Electromagnetic signatures of supermassive black hole binaries resolved by PTAs

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Received 1 May 2013
Published 4 November 2013

Abstract
Pulsar timing arrays (PTAs) may eventually be able to detect not only the stochastic gravitational-wave (GW) background of SMBH binaries, but also individual, particularly massive binaries whose signals stick out above the background. In this contribution, we discuss the possibility of identifying and studying such ‘resolved’ binaries through their electromagnetic emission. The host galaxies of such binaries are themselves expected to be also very massive and rare, so that out to redshifts $z \approx 0.2$ a unique massive galaxy may be identified as the host. At higher redshifts, the PTA error boxes are larger and may contain as many as several hundred massive-galaxy interlopers. In this case, the true counterpart may be identified, if it is accreting gas efficiently, as an active galactic nucleus (AGN) with a peculiar spectrum and variable emission features. Specifically, the binary’s tidal torques expel the gas from the inner part of the accretion disc, making it unusually dim in x-ray and UV bands and in broad optical emission lines. The tails of the broad wings of any $\text{FeK}\alpha$ emission line may also be ‘clipped’ and missing. The binary’s orbital motion, as well as the gas motions it induces, may trigger quasiperiodic variations. These include coherent flux variability, such as luminous, multi-wavelength flares, as well as Doppler shifts of broad emission lines and ‘see-saw’ oscillations in the $\text{FeK}\alpha$ line. Additional features, such as evidence for a recent major merger or dual collimated jets, could also corroborate the counterpart. These properties would make resolved PTA sources stand out among AGN with similar overall luminosities and allow their identification.

PACS numbers: 04.25.dg, 95.85.Sz, 98.54.Aj, 98.62.Js, 98.62.Mw

1. Introduction
Multi-messenger observations of SMBH binaries—that is, synergistic studies of both their electromagnetic (EM) and gravitational-wave (GW) emission—represent an extraordinary
astronomical opportunity to probe SMBH accretion, general relativity and cosmic expansion (see reviews by [1–3]). To date, theoretical studies of multi-messenger SMBH astronomy have centered around massive binaries whose coalescences can be observed by a future space-based laser interferometer such as eLISA [4]. In this paper, we discuss the prospects of multi-messenger astronomy for SMBHs that are individually detected (‘resolved’) by pulsar timing arrays (PTAs) because their GW signals stick out above the stochastic ~nHz background [5–10]. PTA sources differ from eLISA sources in that the former are much more massive (total mass $M \gtrsim 10^{5.4} \, M_\odot$ as opposed to $\sim 10^{5.5–7} \, M_\odot$), nearby (redshifts $0.1 \lesssim z \lesssim 1$ versus redshifts up to $z \sim 20$), and are most likely to be ‘caught’ well before their coalescence. In fact, the vast majority of PTA sources will not merge within a human lifetime.

Given that most galaxies appear to have a massive nuclear BHs e.g. [11], the formation of SMBH binaries is an inevitable consequence of the hierarchical structure formation paradigm, in which galaxies are built up by mergers between lower-mass progenitors. The generic expectation is that merger events deliver the two nuclear SMBHs e.g., [12, 13]—along with stars and gas [14]—to the central regions of the new post-merger galaxy. A close BH pair (separated by a ~kpc) is formed, surrounded by a stellar bulge and dense nuclear gas [15, 16], subsequently decaying its orbit and becoming a bound binary. The nuclear gas is expected to cool rapidly, and settle into a rotationally supported circumbinary disc [17, 18]. Such a gas disc can serve the dual purpose of promoting the binary’s orbital decay and producing EM emission in the form of a luminous active galactic nucleus (AGN).

There are large theoretical uncertainties, regarding both the formation of compact SMBH binaries and their EM signatures. The ‘final parsec’ problem—whether the binary can coalesce in a Hubble time [15]—is still an open issue for the most massive ($\gtrsim 10^9 \, M_\odot$) BH pairs. The efficacy of gas in bringing the binary to the compact, GW-emitting regime remains unclear [18–24], especially in light of the fact that the massive disc required may be gravitationally unstable for these BHs [25–27]. On the other hand, recent $N$-body simulations suggest that stellar scatterings may harden SMBH binaries more efficiently than was previously recognized e.g., [28, 29]. At the sub-parsec separations relevant to GW emission, open questions include (i) the expected amount and distribution of gas in the binary’s vicinity, (ii) the coupled dynamical evolution of the binary+gas system, and (iii) the generation of radiation and radiative transfer effects (i.e., AGN physics in general).

