with $r_{\rm acc} = 1.5r_t$, $3r_t$, and $6r_t$ and the results are nearly independent of $r_{\rm acc}$.

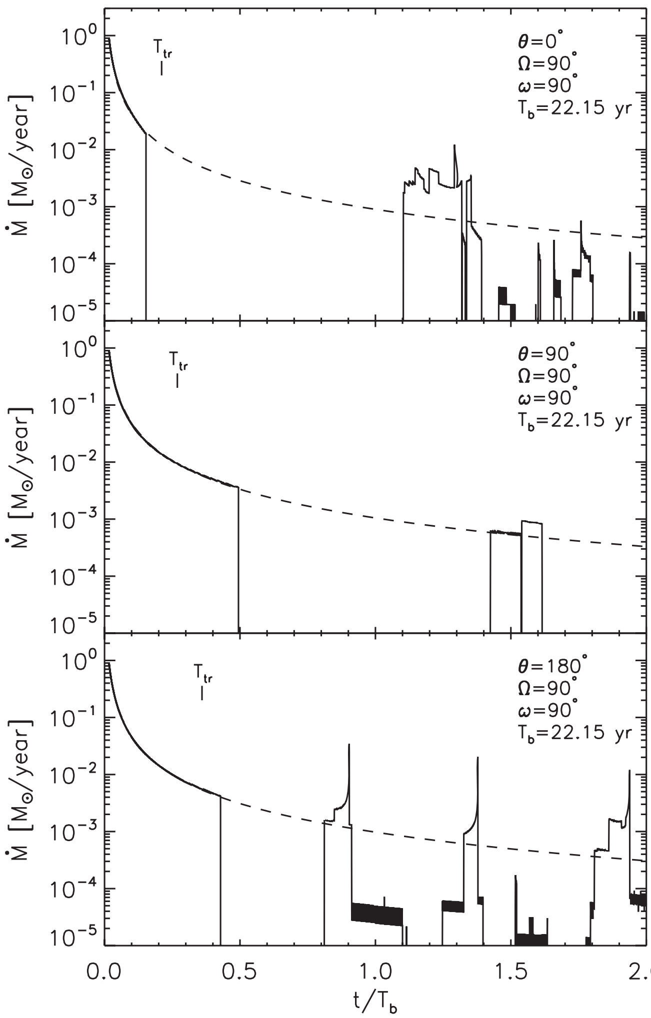

Figure 1. Accretion rates of gaseous debris in units of solar mass per year vs. time. Time starts at tidal disruption and is in unit of the binary orbital period $T_{\rm b} = 22.15$ yr. The solid lines are the simulation results and the dashed lines give the standard $\sim t^{-5/3}$ in single BH systems. $T_{\rm tr}$ marks the interruption time estimated with Equation (5). The upper, middle, and bottom panels are, respectively, for $\theta = 0°$, $90°$, and $180°$.

4. DISCUSSIONS

We investigated the accretion of tidally disrupted stellar debris in SMBHB systems. For simplicity, we assumed for the tidal debris gas: (1) a constant distribution of mass in binding energy at the tidal radius, (2) ballistic motion and negligible interaction of the fluid elements after tidal disruption, and (3) instant circularization of the debris gas probably due to shocks because of interaction between the fluid elements returned to within a radius two times the tidal radius. The first two assumptions have been justified by numerical hydrodynamic simulations (e.g., Evans & Kochanek 1989; Lodato et al. 2009), but the third one

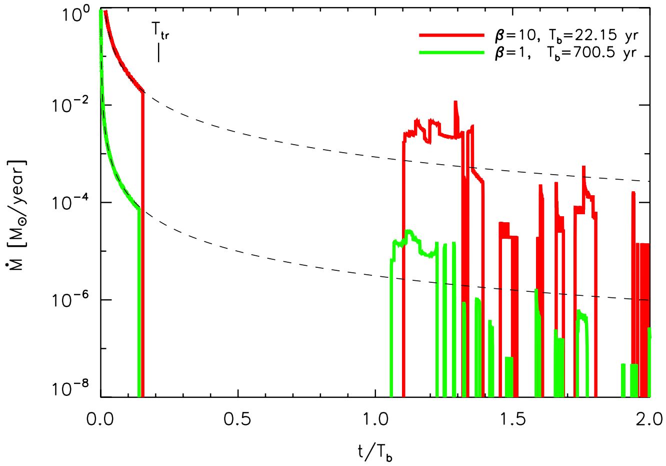

Figure 2. Accretion rates of gaseous debris vs. time for different β at $\theta = 0$. The red and green solid lines correspond to $\beta = 10$ and $\beta = 1$, respectively. The other parameters are the same as those in Figure 1.

