# BLINDLY DETECTING MERGING SUPERMASSIVE BLACK HOLES WITH RADIO SURVEYS

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## ABSTRACT

Supermassive black holes (SMBHs) presumably grow through numerous mergers throughout cosmic time. During each merger, SMBH binaries are surrounded by a circumbinary accretion disk that imposes a significant ($\sim 10^4$ G for a binary of $10^8\,M_\odot$) magnetic field. The motion of the binary through that field will convert the field energy to Poynting flux, with a luminosity $\sim 10^{43}$ erg s$^{-1}$ $(B/10^4\,\mathrm{G})^2(M/10^8\,M_\odot)^2$, some of which may emerge as synchrotron emission at frequencies near 1 GHz where current and planned wide-field radio surveys will operate. We find that the short timescales of many mergers will limit their detectability with most planned blind surveys to <1 per year over the whole sky, independent of the details of the emission process and flux distribution. Including an optimistic estimate for the radio flux makes detection even less likely, with <0.1 mergers per year over the whole sky. However, wide-field radio instruments may be able to localize systems identified in advance of merger by gravitational waves. Further, radio surveys may be able to detect the weaker emission produced by the binary's motion as it is modulated by spin–orbit precession and inspiral well in advance of merger.

*Key words:* black hole physics – cosmology: observations – radio continuum: general – surveys

*Online-only material:* color figures

## 1. INTRODUCTION

Based on relativistic simulations incorporating force-free electromagnetic (EM) fields, Palenzuela et al. (2010) suggest that mergers of supermassive black holes (SMBHs) which occur in the presence of an accretion disk may have significant Poynting flux. This Poynting flux may be detectable as an EM counterpart to the gravitational wave (GW) signature of the merger (other mechanisms have been proposed as direct and indirect EM signatures of merger; see Schnittman 2011, and references therein). These mergers will also produce GW signatures, accessible to the *Laser Interferometer Space Antenna* (*LISA*; for BH masses $M$ in the range $\simeq [10^3, 10^7]\,M_\odot$) and for exceptionally low masses to ground-based GW detectors ($M \lesssim 10^3\,M_\odot$; see, e.g., Reisswig et al. 2009). Whether measured via GW or EM, the measured merger history will strongly constrain our understanding of the formation and evolution of SMBHs (Sesana et al. 2007, 2011).

Only recently radio surveys have moved beyond inhomogeneous archival data sets to systematic examinations of the variable sky (e.g., Lenc et al. 2008; Croft et al. 2011; Ofek et al. 2011), and the situation will continue to improve. Advances in receivers and digital processing make instantaneous fields of view of $>10 \deg^2$ possible at GHz frequencies, enabling repeated surveys of wide areas of the sky. These technologies are being implemented as part of Square Kilometer Array pathfinders under construction (Johnston et al. 2007; Booth et al. 2010).

While all searches for compact object mergers have so far been negative (e.g., Abadie et al. 2010), the improving performance of both gravitational (see Harry & the LIGO Scientific Collaboration 2010) and EM surveys increases the discovery potential for a wide range of events. In this *Letter*, we consider the detectability of the merger event with radio surveys centered near frequencies of 1 GHz. We show that the flare itself is very unlikely to be detected in the current generation of radio

surveys, largely independent of the amount of EM flux emitted. However, prior to the flare there could be other modulation present which may be detectable. In what follows, we use a flat $\Lambda$CDM cosmology with $\Omega_\mathrm{M} = 0.27$ and $h = 0.72$.

