Stellar Tidal Disruption as a Prompt Electromagnetic Signature of Supermassive Black Hole Coalescence

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Gravitational radiation offers a direct means to identify merging black holes in the universe, perform precision tests of general relativity, and perhaps even probe cosmological parameters. However, there are many technical obstacles gravitational wave astronomy has yet to overcome, and the current limitations of gravitational wave detectors motivate the search for electromagnetic counterparts to black hole coalescence. In this paper we propose prompt and sequential tidal disruptions of stars as a counterpart to the gravitational waves emitted during the merger of two supermassive black holes. The kick imparted to the merged black hole shifts the six-dimensional stellar distribution function in velocity space, creating a new loss cone, which can contain a significant number of stars. This shift increases the tidal disruption rate to unusually high levels, set by the dynamical times of stars in the new loss cone. For certain pre-kick density profiles and black hole masses, the rate of tidal disruptions can be initially as high as 1 yr^{-1}, and disruption rates of ~ 0.1 yr^{-1} are expected for the most physically plausible pre-kick density profile. The prompt tidal disruption events following a black hole recoil can offer detectable electromagnetic signals $\sim 1-10$ years after the merger, and sequential disruption of multiple stars in the same galaxy are a potentially unique signature of recent black hole coalescence. Prompt disruption flares offer a useful followup to and confirmation of gravitational wave observations, while sequential TDEs could serve as both a followup and as an indicator of SMBH coalescence in their own right.

Introduction Recent work in numerical relativity has indicated that black hole coalescence is generally accompanied by anisotropic emission of gravitational radiation[1]. Conservation of linear momentum causes the merged black hole to recoil at velocities which can reach thousands of km/s. The coalescence of astrophysical SMBHs is a generic consequence of galaxy mergers (given enough time for the initial SMBH binary (SMBHB) to shed its angular momentum) and the resultant gravitational waves are potentially detectable by the proposed Laser Interferometer Space Antenna (LISA) or pulsar timing arrays (PTAs).

LISA and PTAs are the two gravitational wave observatories which could plausibly detect gravitational radiation signals from merging SMBHs in the next decade. LISA is most sensitive to SMBHBs with a total mass of $10^6 M_\odot$, but is able to localize SMBHBs up to masses of $\sim 10^7 M_\odot$[2]. PTAs have significantly poorer peak localization ability (typical error is ~ 40 square degrees, versus $\lesssim 1$ square degree for LISA), but are able to detect much heavier SMBH binaries, with masses $\sim 10^8 M_\odot$ around the peak of the PTA sensitivity[3]. Gravitational wave observations determine the luminosity distance to the merging SMBHB, with positional error in the sky being the primary uncertainty. An electromagnetic (EM) counterpart would greatly reduce this positional error, and also determine the redshift of the source, which would enable its use as a "standard siren" independent of the cosmic distance ladder for precision measurements of the dark energy equation of state[4].

For these reasons, EM signals are a widely hoped for counterpart to SMBHB coalescence. Several EM signals have already been proposed, with most assuming the presence of a circumbinary accretion disk prior to coalescence. Dissipation of gravitational wave energy in the disk will result in a weak EM transient hours after the merger[5], re-equilibration of the inner edge of the disk will create a large X-ray luminosity in a time $10-10^3$ yr[6], shocks produced by the kick can generate EM transients on a timescale of weeks after recoil[7], and smaller density perturbations can take $\sim 10^4$ years to dissipate as enhanced IR luminosity[8]. The portion of the accretion disk that remains bound to the merged SMBH would be detectable as a kinematically[9], and, eventually, a spatially offset quasar[10], although its duration is limited by the supply of gas that can remain gravitationally bound[11]. All of these EM signals, however, rely on the existence of substantial accretion flows around the black hole. The EM counterpart we are proposing does not depend on the presence of gas. Stellar tidal disruption flares would be visible in mergers which were dry to begin with, and also those in which all of the gas had been used up in accretion and star formation prior to SMBH coalescence. Although tidal disruption flares spatially offset from the center of their host galaxy have been studied before as a signature of black hole recoil[12], this paper investigates the production of prompt flares in the years following the coalescence of a SMBHB.