Despite these uncertainties, theoretical studies have converged on a relatively simple picture for the behavior of a SMBH binary embedded in a thin, prograde, co-planar circumbinary disc. In this paper, we apply this picture to assess the prospects for uniquely identifying EM counterparts of binaries resolved by PTAs. We focus our attention on two distinct theoretical expectations that make these prospects favorable. The first is the fact that, being the most massive SMBHs in the local Universe, resolved PTA sources are likely to reside in host galaxies that are very massive and rare, which will greatly narrow the search for candidate host galaxies in the detection error box\(^3\). The second is that an AGN accretion disc is predicted to have qualitatively different geometrical and dynamical properties when the central object is a prograde binary SMBH instead of a solitary SMBH. We will detail the various persistent and time-variable EM signatures that have been predicted for accretion flows onto pre-coalescence SMBH binaries.

The remainder of this paper is organized as follows. In section 2, we discuss the likely properties of host galaxies of PTA sources, and estimate the number counts of hosts within the expected detection error volume. In section 3, we review the current understanding of the orbital evolution of SMBH binaries, with an emphasis on the role and distribution of a circumbinary

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\(^3\) The flip-side of this is the relatively low expected number—a few tens—of resolved PTA binaries.
accretion disc. An overview of the EM signatures proposed for accreting, compact SMBH binaries are presented in section 4. We offer our brief conclusions in section 5.

2. Demography of resolved PTA sources and their host galaxies

According to population synthesis studies [5, 7, 30, 31], binaries individually detectable by PTAs will have large chirp masses \( M \equiv M_1^{1/5} M_2^{2/5} M^{-1/5} = \eta^{3/5} M \sim 10^{8-9} M_\odot \), where \( M_2 \leq M_1 \) are the masses of the two BHs, and \( \eta \equiv M_1 M_2 / M^2 \leq 1/4 \) is the symmetric mass ratio. The PTA binaries are also relatively nearby, with their redshift distribution declining steeply outside the range \( 0.1 \leq z \leq 1.5 \) (the cutoffs are due to the small local volume at low \( z \), and to the attenuation of the GW signal at high \( z \)). Finally, resolved PTA binaries are expected to have periods of \( P \sim 0.1-10 \) yr. They are expected to be—almost by definition, because they rise above the stochastic GW background—the most massive and nearly equal-mass (i.e. \( M_1 \sim M_2 \)) SMBH binaries in the local Universe.

It is well known that the masses of nuclear SMBHs correlate with the velocity dispersion \( \sigma \) [32–36] and the luminosity \( L \) [11, 37–40] of the host galaxy. More massive SMBHs also reside in more massive dark matter halos [41, 42], although this correlation may be less tight e.g. [43]. Thus, the exceptional masses of resolved PTA sources imply that their hosts should be either giant elliptical galaxies or among the most massive spiral galaxies (with \( \sigma \geq 200 \text{ km s}^{-1} \) of the spheroid component e.g. [35]). It is also reasonable to expect the host galaxy to be the product of a relatively recent major merger. Based on the fact that cosmological simulations exhibit a weak environmental dependence of the major merger rates of halos on overdensity [44–46] concluded that PTA sources are more likely to reside in a field galaxy than in a cluster. Finally, it is plausible that a PTA source is more likely to be shining as a luminous AGN than the average SMBH, because (i) major galaxy mergers have been associated with luminous quasar activity e.g. [47–49], and (ii) the presence of gas may be instrumental in bringing the binary to small separations where they emit GWs (see section 3 below). Because the Eddington ratio of luminous AGN tends to peak around a value \( \sim 0.2 \) e.g. [50], one could also look for counterparts by focusing on the most luminous AGN in the error volume (as opposed to all galaxies).