## 2. ELECTROMAGNETIC COUNTERPARTS OF MERGER FLARES

Palenzuela et al. (2010) simulated the merger of two $10^8\,M_\odot$ BHs. They found a flare of Poynting flux (with $L \simeq 4 \times 10^{43}$ erg s$^{-1}$ over $\approx 5$ hr) that occurred at the same time as the GW emission peaked. They also found lower-level emission before the flare ($L \simeq 10^{43}$ erg s$^{-1}$). Neilsen et al. (2010) interpreted the pre-merger secular emission as two steady jets powered by the motion of each black hole through the background magnetic field, with luminosity $\propto (v/c)^2 B^2 M^2$. For unequal masses, we physically expect the luminosity to be provided by the faster, smaller black hole moving through the magnetic field. Using the model of Neilsen et al. (2010), if the more massive black hole has mass $M$ and the less massive has mass $qM$, we expect a luminosity $L \propto q^2 M^2$.

The choice of magnetic field directly affects the EM luminosities inferred from these simulations. Conservatively, Palenzuela et al. (2010) chose a magnetic field that limited their jet luminosity to a small fraction $L \sim 0.002\,L_\mathrm{Edd}$ of the Eddington luminosity at merger.[5] We adopt the same assumption: a jet luminosity limited to a small fraction $\epsilon_\mathrm{Edd} = 0.002$ of

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[5] The limiting magnetic field required to reach this luminosity ($B \simeq 6 \times 10^4$ G$(M/10^8\,M_\odot)^{-1/2}$) is substantially smaller than the magnetic field created by the magnetorotational instability at the inner edge of the circumbinary disk, which we estimate to be $\sim 10^6$ G$(\alpha M/10^8\,M_\odot)^{-7/20}$ (Pessah et al. 2006; Begelman & Pringle 2007). Rather than adopting this large circumbinary field, we implicitly absorb uncertainties into the ill-determined efficiency $\epsilon_\mathrm{Edd}$.

the Eddington limit at the merger event:

$$L_{\text{flare}} = \epsilon_{\text{Edd}} L_{\text{Edd}} \qquad (1)$$

for $q = 1$, while for other mass ratios we assume that $L \propto q^2$.

Given the expected range of magnetic fields ($B = 6 \times 10^4 \, (M/10^8 \, M_\odot)^{-1/2}$ G, with black hole masses going from $10^3 \, M_\odot$ to $10^{10} \, M_\odot$), electrons advected with the flow might emit synchrotron radiation near 1 GHz, as mentioned by Palenzuela et al. (2010). Thus, the merger flare could be a distinctive radio signature out to cosmologically significant distances:

$$d_{L,\text{Edd}} \simeq \sqrt{L/4\pi F_{\text{min}}}$$
$$\simeq 14.2 \, \text{Gpc} \sqrt{q^2 (M/10^6 \, M_\odot) \frac{\epsilon_{\text{radio}}(\epsilon_{\text{Edd}}/0.002)}{(F_{\nu,\text{min}}/\,\text{mJy})(\nu/\text{GHz})}}, \qquad (2)$$

(corresponding to $z \approx 2$) where for simplicity we assume $F_\nu \propto L/\nu$. In this expression, rather than modeling the emission mechanism (i.e., spectrum and beaming) in detail, we assume that a fraction $\epsilon_{\text{radio}}$ of this energy is emitted isotropically in radio frequencies. Given the modest Lorentz factor and magnetic field, beaming is not likely to be too strong. As much as possible in what follows, we attempt to give results that are independent of $\epsilon_{\text{radio}}$.

Though the emission *spectrum* is uncertain, the emission *duration* is not: it scales with the total mass of the system, as it depends on the orbital timescale near merger. Based on Palenzuela et al. (2010), we estimate the merger flare duration by

$$\tau_{\text{flare}} \approx 5 \, \text{hr} \left( \frac{M}{10^8 \, M_\odot} \right).$$

We adopt this estimate for all mass ratios, since the orbital (and hence merger) timescale is determined by the more massive BH.

### 2.1. Merger Rates

To assess the visibility of merger flares, we employ a merger rate distribution that depends on black hole masses and redshift. As each comparable-mass merger doubles the black hole mass, given the masses and growth timescales over which they assemble, the SMBH merger rate must be both low, less than $10^{-8} \, \text{Mpc}^{-3} \, \text{yr}^{-1}$, and strongly biased toward low-mass mergers: only a few merger events occur per year on our past light cone.