Tidal disruption flares associated with a phase space shift could possess two identifying characteristics: prompt occurrence and sequential repetition. If a LISA or PTA gravity wave signal localizes a SMBH merger to $N < 10^5$ galaxies, a tidal disruption event (TDE) within $10^{-5}N$ years of the merger would likely have the same galaxy of origin, given that the galaxy-averaged tidal disruption rate is $\sim 10^{-5}$ events per year[13]. Such an identification could be further strengthened by followup observations of the TDE's host galaxy, to search for morphological or AGN evidence of a recent galaxy merger. A second (and in the case of poor localization more conclusive) signature tying a tidal disruption flare to a SMBH merger would be the sequential disruption of two or more stars within the same galaxy. Sequential disruptions are extremely unlikely for galaxies with stationary supermassive black holes, and the only other known mechanism to produce rates as high as $\gtrsim 10^{-1}$ yr^{-1} is the dynamical friction phase of a SMBHB orbit[14]. However, sequential disruptions from a SMBHB could potentially be distinguished from those due to phase space shift for a recoiling black hole. The dynamics of the tidal disruption flare encode information on the mass of the SMBH, and sequential disruptions in an unequal-mass SMBHB would reveal different black hole masses. Furthermore, the dynamics of the tidally disrupted debris streams could potentially be altered by the time-dependent potential of an SMBHB system.

Physics of the Loss Cone A star will be tidally disrupted by a SMBH of mass M_{BH} if it passes within a tidal radius given by

$$r_t = r_* (\eta^2 M_{BH}/m_*)^{1/3}. \tag{1}$$

Here the star has mass m_* and radius r_*, and η is a dimensionless constant of order unity[15] related to the stellar structure. Tidal disruption does not occur if $r_t < r_h$ - in this case, the star is swallowed whole by the event horizon. For Schwarzschild black holes and main sequence stars, the event horizon r_h moves outside the tidal radius for $M_{BH} > 10^8 M_\odot$, although in the Kerr metric significant black hole spin can allow for continued (angle-dependent) tidal disruption of stars by SMBHs with $M_{BH} \lesssim 7 \times 10^8 M_\odot$[16]. During disruption, ~ 0.5 of the star's mass is immediately unbound, while the bound half free streams on Keplerian trajectories, until these streams return to pericenter and collisionally shock each other[17]. These gas streams (which return with a characteristic rate $\dot{M} \propto t^{-5/3}$) form an accretion disk whose blackbody emission peaks in the UV or soft X-ray, and can have luminosities comparable to a supernova[18]. Other sources of emission include line radiation from the unbound debris[19], and a brief period of super-Eddington mass fallback, the physics of which are still controversial[18]. These features of TDE physics are all potential observational signatures useful for differentiating disruption flares from supernovae or AGN variability, but it is unclear if they will be significantly altered by the presence of a strong preexisting accretion flow (due either to sequential tidal disruptions on short timescales, or an accretion disk that has remained bound to the SMBH post-recoil). However, the luminosity of any circumbinary disk will have been significantly reduced by the decoupling of the SMBHB from the inner edge of the disk in the final stages of inspiral[6][8]. The disk will not refill and return to its full luminosity for a time $\sim 7(1+z)(M_{BH}/10^6 M_\odot)^{1.32}$ yr, allowing prompt TDEs to generally outshine any preexisting disk.

In a spherical galaxy with a stationary SMBH, the criterion for stellar disruption is

$$J^2 = |\vec{x} \times \vec{v}|^2 < J^2_{crit} \approx 2GM_{BH} r_t, \tag{2}$$

where J is specific angular momentum, and we have approximated doomed orbits as nearly radial. Such orbits are said to fall in the loss cone. The rate of tidal disruptions in a galaxy with a stationary SMBH is set by relaxational processes: inward of a certain radius, the loss cone will be empty, but past that will be in the "pinhole" regime where the rate of scatter into and out of the loss cone is greater than the dynamical time[20][21]. However, a recoiling black hole will be seen by its stellar population as acquiring an almost instantaneous velocity, so if we stay in the rest frame of the black hole it is as if there had been an instantaneous shift in one velocity coordinate. The new loss cone will be given by

$$J^2 = |\vec{x} \times (\vec{v} - \vec{v}_k)|^2 < J^2_{crit} \approx 2GM_{BH} r_t, \tag{3}$$

where $\vec{v}_k$ is the SMBH recoil velocity.