The fact that their hosts should (on average) also be massive and rare objects can be used to the observer’s advantage in the search for EM counterparts. Figure 1 (adopted from [46]) shows the approximate counts of host-galaxy interlopers—i.e., the number of dark matter halos, galaxies and AGN that are massive or luminous enough to plausibly host a nuclear SMBH binary of mass \( M_{\text{min}} \)—in the PTA detection error volume estimated by [7]. The number of massive halos was calculated using the \( M_{\text{BH}} - M_{\text{halo}} \) relation of [42] and the halo mass function of [51]; the luminous galaxies using the \( M_{\text{BH}} - L_{\text{gal}} \) relation of [39] and the luminosity function of [52]; and luminous AGN using the luminosity function of [53] while assuming a conservative minimum Eddington ratio of 0.01. We note that the estimate of interloping AGN counts is based on optical luminosity functions. This is important, because as we will discuss below in section 4, the PTA sources may have unusually weak UV and x-ray signatures.

The error volume consists of a luminosity distance uncertainty of 20% and an angular uncertainty of \( \Delta \Omega = 3 \text{ deg}^2 \). This is an optimistic estimate, in that it assumes that the distances to the pulsars in the array can be used to locate the source (see also [8–10]). Figure 1 suggests that in a random volume of such a size, the number of luminous/massive interloping galaxies are at most a few dozen if \( M \gtrsim 10^9 \), and of order one or less for a wide range in redshift. More conservative error boxes e.g. [6] result in \( \sim 10 \) times more interlopers, but the expected number is still of order unity or less for the most massive (\( \gtrsim 10^9 M_\odot \)) SMBHs at \( z \lesssim 0.5 \) [46]. These
Figure 1. Estimated number counts in a PTA detection error volume ($\Delta \Omega \sim 3 \text{ deg}^2$, luminosity distance error 20%; [7]) of (a) dark matter halos, (b) galaxies and (c) AGN that are massive/luminous enough to host a SMBH with minimum mass $M_{\text{min}}$. SMBH-host correlations and mass/luminosity functions are drawn from previous studies as described in the text. In this idealized estimate, the number of plausible host candidates (interlopers) may be sufficiently low for $M \gtrsim 10^9 M_\odot$ binaries at $z \lesssim 1$ to allow for the unique identification of the EM counterpart.

estimates suggest that in the best-case scenario, the error volumes of resolved PTA sources may contain one or a handful of massive galaxies or luminous AGN that can harbor them. At worst, narrowing the search field to the most luminous hosts could facilitate the identification effort. Additional considerations, such as morphological evidence of a recent major merger, may also serve as a 'smoking gun' feature that gives away the host galaxy.

However, figure 1 also shows that in many cases, the number of host-galaxy interlopers could be in the hundreds. Furthermore, SMBH-host correlations are trends only, and trends have outliers e.g. [54]. It is also not out of the question that SMBH binaries and their host galaxies may preferentially lie on extreme tails of known SMBH-host correlations. Therefore, additional observable signatures of PTA sources are desirable, both to corroborate the tentative identification of the EM counterpart when the number of ‘plausible’ hosts is one, and to positively identify the true host when the number of interloping luminous galaxies is large.

3. Co-evolution of SMBH binaries and their circumbinary discs

In this section, we briefly review the current theoretical understanding of how SMBH binaries evolve to the small separations where they emit GWs and can be detected by PTAs. This will serve to lay out a basic framework for the gaseous environment of PTA sources, which will in turn inform predictions for their EM signatures (section 4).

During and following a galaxy merger, the two nuclear SMBHs sink to the center of the post-merger potential well through dynamical friction, and form a bound binary. Minor
mergers of galaxies are unlikely to produce SMBH binaries, as the smaller galaxy can be tidally stripped and dynamical friction will be unable to deliver its SMBH to the center of the post-merger galaxy e.g. [20]. Therefore, astrophysical SMBH binaries are expected to consist of BHs of comparable masses ($0.01 \lesssim q < 1$ e.g. [31]). The binary’s subsequent orbital decay is illustrated in figure 2 (adapted from [27]), which shows the theoretical residence time $t_{\text{res}} = -\frac{a}{(da/dt)}$—where $a$ is the binary’s semimajor axis—for equal-mass binaries of various masses, as a function of their orbital time. As the binary evolves from large to small separations, it undergoes three distinct regimes of evolution.

**Stellar scattering.** At large separations, the orbital decay is driven by three-body interactions with stars that wander into the binary’s orbital path. The residence time in this regime is shown by the solid magenta lines in figure 2. These curves, which employ equation 10 from [26] based on the results on [55], as well as the $M-\sigma$ relation from [41], assume that the loss cone is refilled by stars diffusing on the steady-state, two-body relaxation timescale in a spherically symmetric potential. These curves are conservative; recent $N$-body simulations have shown that time-dependent, rotating, triaxial or axisymmetric stellar potentials can accelerate binary evolution substantially e.g., [28, 29].