The assembly of SMBHs is reconstructed through Monte Carlo merger simulations, following the hierarchical structure formation paradigm. These models evolve the BH population starting from BH "seeds," through accretion episodes triggered by galaxy mergers, and include the dynamical evolution of SMBH–SMBH binaries. The SMBH population is consistent with observational constraints, e.g., the luminosity function of quasars at $1 < z < 6$, the $M$–$\sigma$ relation, and the BH mass density at $z = 0$ (Volonteri et al. 2003, 2008; Volonteri & Begelman 2010). We adopt two of the fiducial merger distributions used in Arun et al. (2009): models LE and SE, where S versus L refers to the seed size—large or small—and E refers to "efficient" accretion; see Sesana et al. 2011. These models are representative of a range of plausible SMBH growth scenarios. As with uncertainties in $\epsilon_{\text{radio}}$, we attempt to make our conclusions robust to specific merger assumptions.
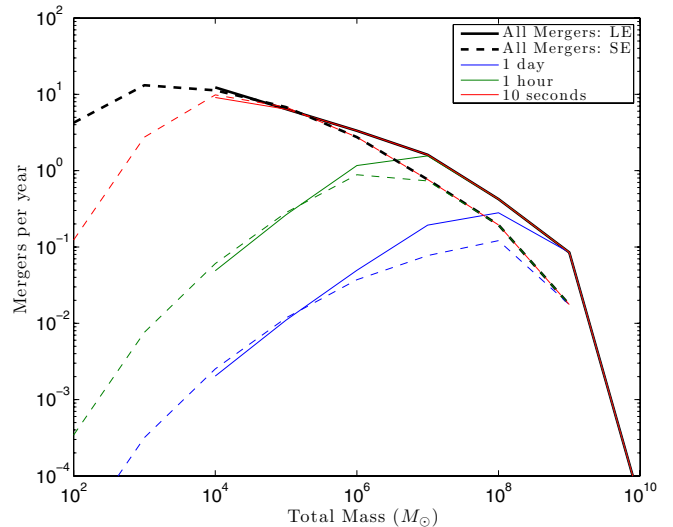


**Figure 1.** Rate of mergers per year on our light cone, for a range of total system masses. The thick curves include all mergers for two models from Arun et al. (2009), with solid lines based on the "LE" model and dashed lines based on the "SE" model. The thin curves reduce this number by $\max(\tau_{\text{flare}}/T, 1)$ for cadences $T = 1$ day (blue), 1 hr (green), and 10 s (red), assuming the flare event duration $\tau_{\text{flare}} \simeq 5 \, \text{hr} \, (M/10^8 \, M_\odot)$.

(A color version of this figure is available in the online journal.)

## 3. THE VISIBILITY OF MERGER FLARES

Figure 1 shows the total merger rate as a function of BH mass, integrating over redshifts 0–10. Only a few mergers per year are expected, even from low-mass ($<10^6 \, M_\odot$) systems. This rate is relevant to untriggered searches by all-sky detectors such as GW observatories (LIGO, *LISA*), which survey the entire sky with roughly uniform sensitivity at high duty cycle. For simplicity, in what follows we will provide quantitative results primarily for the LE model; results from the two models are comparable for the purposes of this discussion.

For limited-aperture surveys, other factors limit the detectable fraction of events (see the discussion in Cordes et al. 2004, for example). Ignoring any flux limits, two effects are important. First, surveys only cover a fraction of the sky $\Omega/4\pi$, with smaller coverage in each pointing. For example, the curvature of the Earth restricts telescopes at temperate latitudes to $\Omega/4\pi \lesssim 80\%$; individual surveys will cover less.

