Recurrence flares from supermassive black hole binaries: implications for tidal disruption candidates and OJ 287

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ABSTRACT

I discuss the possibility that accreting supermassive black hole (SMBH) binaries with sub-parsec separations produce periodically recurring luminous outbursts that interrupt periods of relative quiescence. This hypothesis is motivated by two characteristics found generically in simulations of binaries embedded in prograde accretion discs: (i) the formation of a central, low-density cavity around the binary and (ii) the leakage of gas into this cavity, occurring once per orbit via discrete streams on nearly radial trajectories. The first feature would reduce the emergent optical/UV flux of the system relative to active galactic nuclei powered by a single SMBH, while the second can trigger quasi-periodic fluctuations in luminosity. I argue that the quasi-periodic accretion signature may be much more dramatic than previously thought, because the infalling gas streams can strongly shock-heat via self-collision and tidal compression, thereby enhancing viscous accretion. Any optically thick gas that is circularized about either SMBH can accrete before the next pair of streams is deposited, fuelling transient, luminous flares that recur every orbit. Due to the diminished flux in between accretion episodes, such cavity-accretion flares could plausibly be mistaken for the tidal disruptions of stars in quiescent nuclei. The flares could be distinguished from tidal disruption events if their quasi-periodic recurrence is observed, or if they are produced by very massive (> 10^9 M⊙) SMBHs that cannot disrupt solar-type stars. They may be discovered serendipitously in surveys such as LSST or eROSITA. I present a heuristic toy model as a proof of concept for the production of cavity-accretion flares, and generate mock light curves and spectra. I also apply the model to the active galaxy OJ 287, whose production of quasi-periodic pairs of optical flares has long fuelled speculation that it hosts an SMBH binary.

Key words: accretion, accretion discs – black hole physics – galaxies: active – BL Lacertae objects: individual: OJ287 – galaxies: nuclei.

1 INTRODUCTION

Given that massive galaxies assemble through hierarchical mergers and that virtually all of them host a supermassive black hole (SMBH) in their nuclei (see e.g. the review by Ferrarese & Ford 2005, and references therein), it is inevitable that they spend a fraction of their time hosting two or more SMBHs. Such a configuration will eventually result in the formation of a bound SMBH binary, whose orbit becomes increasingly compact as it loses its orbital angular momentum and energy – (I) first through dynamical friction with the stellar and gaseous background, (II) then through three-body interactions with stars and/or tidal interactions with a gaseous accretion disc, and (III) finally, at separations well below a parsec, being driven to merger through the emission of gravitational waves (Begelman, Blandford & Rees 1980; Yu 2002; Haiman, Kocsis & Menou 2009; Colpi & Dotti 2011).

If identified, such systems could unveil invaluable clues about the physics of accretion processes in active galactic nuclei (AGN) and the co-evolution of galaxies and their nuclear SMBHs. An especially tantalizing possibility is that of observing near-merger binaries contemporaneously through both electromagnetic- and gravitational-wave signatures. Not only would such multimessenger studies provide unprecedented independent determination of the masses and spins of the central AGN engines, they can also be used to probe the cosmic expansion history (Holz & Hughes 2005; Kocsis et al. 2006; Bloom et al. 2009; see Schnittman 2011; Tanaka & Haiman 2013 for an overview of proposed electromagnetic counterparts).

SMBH binaries, however, have thus far mostly eluded discovery. Although there are now numerous examples of dual and even triple AGN at kpc-scale separations (e.g. Komossa et al. 2003; Barth et al. 2008; Bianchi et al. 2008; Comerford et al. 2009; Green et al. 2010; Liu et al. 2010; Liu, Shen & Strauss 2011), there is only

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one unambiguous example of a gravitationally bound binary, which has a projected separation of 7.3 pc (the radio galaxy 0402+379; Rodriguez et al. 2006). In searches for periodic variability in AGN, a binary explanation has been ruled out for dozens of candidates (Halpern & Filippenko 1988; Eracleous et al. 1997; Halpern & Eracleous 2000; Eracleous & Halpern 2003; Chornock et al. 2009). While there are several examples of AGN with double-peaked broad lines (Gaskell 1983, 1996; Peterson, Korista & Cota 1987; Boroson & Lauer 2009), shifted lines (Bogdanović, Eracleous & Sigurdsson 2009; Dotti et al. 2009) or suggestive radio lobe morphology (Roos, Kaasta & Hummel 1993; Gopal-Krishna, Bierrmann & Wita 2003; Liu, Wu & Cao 2003), such features have alternate explanations that do not require the presence of a binary (see the review by Komossa 2006). The blazar 0f 287 (a.k.a. EGO 0851+202), which we will revisit in Section 3.4, has been suggested to host a binary SMBH because it produces pairs of optical flares at regular intervals of approximately 11–12 yr (Sillanpaa et al. 1988; Valtonen et al. 2008).