needs to be verified by hydrodynamic simulations capable of capturing strong shocks. With these three assumptions, the fluid elements and SMBHB compose restricted three-body systems, so we can investigate the accretion of the gaseous stellar debris by analyzing the stability of the three-body systems using the *resonance overlap stability criterion* (Mardling 2007). Because of the chaotic nature induced by the nonlinear overlap of several orbital mean motion resonances, the fluid elements inside the chaotic regions significantly change their orbits on a dynamical timescale and do not return to the tidal radius to fuel the BH, leading to the interruption of accretion. We also investigated the evolution of the stellar debris using three-body scattering experiments. Our results obtained both analytically and numerically show that the accretion rate of the debris gas decreases with a power law $\dot{M} \sim t^{-5/3}$ until a critical time $T_{\rm tr}$. At time $t > T_{\rm tr}$, the accretion pauses until about one SMBHB orbital period $T_{\rm b}$. $T_{\rm tr}$ relates to $T_{\rm b}$ with $T_{\rm tr} = \eta T_{\rm b}$, where η is typically 0.25 and in the range $0.15 \lesssim \eta \lesssim 0.5$, depending on the initial orbital parameters (θ, Ω, ω) of the fluid elements at tidal radius and on the eccentricity of the SMBHB, but being nearly independent of the SMBHB semimajor $a_{\rm b}$, BH masses, and mass ratio q. This suspension of accretion would result in an interruption of the tidal flare, although the residual accretion disk may still radiate weak optical, UV, and X-ray emission during the interruption.

Our numerical results indicate that the accretion of the gaseous stellar debris restarts at a time $T_{\rm r}$, leading to a flicker of flare. The exact recurring time, $T_{\rm r} = \xi T_{\rm b}$, depends on the initial orbital parameters θ, Ω, and ω, but our numerical results suggest that ξ is of order unity and $1 \lesssim \xi \lesssim 1.5$. The interruption timescale of the tidal flare in a SMBHB system is

$$\Delta T = T_{\rm r} - T_{\rm tr} \simeq (\xi - \eta) T_{\rm b}. \quad (8)$$

Our numerical simulations suggest that the accreted plasma during the discrete accretion consists of both the tidal debris gas falling back to the tidal radius after one Keplerian time and a fraction of those fluid elements with chaotic orbits falling back to the accreting torus on a timescale longer than its Keplerian time. When $T_{\rm tr}$ and ΔT are determined observationally, constraints on η and $T_{\rm b}$ could be made if we take $\xi \simeq 1$.

In our simulations, we assume that the orbital binding energy E_b of the tidally disrupted star is negligible compared to the spread in specific energy ΔE. For such tidal-disruption events, Equations (3) and (7) imply that the standard power-law decay and the interruption of tidal flares are detectable if

$$\beta < \beta_{\rm max} \approx 130 \sigma_{110}^{-2} M_7^{1/3} q_{-1} (1+q)^{-4/3} \left(\frac{k}{2}\right) \times \left(\frac{\eta}{0.25}\right)^{2/3} \left(\frac{R_*}{r_\odot}\right)^{-1} \left(\frac{m_*}{M_\odot}\right)^{2/3}. \quad (9)$$

If the tidally disrupted star is initially very bound to one of the binary BHs so that $|E_b|$ is comparable to ΔE (Chen et al. 2009), the time $T_{\rm min}$ would be much shorter and the interruption of tidal flare is detectable even in an ultra-hard SMBHB with $\beta \gg \beta_{\rm max}$. For a SMBHB with $\beta \sim 100$, the semimajor axis of the binary $a_{\rm b}$ is about $a_{\rm b} \simeq 9.3 \times 10^2 r_{\rm g} q_{-1} (1+q)^{-1} \sigma_{110}^{-2}$. The GW radiation emitted by such SMBHBs could be detected by PTA.

An interrupted tidal flare could be caught if $T_{\rm tr}$ is shorter than the mission duration of an transient survey $t_{\rm sv} \sim$ 1–10 yr, which corresponds to SMBHBs with $\beta \sim (5\text{–}100) \times q_{-1} M_7^{1/6}$. Here, we use the $M_\bullet$–σ_* relation (Tremaine et al. 2002). Because a hard SMBHB with $q = 0.1$ spends most of its life time at $\beta \sim$ 5–100 (Yu 2002; Sesana et al. 2008), we have a good chance to detect them with upcoming transient surveys. However, if one wants to catch an interrupted tidal flare from SMBHBs emitting strong GW radiation ($\beta \sim 1000$), the time resolution of the survey should be $\lesssim 0.1$ yr. Because a SMBHB spends a small fraction of its lifetime at this stage, high-sensitivity and deep transient surveys are needed to accumulate many more tidal-disruption events.

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