Second, surveys return to the same area of the sky with a specific cadence $T$. A telescope which surveys a single area continuously (i.e., field of view $\Delta\Omega = \Omega$) has $T \simeq 0$. More commonly $\Delta\Omega \ll \Omega$ and the telescope spends time doing other tasks. For instance, a survey might cover $\Omega = 10{,}000 \, \text{deg}^2$ with 333 pointings of $\Delta\Omega = 30 \, \text{deg}^2$, each lasting 30 s. The survey finishes in $<3$ hr (the smallest possible cadence). If the survey returns to each individual pointing 24 hr later, the cadence is $T = 24$ hr.

With such a survey, the fraction of events that can be detected is the fraction that happen to occur when observations are ongoing: $\min[\tau_{\text{flare}}(1 + z)/T, 1]$, assuming $\tau_{\text{flare}}$ is much longer than both each pointing and any dispersive delay across the bandpass (see Section 4.1) and simplifying the flare emission as either on or off (e.g., Cenko et al. 2011). In Figure 1, we illustrate how this simple cadence cutoff reduces the fraction of low-mass merger flares that could be found on the past light cone of a survey with cadences $T = 1$ day, 1 hr, and 10 s. Though
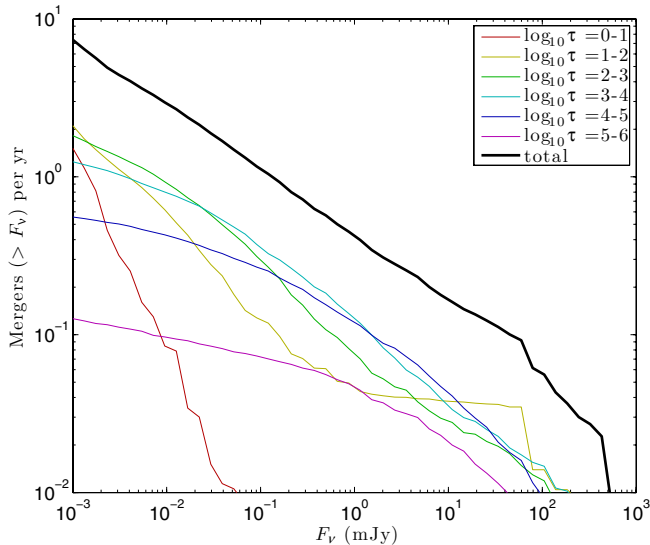
**Figure 2.** Cumulative rate of mergers per year (based on the "LE" model) brighter than a given flux density $F_\nu$ in mJy, for logarithmic bins of observed duration $\tau = \tau_{\text{flare}}(1 + z)$ in seconds. The thin lines are for each bin, while the thick line is for the total considering durations of $10^0$ s to $10^6$ s. We assumed timescales for the flare event that scale as $\tau_{\text{flare}} \approx 5\,\text{h}(M/10^8\,M_\odot)$, along with efficiency $\epsilon_{\text{radio}} = 1.0$ and a frequency $\nu = 1$ GHz.

(A color version of this figure is available in the online journal.)

many low-mass mergers should occur, the short durations of their merger flares makes them nearly impossible to identify.

In the LE (SE) model, the total number of mergers on our past light cone (summing over all redshifts, mass ratios, and masses) is about 24 (39) per year. A survey with $T = 10$ s cadence would recover most of the events, as even the short low-mass events are sufficiently stretched by cosmology that they would be visible for $M \gtrsim 10^4\,M_\odot$. However, a 1 hr survey is only expected to see 3 (2) mergers per year out to $z = 10$ over the whole sky; surveys with finite area will see correspondingly fewer. Restricting the cadence to 1 day reduces the accessible number further to $0.5\,\text{yr}^{-1}$ ($0.2\,\text{yr}^{-1}$).