**Binary-disc angular momentum exchange.** At smaller separations, the binary can accelerate its orbital evolution by exchanging orbital angular momentum with a surrounding gas disc. This interaction also distorts the surface density profile of the disc near the binary’s
orbit. Over these long timescales, this interaction is expected to align the binary and the disc, so that they become prograde and coplanar e.g. [56]. In the mass-ratio regime of interest \( (q \gtrsim 0.01) \), the secondary is massive enough to open a low-density annular gap about its orbital path. The secondary is essentially a particle in the disc, and migrates inward on the viscous diffusion timescale (so-called type II’ migration). The dotted blue lines in figure 2 show the residence times in this regime. At sufficiently small orbital radius, the local disc mass becomes too small to substantially absorb the orbital angular momentum of the secondary, slowing its migration. The red curves in figure 2 show the residence times in this regime. In standard models of geometrically thin discs [57], this stalling occurs at fairly large orbital separations, typically several thousand Schwarzschild radii. Finally, the outer disc may be unstable against gravitational fragmentation e.g. [25, 27]; critical values of \( a \) for gravitational stability are marked with red dots in figure 2. As the figure shows, this is a particular problem for the most massive \( (\gtrsim 10^9 M_\odot) \) binaries, whose stable disc may extend only over a factor of few in radii.

**GW emission.** Finally, once the binary is sufficiently compact, its orbit will decay via GW emission. The black curves in figure 2 show the evolution in this regime, using the quadrupole formula for circular binaries [58]. The evolution in this final regime is strongly self-accelerating, with \( t_{\text{res}} \propto a^4 \).

Figure 2 also shows the three zones of a standard thin accretion disc, depending on the dominant source of opacity (free-free in the outer region; electron-scattering otherwise) and pressure (radiation in the inner region; gas pressure otherwise).

The distribution and behavior of gas in the immediate vicinity of the BHs are two crucial factors that determine the EM signatures of the binary. Unfortunately, the details are the most murky for the compact systems of interest here. In the late stages of disc-driven migration, when the secondary is more massive than the local disc mass, the system is unable to maintain steady-state type II migration. The evolution of the binary and the disc become strongly coupled. Because numerical simulations cannot cover the time-spans necessary to study the system from disc-binary coupling to merger, much of the current theoretical understanding of binary evolution in this regime comes from analytic and 1D calculations e.g., [23, 56, 59–64].

The gas interior to the secondary’s orbit, where the viscous time is short, is believed to drain onto the primary, creating a central circumbinary cavity [65]. As gas continues to accrete inward from larger radii, it is pushed outward by the binary’s tidal torques and piles-up outside a radius \( R \sim 2a \) [66], much like a ‘dam’ in a river [56, 59, 67, 68]. Such inner cavities are seen in many numerical simulations, beginning with the seminal work by [66]. However, in the absence of comprehensive numerical calculations, it is unknown whether cavities remain open throughout the binary’s evolution. Ongoing accretion may refill the cavity if the ‘dam’ is leaky—or, even if the ‘dam’ is initially effective, continued accumulation of gas may eventually cause it to ‘burst’ and fail (but this may not occur in the most massive binaries) [62, 63]. If the ‘dam’ holds, then its location is expected to follow the binary’s orbital decay—the damming comes at the expense of the binary’s orbital angular momentum—i.e. always remain at the resonance radius \( \sim 2a \), at least until the binary becomes GW-driven and decouples from the disc (see below).

Simulations also show that even when binary torques open a cavity, the ‘dam’ is generally porous. Modulated by the binary orbit, circumbinary gas leaks periodically into the cavity, in narrow, elongated streams [26, 69–73]. The rate at which mass ‘leaks’ into the cavity is of order \( \sim 10–100\% \) of the accretion rate in the circumbinary disc far outside the cavity [74, 75].