To investigate the stellar population around a SMBHB in the last stages of inspiral, we first consider the simple density profile where

$$\rho = \rho_0 (r/r_0)^{-\gamma}. \tag{4}$$

This density profile corresponds to an isotropic pre-kick distribution function

$$f(r,v) = C(2GM_{BH}/r - v^2)^{\gamma - 3/2}. \tag{5}$$

Here we set the normalization constant C by using the observationally calibrated[26] radius of influence (the radius containing $2M_{BH}$ masses of stars)

$$r_{infl} = 35\ pc (M_{BH}/10^8 M_\odot)^{0.56}. \tag{6}$$

Stars will be bound to the black hole(s) before and after coalescence if

$$\vec{v}^2 < 2GM_{BH}/r \tag{7}$$

and

$$(\vec{v} - \vec{v}_k)^2 < 2GM_{BH}/r. \tag{8}$$

The intersection of these two velocity space spheres with each other and with the loss cone is the region of phase space containing stars which can be tidally disrupted after the recoil event. By integrating the appropriate distribution function over this region (and excluding the original loss cone) we can calculate the number of post-recoil TDEs. We have neglected the contribution of unbound stars, but carrying out the integral shows that they provide $\lesssim 10\%$ of the total number of TDEs.

In a gas-free star cluster, a cusp with $\gamma = 1.75$ will be the dynamically relaxed equilibrium state of a stellar population around a massive central object[22]. However, core galaxies are believed to be the endproduct of SMBHB inspiral, as the SMBHs shed angular momentum by ejecting stars in 3-body interactions. Numerical simulations of this process show that an SMBHB hardening its orbit through scattering of stars will excavate a core[23], but at some point depletion of the remaining stars in the SMBHB loss cone will lead to a stalling of the binary, the so-called "final parsec problem"[24]. If we continue to assume the role of gas is negligible, then the binary can only proceed to merger via repopulation of the loss cone. Significant triaxiality of the galaxy potential[25] will repopulate the loss cone but preserve a core with $\gamma \approx 1$[26]. Alternatively, collisional loss cone repopulation will drag inward a cusp of stars[26]. These gas-free scenarios lead us to consider both core galaxies, where $\gamma = 1$, and galaxies with a joint core-cusp density profile, where a $\gamma = 1.75$ profile meets a $\gamma = 1$ profile at $r_0 = 0.2 r_{infl}$[26], and the total mass inside r_{infl} is set to M_{BH} (i.e. we assume the black hole binary has ejected its own mass in stars from the pre-kick radius of influence).

In wet mergers the choice of pre-kick density profile becomes more complicated. Rapid loss of angular momentum due to dynamical friction off of gas can produce a core by denying stars the time needed to relax into a central cusp as described above[26]; on the other hand, *in situ* star formation could rebuild nuclear cusps while the SMBHB orbit hardens. The possibility of star formation motivates us to consider cusp values $\gamma = 1.5, 1.75, 2$.

We compute the number of stars in the new loss cone by Monte Carlo integration in our 6-dimensional phase space. To evaluate the observability of the TDEs caused by the recoil-induced velocity space shift, we consider the quantity $N_{<100}$, the number of stars in the new loss cone which will be tidally disrupted in fewer than 100 years. In practice, stars which fall into the new loss cone will, at the time of the SMBH merger, be at a position $(\vec{r}, \vec{v})$ which is their apocenter in the frame comoving with the kicked black hole - thus $N_{<100}$ is the number of stars with orbital periods $P < 200$ yr. We checked the validity of our integration by using an analytic inverse of the cumulative distribution function to directly sample $f(r, v)$ for the special cases of $\gamma = 1, 1.5$.

Discussion The results of Monte Carlo integrals over six-dimensional phase space, using the density profiles described above, are given in Figures 1 and 2. For all values of γ and M_{BH} considered, the size of the short-period loss cone is roughly constant over the kick velocity range 100 km s^{-1} < $\mathrm{v_k}$ < 1000 km s^{-1}, and decreases quickly for more extreme values of v_k. The pure core profile ($\gamma = 1$) did not produce short-period loss cone populations of interesting size, but within the range 100 km s^{-1} < $\mathrm{v_k}$ < 1000 km s^{-1} all other profiles we investigated are likely to have $N_{<100} \gtrsim 1$ if $M_{BH} > 10^7 M_\odot$. The most physically motivated density profile, the joint core-cusp discussed above, has $N_{<100} \approx 6$ for a $10^7 M_\odot$ SMBH, rising to $N_{<100} \approx 20$ for $10^8 M_\odot$. Pure cusp profiles, such as the Bahcall-Wolf or isothermal sphere, have $1 \lesssim N_{<100} \lesssim 10$ for ($M_{BH} \sim 10^6 M_\odot$), rising to $N_{<100} \sim 100$ (!) for $10^8 M_\odot$ SMBHs.