### 3.1. Flux Distribution

So far, we have only counted the number of mergers on the light cone of our survey. Using the predicted luminosities from Palenzuela et al. (2010), we provide in Figure 2 the cumulative rate of events greater than a flux threshold for a limiting cadence of 1 s (to make the numerous low-mass mergers visible).

Figure 2 shows that merger flares are rare events; the flux density corresponding to $>1\,\text{yr}^{-1}$ over the whole sky is only 0.13 mJy (assuming efficiencies of $\epsilon_{\text{radio}} = 1$ and $\epsilon_{\text{Edd}} = 0.002$).[6] The brightest events (tens of mJy) are extremely rare and come from high-mass mergers, generally at moderately high redshift.

In this figure, we have also limited the maximum possible duration of a merger flare to $10^6$ s (roughly 12 days). Longer events are both rare—excluding them changes little—and will be increasingly difficult to localize in time and separate from systematic trends.

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[6] We assume approximately isotropic emission. If the emission is tightly beamed, single events will be detectable further away, but fewer events will be visible on our light cone. Since the detectability with potential surveys is mostly limited by the small number and short timescale of mergers, strong beaming will further reduce the numbers considered here.

## 4. DISCUSSION AND CONCLUSIONS

Because high-mass mergers are rare (though long-lasting) and low-mass mergers produce short and faint flares (though common), the rate of potentially detectable merger flares is small. Even with optimistic choices for the efficiencies $\epsilon_{\text{radio}}$ and $\epsilon_{\text{Edd}}$, we expect $<1$ merger per year with the surveys to be conducted in the next decade, consistent with zero detections to date. Greater flux sensitivity will not increase the detectable rate substantially, as the finite numbers and short timescales limit detectability. Our results depend only weakly on the assumed merger rate: while the low-mass and low-redshift merger rates are weakly constrained observationally, their merger flares will rarely be visible.

In the radio, ongoing and planned wide-field surveys have instantaneous fields of view of $1$–$30\,\text{deg}^2$ (e.g., Croft et al. 2010; Johnston et al. 2007) at GHz frequencies (this increases to several hundreds or even $1000\,\text{deg}^2$ at a few hundred MHz). Some have relatively frequent sampling, and cover the same area of the sky on timescales from minutes to months, but generally only cover a total of $<10^3\,\text{deg}^2$. Surveys that cover a wider area will likely have a cadence of at least 1 day. None have the combination of a very rapid cadence (ideally $<1$ minute) and very wide sky coverage ($>10^4\,\text{deg}^2$) that are likely necessary to detect a flare blindly, especially with a required sensitivity of $<0.01$ mJy. Since the instantaneous fields of view and cadences of planned optical surveys are typically less than or comparable to those of radio surveys and the cadence considerations are independent of wavelength, optical surveys will be unlikely to discover events like these. Only at X-ray and $\gamma$-ray energies would planned instrumentation be well suited to the timescales and rates of merger flares, although the low fluxes ($\sim 8 \times 10^{-5}(M/10^8\,M_\odot)(E_{\text{photon}}/10\,\text{keV})^{-1}$ photon cm$^{-2}$ s$^{-1}$ at a redshift of 0.1) might require a next-generation mission to be detectable.

### 4.1. GW Counterparts

While Figure 2 suggests that radio flares associated with mergers will be difficult to detect, next-generation surveys may reach limits more amenable to detections. We should consider how merger flares could be identified as such and what physics may be learned from them.

Unlike many proposed counterparts to SMBH mergers, this prompt emission mechanism might allow coincident detection of EM and GW signals from the same event, even though the circumbinary disk is evacuated and no accretion onto the compact objects takes place. Spatial and temporal coincidence can confirm that a radio transient is indeed the signature of a binary SMBH merger. As reviewed in Bloom et al. (2009), coincident EM and gravitational signals provide an independent cosmological distance ladder, if accessible at cosmological distances (Holz & Hughes 2005). Additionally, nearby EM counterparts might be localized to individual host galaxies, allowing study of galaxy–SMBH relations (Schnittman 2011).