Thus, the strongly coupled evolution and behavior of the binary and the disc remains a highly nontrivial and open theoretical problem, despite the considerable progress made by both
semi-analytic and numerical (including GR and/or MHD) calculations. Ironically, for GW-emitting binaries, an additional complication is posed by the fact that the binary decouples from the disc. Because GWs cause the binary’s orbital decay to accelerate as \( \frac{da}{dt} \propto a^{-3} \), the binary will eventually harden faster than the surrounding gas can viscously respond, and begin to outrun it [65]. Even when the binary and disc become thus decoupled, a significant amount of gas may be able to follow the binary as ithardens (note that the torques holding the ‘dam’ recede, as the binary accelerates; [46, 76]). Simulations in the relativistic regime found that gas streams can follow the binary to small radii (several gravitational radii, \( R_g \equiv GM/c^2 \); e.g. [77–79]), although these simulations start with small binary separations and assume that the gas is present near the binary at those initial separations. Nevertheless, considering that prior to becoming GW-driven the gas density outside the ‘dam’ could have been very high due to pile-up, it is plausible that even GW-driven binaries are surrounded by copious amounts of accreting gas.

Finally, since the circumbinary gas can accelerate the evolution of the binary, it can reduce the total expected number of PTA sources. As figure 2 shows, at PTA frequencies, gas is more important for lower-mass binaries. This produces the happy result that the unresolved GW background (composed of the emission from \( M \lesssim 10^8 M_\odot \) binaries) is reduced, while the more massive, individually resolvable binaries are largely unaffected and therefore stand out at higher signal-to-noise ratio [30].

Because the innermost regions of accretion flows are where most of the luminosity and broad emission lines of AGN are generated, an empty or low-density cavity would have significant consequences for the observational appearance of an accreting SMBH binary. Similarly, any time-dependent dynamical features of the accreting gas driven by the binary’s orbital motion is likely to produce conspicuous time-variable signatures. In the next section, we turn to the specific EM signatures that have been proposed.

4. Electromagnetic signatures

Here, we review the various EM signatures that have been predicted for compact SMBH binaries that may be individually resolved by PTAs. All of these signatures assume that the binary is accreting gas from large radii at a rate comparable to a ‘normal’ AGN (i.e. close to the Eddington rate), and rely on the basic geometrical and dynamical features of the accretion flow that distinguish these binaries from solitary SMBHs. The underlying features fall roughly into three categories: (i) imprint of the binary on the distribution of gas in its neighborhood or the geometry of its accretion flow; (ii) dynamics of the accreting gas, as driven by the binary’s time-dependent potential; and (iii) the orbital motion of the binary itself.

4.1. Signatures due to the cavity

The presence of a central, empty (or nearly empty) cavity directly implies that the binary would be deficient in high-energy thermal photons. To see this, one can naively compute the AGN spectrum for a standard thin disc that is truncated inside the ‘dam’ radius \( R \approx 2a \). The spectral energy distribution (SED) of such a disc peaks at a frequency corresponding to the black-body temperature at this truncation radius,

\[
\nu_{\text{peak}} \sim 10^{15} \left( \frac{M}{10^9 M_\odot} \right)^{1/4} \dot{m}^{1/4} \left( \frac{P}{1 \text{ yr}} \right)^{-1/2} \text{Hz},
\]

which is much smaller than \( \nu_{\text{peak}} \sim 10^{16}–10^{17} \text{Hz} \) in a comparable accretion disc around a solitary SMBH of the same mass [46, 80, 81]. Above, \( \dot{m} \) is the accretion rate outside the cavity.
Figure 3. Estimated SEDs of circumbinary discs around a SMBH binary with total mass $M = 10^9 M_\odot$ and mass ratio $M_1 : M_2 = 4 : 1$. The dotted curves show the emission from the circumbinary disc truncated by a central cavity (bump at $\nu \sim 10^{15} \text{ Hz}$) and from the circumsecondary disc (higher-frequency bump). The solid curves show the composite spectrum, and the dashed curve shows, for comparison, the SED of an Eddington accretion disc around a single SMBH of the same total mass.

in units of the critical rate corresponding to the Eddington luminosity. This estimate remains valid even when accounting for the surface density pile-up, until the very final stages before the merger, when GW emission has caused the binary to completely leave the circumbinary disc behind [46]. Gas inside the cavity, as well as the additional heating caused by the pile-up, can compensate somewhat for the high-energy decrement in the SED, but this extra heating is significant only for lower ($M \lesssim 10^8 M_\odot$) binaries [63], and not enough to shift the peak frequency [23].