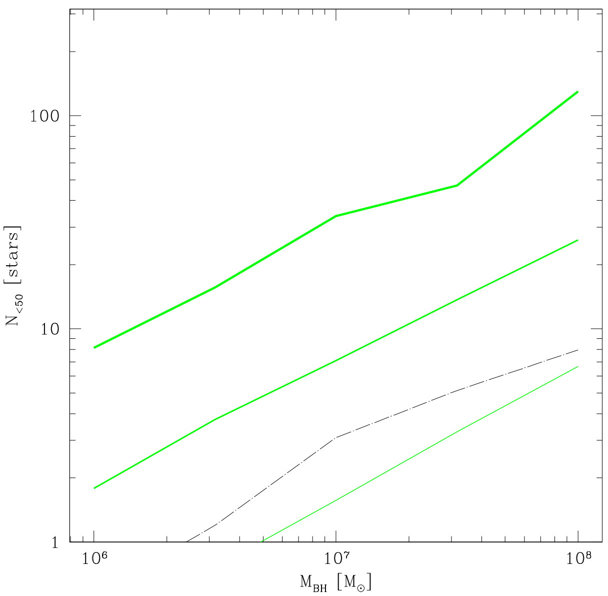

FIG. 1. Size of short period loss cone $N_{<50}$ as a function of black hole mass M_{BH}, for $v_k = 100$ km s^{-1}. The green solid lines are power-law cusps, with $\gamma = 1.5, 1.75, 2$ corresponding to the thinnest, middle, and thickest lines. The dashed line is a joint core-cusp distribution.

In conclusion, galaxies with merging black holes of $M_{BH} \sim 10^7 M_{sun}$ will generally produce prompt tidal disruption flares on a timescale of ~ 10 years after coalescence in the case of a dry merger with collisional angular momentum loss, or ~ 1 year after coalescence for a wet merger with enough star formation to rebuild a stellar cusp. These galaxies are also capable of producing sequential tidal disruptions on the same timescales. Even higher rates of tidal disruption are found for more massive black holes, reaching $1\mathrm{yr}^{-1}$ for $M_{BH} \sim 10^8 M_\odot$ and cuspy density profiles. Prompt TDEs can potentially provide an EM signal in both wet and dry mergers, and do not depend on the recoil velocity being especially large. However, wet or dry mergers which produce pure cores are less likely to generate a prompt or sequential tidal disruption signal over times of interest to observers.

Several relevant questions remain for future investigation. The pre-coalescence distribution function, and the degree of star formation in gas-rich scenarios, are the most important of these. Other questions of interest include the dynamics of sequential tidal disruption flares (or more generally, tidal disruption events in the presence of a pre-existing accretion disk) and the effect of velocity or spatial anisotropies created by the SMBHB on the population of the shifted loss cone. However, unless both collisional loss cone repopulation and *in situ* star formation are proven unimportant during the last pre-GW stages of an SMBHB orbit, it is likely that tidal disruption flares will provide a robust electromagnetic counterpart to the gravitational wave signature of black hole coalescence, enabling accurate determination of the host galaxy and precision measurements of cosmological parameters. Sequential tidal disruption flares could even find evidence for black hole recoil without a gravitational wave signal, providing an independent test of strong-GR predictions.

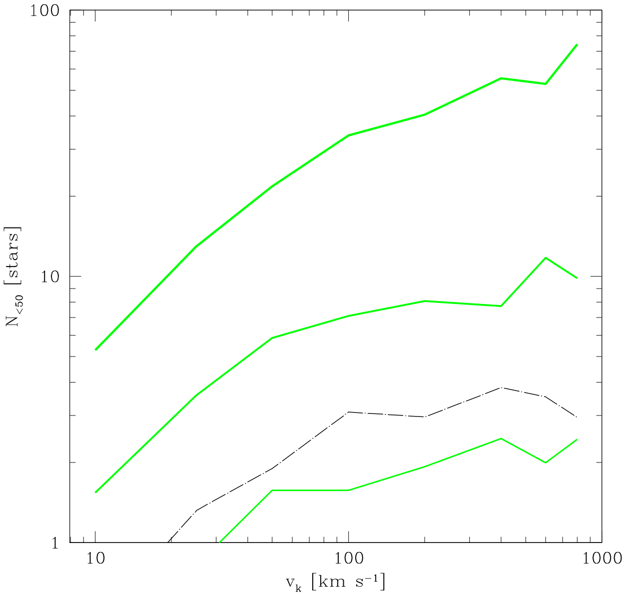

FIG. 2. Size of short period loss cone $N_{<50}$ as a function of recoil velocity v_k, for $M_{BH} = 10^7 M_\odot$. The lines represent the same distribution functions as in Figure 1.

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