In contrast with EM surveys, GW detectors have roughly uniform all-sky sensitivity at all times and a signal that is visible long before merger. Using the GW signal as a trigger, EM observations would be freed of the need to survey the whole sky continuously; follow-up observations would be limited by flux thresholds alone. Here, the large pointing uncertainties on current-generation GW facilities (ideally $\sim 100\,\text{deg}^2$ for a $<10^3\,M_\odot$ SMBH merger with a signal-to-noise ratio of 8; e.g., Fairhurst 2009) will make optical follow-up difficult (e.g.,

Haiman et al. 2009), but are well suited to the fields of view of instruments such as the Australian Square Kilometre Array Pathfinder (Johnston et al. 2007). Moreover, the GW signal may allow identification of an impending merger well in advance. For prime *LISA*-scale sources ($10^5$–$10^7 \, M_\odot$), the sky location of an inspiralling binary can be located to within $10 \deg^2$ hr to weeks before the merger event (Menou et al. 2008; Kocsis et al. 2007). For the merger trees discussed in this Letter, this translates to several events per year (slightly less than 1/3 of all *LISA*-detectable events) that can be localized this precisely (Arun et al. 2009). For an optimistic conversion of EM to radio energy, follow-up pointings will identify all *LISA* events with a flare only if they reach a flux sensitivity $0.01 \, \text{mJy} (\epsilon_{\text{Edd}}/0.002) \epsilon_{\text{radio}}$. Less-sensitive follow-up observations will recover only a fraction of events: roughly $\simeq 17[1 - 0.4(\log F_{\nu, \min}/ \, \text{mJy} - 0.5)]$ events per year for $F_{\nu, \min} \in 0.01$–$3 \, \text{mJy}$ and our fiducial efficiencies, including all mass ratios.

For lower-mass mergers ($M \simeq 10^3 \, M_\odot$), ground-based GW detectors will not identify a sky location before the GW merger signal. Nonetheless, if quickly processed, their sky localization can still help target EM follow-up, as dispersion delays the EM signal. Plasma dispersion will occur in the Milky Way, in the host galaxy of the SMBH, and along the line of sight in the intergalactic medium. For cosmological sources the total dispersion measure (DM, the integral of the electron column density) may reach $>1000 \, \text{pc cm}^{-3}$ (Inoue 2004). This implies a time delay $\Delta t = 4.15 \nu_{\text{GHz}}^{-2} \, \text{DM ms}$, requiring rapid localization and repointing. Even for short flares with modest dispersions, such a delay would be hard to detect, but it is possible if the radio cadence is sufficiently short or the observing frequency low. It may also be possible to detect dispersion within the radio data itself, by measuring the relative delays of different frequencies across a bandpass of width $\Delta \nu$ ($\delta t = 8 \nu_{\text{GHz}}^{-3} \Delta \nu_{\text{GHz}} \, \text{DM ms}$). This is more difficult, since across a finite bandpass the relative delay is even smaller, but is routinely done (e.g., Lorimer et al. 2007). In fact, for very low mass events $M \lesssim 10^4 \, M_\odot (\text{DM}/1000 \, \text{pc cm}^{-3})(\nu/1 \, \text{GHz})^{-3}(\Delta \nu/300 \, \text{MHz})$ dispersive smearing will exceed $\tau_{\text{flare}}$, but this will not greatly change Figure 1. However, matching this "internal" delay with that relative to GW observations could prove a powerful confirmation of the nature of the event.