Figure 3 (adopted from [46]; see also [65, 76, 81]) shows the SEDs from (i) the circumbinary disc (dotted lines, low-frequency bump) alongside (ii) a circumsecondary disc (high-frequency bump) with a size equal to the Hill stability radius. The binary in this example has a total mass $10^9 M_\odot$, mass ratio $q = 1/4$ and orbital periods of 1 yr (top panel) and 0.1 yr (bottom). The circumbinary gas profile around the GW-driven binary was calculated from the point of decoupling, using a 1D diffusion equation with a moving inner boundary condition for the ‘dam.’ The surface density of the circumsecondary disc is calculated by assuming that it is fueled via leakage of gas into the cavity, at a rate that is 10% of the circumbinary gas supply rate. The circumbinary gas density is enhanced by a factor of 3 to show the effect of gas pile-up. The composite SEDs are shown by solid lines, and the SED from a disc (with no pile-up) around a single SMBH of the same total mass is shown by the dashed curves for comparison.

Apart from the conspicuous depression of the flux in the UV and x-ray bands, figure 3 shows that for moderately wide ($P$ of several years) and/or distant ($z \gtrsim 0.5$) binaries, the downturn in the spectrum could be observed even at optical wavelengths. These features may
Figure 4. The change in the broad FeKα line profile due to a central cavity in a circumbinary accretion disc. Left panel: ‘clipped wings’ due to central cavity. The broad FeKα emission is assumed to originate from the region of a standard accretion disc inside 100\(R_g\), with an \(r^{-2.5}\) x-ray emissivity profile, and the disc is viewed at an inclination angle of \(\theta = 60°\). The solid black curve shows the ‘usual’ line profile for a single BH, with the inner disc extending from 100\(R_g\) inward to 6\(R_g\). Other curves assume the disc has a central cavity, and the gas distribution extends inward only to 20\(R_g\) (red curve), 40\(R_g\) (green curve), 60\(R_g\) (dark blue curve), or 80\(R_g\) (light blue curve). As the size of the central cavity increases, the broad component of the line decreases in magnitude and its blue and red wings are increasingly suppressed. Right panel: ‘see-saw wings’ due to circumsecondary’s orbital motion. The black curve shows the Fe Kα emission line from the main circumbinary disc (55–100\(R_g\); i.e. in-between the green and dark blue curves in the left panel) plus a weak secondary broad component (10\% of the intensity of the full disc profile) due to an accretion disc around the secondary black hole, located at 30\(R_g\), centered on the line centroid energy (6.40 keV). The red curve shows the effect of shifting the centroid of the weak secondary component red-ward to 5.2 keV. The blue curve shows the effect of shifting the centroid of the weak secondary component blue-ward to 7.3 keV. The progression from red curve to blue curve occurs over half the orbital time of the binary. Observationally, we expect a ‘see-saw’ oscillation between the blue and red wings of the line over the binary’s orbit. The curves in both panels are binned at approximately the energy resolution (\(\sim 7\) eV) expected for Astro-H.

cause SMBH binaries to be misidentified as quiescent galaxies, because they may be missed in color- and x-ray-selected samples. The presence of the cavity would also suppress UV and optical broad emission lines [46], as well as the x-ray FeKα line. In figure 4, we show an illustration of the latter: the left panel shows the expected line profile (adapted from [82]) for a solitary BH with the accretion disc extending from 6–100 gravitational radii (black curve) and for binary BHs that carve out a central cavity of various sizes (other, colored curves). For a fiducial disc with viscosity parameter \(\alpha = 0.01\) and scale-height \((H/r) = 0.1\) around a 10\(^7\) M\(_\odot\) SMBH, we expect the profile to progress from the solid black curve to the solid blue curve on a timescale of \(\sim 150\) yrs. These ‘clipped wing’ features will therefore be stable (unevolving) for massive PTA binaries, and possibly observable for binaries caught at small enough separations (\(\leq 100\) gravitational radii) where the FeKα line is detectable.

As mentioned above, the cavity may not be completely empty, because the gas inside the annular gap may not have been completely depleted [23, 83], or because gas leaking into the cavity may fuel small ‘mini-discs’ around one or both SMBHs [31, 79, 84]. In general, gas inside the cavity can produce high-frequency photons, but not enough to shift the peak in the thermal SED; the decrement is still significant [46, 80]. In very late stages of merger, gas inside the cavity may be tidally heated by the shrinking binary, resulting in enhanced high-frequency emission [60, 83] (although unfortunately, this effect is expected to be weak; see [85]). For systems that are on the verge of merger or that have recently merged, we may witness the birth of a bright quasar: the SED of the outer disc may harden gradually and monotonically, as the cavity fills in, with brightening optical and UV emission, over several decades [86].
4.2. Dynamics: variability due to periodic accretion into the cavity

The gas that leaks into the cavity may trigger periodic luminosity variations on either the orbital timescale e.g. [27, 69] or its harmonics [31, 75]. The periodic mass supply onto the circumprimary and circumsecondary mini-discs can cause periodic fluctuations in luminosity e.g. [26, 84]. The streams may also shock the mini-discs [46], or be flung back out and shock the cavity wall [75]. These fluctuations may be detectable with high-cadence, long-term monitoring, but a major challenge will be to disentangle them from intrinsic AGN variability e.g. [87, 88]. Here a possibility is to look for the presence of harmonics: in particular, for an unequal-mass binary (with, say \( q \approx 0.3 \)), a periodogram of the mass accretion rate into the central regions of the cavity shows strong spikes at both the binary’s orbital time \( t_{\text{orb}} \), as well as at \( 0.5t_{\text{orb}} \) (and also at the orbital period at the cavity wall, \((3-4)t_{\text{orb}}\)) [75]. Seeing periodic variability on two timescales with a 1:2 ratio (plus a longer timescale) could therefore be a ‘smoking gun’ for the presence of a binary.

Recently, [81] proposed that periodic streams into the cavity may trigger much more prominent variability than previously thought. The tidal elongation of the streams would cause the leading end to collide with the trailing portions shortly after pericenter, and shock-heat. Because the streams are highly eccentric and have large kinetic energies relative to the circular-orbit value at pericenter \( (\sim 0.1a \text{ from simulations of } [26, 84]) \), the shock can circularize the gas orbits about the nearby SMBH and heat it to nearly viral temperatures. Such a hot, optically thick accretion flow could accrete on timescales shorter than a binary orbit (provided that the pericenter of the stream is less than the Hill radius of the nearby SMBH), and fuel transient, luminous flares instead of long-lasting mini-discs. Interestingly, such binary-induced flares—rapidly decaying, multi-wavelength flares with AGN-like SEDs peaking in the UV—may closely resemble tidal disruptions of stars. However, because PTA sources are too massive to cause tidal disruption events, a measurement of the SMBH mass in the flaring system should distinguish between the two flare mechanisms. The observation of repeating flares in the same galaxy (on the timescale of a few years, matching the GW frequency) could also corroborate a SMBH binary origin, since the tidal disruption rate is thought to be only \( \sim 10^{-5} \text{ yr}^{-1} \) in typical galaxies\(^4\).

Quasi-periodic luminosity fluctuations have been observed in several AGN, most notably in OJ 287, a BL Lac object that exhibits pairs of optical flares—brightening by as much as five magnitudes—every \( \approx 11.7 \) years, going back to the late 19th century. Other, less prominent examples include 3C345 e.g. [91] and Mrk 501 e.g. [92]. OJ 287 has long been speculated to be a SMBH binary [93]. In recent years, [94–96] have modeled the system as an extremely massive eccentric SMBH binary \( (M_1 = 1.8 \times 10^{10} \text{ M}_\odot \text{ and } M_2 = 1.4 \times 10^8 \text{ M}_\odot) \) with a tilted circumprimary accretion disc (without a cavity). In this interpretation, the flares are caused by an eccentric secondary impacting the disc twice per orbit. Alternatively, [81] suggests that the presence of a cavity and the self-shocking of the periodically leaked gas may explain both the outbursts and the intervening relative quietude without invoking an ultra-massive primary. Because the disc-impacting model makes highly precise predictions of the timing of future flares (based on the relativistic precession of the binary), whereas the cavity-flare model of [81] predicts the flares are only quasi-periodic (with scatter expected in orbital dynamics of the gas leaking into the cavity), future observations could distinguish the two mechanisms. If OJ 287 indeed contains a binary, it would be the closest known object to a source of detectable low-frequency GWs. If the masses in the disc-impacting model of [96]