Second-generation ground-based GW detectors will be sensitive to the lowest-mass mergers ($M \simeq 200$–$10^3 \, M_\odot$) out to a strongly mass- and orientation-dependent threshold $z \simeq 0.1$–2. The associated EM flares will be short (dispersion-limited) and faint. With the most optimistic efficiencies $\epsilon_{\text{Edd}}$, $\epsilon_{\text{radio}}$, radio surveys would have comparable reach to GW surveys at $F_\nu \sim 0.1 \, \text{mJy}$ (Equation (2)); with less efficient conversion or follow-up, fewer coincident events can be found. Unfortunately, unlike SMBH mergers, observations do not directly constrain such merging binaries. The low-mass mergers to which ground-based detectors are sensitive simply may not occur. Even if they do, both GW and radio observations are sensitive to a minute fraction of the universe (not true for third-generation GW detectors; Sesana et al. 2009). That said, if radio surveys can distinguish short ($<1$ s) flares in targeted observations, ground-based GW detectors working in concert with radio telescopes can rule out extremely optimistic ($\gtrsim 10^{-8} \, \text{Mpc}^{-3} \, \text{yr}^{-1}$) low-mass SMBH merger rates and efficiencies.

### 4.2. Non-merger Events

While the rate of potentially detectable mergers is small, other EM emission associated with binary SMBH inspiral could be detectable. EM emission from SMBHs is well known across a range of wavelengths; radio emission from active galactic nuclei (AGNs) is common. We differentiate between generic AGN emission and that associated with an orbiting pair of SMBH through the time domain. AGNs do vary intrinsically but mostly aperiodically; detecting such periodic behavior in a radio light curve would be a strong indication of an inspiralling SMBH pair (e.g., Komossa 2006); we defer additional methods for confirmation to a forthcoming paper (R. O'Shaughnessy et al. 2011, in preparation). A number of binary AGNs are known or suspected (e.g., Komossa 2006; Rodriguez et al. 2006; Smith et al. 2010; Burke-Spolaor 2011). Most of these have evidence from a resolved pair of bright spots or a double set of emission lines, but they all probe systems far from actual merger (Burke-Spolaor 2011). We consider what might happen as the systems approach merger.

Variability will happen over a range of timescales. First, even before the merger the EM flux of the system is expected to increase as $(v/c)^2$ (McWilliams 2011; Neilsen et al. 2010), where $v \sim (t_{\text{merge}} - t)^{-1/8}$ traces the increasing orbital speed during inspiral, going to a maximum of $v_{\max} \approx c/\sqrt{6} \approx 0.4c$ at the innermost stable circular orbit, and with a singularity at merger ($t_{\text{merge}}$). The flux increase will be secular and may be detectable, but the timescales over which it changes appreciably are likely either too long (during the lengthy inspiral) or too short (right before merger), and will be difficult to identify uniquely.

A promising candidate is variability induced by precession (also see Katz 1997 for a related discussion). If there is a Poynting flux associated with a jet, as in Palenzuela et al. (2010), the axis of this jet could precess if the BH spins are not aligned with the orbital angular momentum. This would presumably cause the EM signal to vary on that timescale (although it could be more complicated; Katz 1997). The precession timescale is expected to be $\tau_p \sim M(v/c)^{-5}$ (Apostolatos et al. 1994). The scale of the variations is not known (it depends on the anisotropy of the emission), but could easily be $>50\%$.

While a full treatment is beyond the scope of this Letter, we are drawn to consider the detectability of precessing jets in binary SMBHs for two reasons. First, the time spent at a moderate velocity $v/c \approx 0.1$ compared to the duration of the merger itself is large, scaling as $(v/v_{\max})^{-8}$. A much larger number of systems exist in this state compared to those merging; their timescales are more amenable to detection. Second, a system will undergo many precession cycles, so periodic modulation may be detectable (along with other changes, such as secular increase or orbital modulation); we expect $\mathcal{N}_p \sim (v/v_{\max})^{-3}$ periods to be visible in a roughly logarithmic velocity range. Precession has likely been seen in galactic BH binaries (Katz 1997) and does have observational consequences for the jet emission. In a future paper (R. O'Shaughnessy et al. 2011, in preparation), we will discuss the detectability of binary SMBH jet precession in detail.

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