\(^4\) In principle, the presence of a SMBH binary could also cause multiple genuine stellar tidal disruptions in a short span [89, 90], although the probability for two events to occur within, say, a decade is still exceedingly low, and the events would not be tracing the orbital period.
Figure 5. Toy light curves and SED snapshots for a flaring SMBH binary with $M = 10^9 \, M_\odot$, $M_2/M_1 = 1/4$, $z = 0.3$ and $P_{\text{obs}} = 11.7$ yr. The parameters were chosen to roughly correspond to the known properties of OJ 287. The model assumes one-dimensional accretion of an advective torus that has been shock-heated to its virial temperature.

If gas accretes onto both SMBHs, this may generate a pair of collimated jets [97, 98] that precess and vary with the binary orbit [99]. Dual jets could also leave behind peculiar radio-lobe morphologies as fossil imprints of the preceding histories of accretion, orbital motion and evolution [100–102] and spin evolution e.g., [103, 104] histories of the binary. (However, radio lobe morphologies have alternative explanations e.g. [105, 106].)

Finally, as mentioned above, the gas leaking into the cavity may fuel small ‘mini-discs’ around one or both SMBHs [31, 79, 84]. If these discs are stable and long-lasting (i.e. persist over many binary periods), then time-variable signatures could be produced by their kinematics—i.e. the changing Doppler shifts along the black holes’ orbits.
For example, if both BHs have individual FeKα lines (produced by fluorescence of their individual hot x-ray coronae), then there would be a pair of emission lines [31], shifting in frequency in tandem, and in opposite directions. In principle, it will be feasible, with a next generation x-ray observatory with high spectral resolution (such as Athena) to identify such shifting double FeKα line features. Even if only the secondary BH has its own mini-disc and FeKα line, it could produce measurable ‘See-saw oscillations’ in the blue and red wings of the line [82]. To illustrate this latter possibility, in the right panel figure 4, we show the spectrum of a binary system, which has a ‘naked’ primary (without a disc), but a secondary with a mini-disc (located at 30$R_g$), as well as the circumbinary disc. As the figure shows, as the secondary is moving toward the observer versus receding, its emission adds to the blue versus red wing of the overall line.

In principle, periodic oscillations—or at least shifts—could be visible for broad optical and UV lines, as well, provided that at least one of the BHs has its own broad line region e.g., [3, 107, 108]. A search for such frequency shifts has been performed recently among 88 quasars [109], selected from the SDSS, based on offsets between their broad lines and the quasar’s rest-frame. Follow-up spectroscopy has revealed several candidates with frequency shifts, but further observations are needed to test the binary hypothesis in each case. Although it has turned out difficult, in general, to prove the presence of a binary using only EM observations, any observed frequency shift will be useful as corroborating evidence once combined with the GW observations—especially if the tentative EM periodicity for exactly one of the sources in the GW error box matches the GW period.

5. Conclusions

Discovering the EM emission from a massive PTA binary BH would be revolutionary in several ways, providing unique probes of SMBH accretion astrophysics, general relativity and cosmic expansion. At a more basic level, EM and GW observations could reinforce each other, and together would likely provide a much better evidence for the presence of a compact SMBH binary than either observation by itself. There are several plausible EM signatures, based on the presence of a cavity in the inner $\sim 100R_g$ around the binary, and on time-variability in the continuum and line emission, linked to the binary period. We have highlighted these in this paper, while also emphasizing the large uncertainties that currently exist in the theoretical expectations.

The most robust signatures of a PTA binary is likely to be based on variability. With periods of months to years, the search for periodic EM signals from massive binaries in the PTA range is well suited to forthcoming time-domain surveys, such as the large synoptic survey telescope in the optical and eROSITA in the x-rays. Given the projected time-line of improvements to PTAs (leading up to the the square kilometer array) that will allow them to resolve individual SMBH binaries, it is plausible that convincing candidate PTA binaries could be first identified in such EM surveys [27]. In this case, the pre-cataloged massive binaries could aid in the detection of GWs from these objects, rather than the other way around.

Acknowledgments

We thank Alberto Sesana and Constanze Rödig for useful discussions, and our collaborators Kristen Menou, Barry McKernan, and Bence Kocsis for permission to draw on joint work. ZH acknowledges support from NASA grant NNX11AE05G.
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