The dearth of observational evidence is not surprising, for several reasons. First, the detection of SMBH binaries must lean heavily on indirect observations of kinematic signatures over long periods of time, since resolving images of sub-parsec binaries is intractable in all wavelengths but radio, where it is feasible only for relatively nearby sources (e.g. for the case of 0402+379, which has a redshift of \( z \approx 0.055 \), a projected distance of 1 pc corresponds to \( \sim 1 \) mas on the sky). Secondly, because gravitational-wave emission and accretion disc torque accelerate the orbital evolution of compact binaries, the most compact binaries – whose kinematic signatures would be the easiest to detect – should also be the rarest (e.g. Haiman et al. 2009, and references therein). Thirdly, the emission features of an accreting SMBH binary may deviate significantly from those of AGN hosting a single SMBH, potentially causing such systems to be missed in AGN surveys. For example, many theoretical studies suggest that if the binary’s SMBH masses are similar and its orbit is prograde with its accretion disc, then the binary’s tidal torques can suppress the accretion rate in its vicinity and form a low-density, central circumbinary cavity in the disc (e.g. Artymowicz & Lubow 1994; Hayasaki, Mineshige & Sudou 2007; MacFadyen & Milosavljević 2008; Farris et al. 2012). Such a cavity would result in reduced emission in soft X-ray, UV and even optical frequencies compared to typical AGN (Milosavljević & Phinney 2005; Gültekin & Miller 2012; Tanaka, Menou & Haiman 2012).

Numerical simulations of such circumbinary discs agree that the suppression of the accretion rate into the cavity is not absolute. Once per orbital period, gas leaks into the cavity in discrete, elongated streams (e.g. Artyomowicz & Lubow 1996; Cuadra et al. 2009; D’Orazio, Haiman & MacFadyen 2012), a portion of which will accrete on to one or both SMBHs. The observable signature of the quasi-periodic streams depends on the time-scales on which they are accreted by the SMBHs. If the accretion time-scale of an individual stream is long, then the leaked gas will form a small accretion disc around one or both SMBHs (e.g. Hayasaki, Mineshige & Ho 2008). This quasi-periodic accretion feature has long been suggested to trigger corresponding variability in AGN emission, and invoked to explain objects like OJ 287 as SMBH binaries (Artymowicz & Lubow 1996; Hayasaki, Saito & Mineshige 2012).

In this work, I consider the possibility that the streams are instead accreted on time-scales shorter than the binary’s orbital period. This is motivated by the fact that because the streams are elongated and enter on nearly radial orbits, they are prone to shock-heating by tidal elongation and self-crossing, as well as by tidal compression. Because the streams are marginally bound initially, the fraction of orbital kinetic energy that can be converted to thermal energy is large. Any post-shock gas that is bound to either SMBH will be much hotter than the gas in standard AGN solutions at similar radii, and thus have much shorter viscous diffusion time-scales if it is optically thick. I show that for a wide range of plausible parameters, the shock-heated accretion flow will be consumed by either SMBH on time-scales shorter than the binary orbital period – i.e. before the next pair of streams enters the cavity. In this scenario, the quasi-periodic leakage of gas into the cavity fuels recurrent, transient flares, with UV-bright spectral energy distributions (SEDs) similar to luminous AGN. The flares would recur once or twice per binary orbit, depending on whether one or both SMBHs accrete.

Because the central cavity causes the disc to be dim in between the flares, an individual flare may resemble the tidal disruption of a star by an SMBH (tidal disruption event, hereafter TDE; Rees 1988). Cavity-accretion flares from SMBH binaries may be observed, potentially in large numbers, by deep surveys that revisit the same portions of the sky multiple times, such as LSST\(^1\) (e.g. Gezari 2012) and eROSITA\(^2\) (e.g. Khabibullin, Sazonov & Sunyaev 2013).

This paper is organized as follows. In Section 2, I review the overall geometry of the accretion flow on to the SMBH binary, namely the formation of a central cavity and the periodic leakage of discrete streams into this cavity. I develop a heuristic model for the accretion of the stream in Section 3, by estimating the thermal properties of the stream after it is shock-heated and circularized (Section 3.1) and treating the subsequent gas accretion using an idealized viscosity prescription (Section 3.2). I calculate mock slim-disc SEDs and light curves for two specific examples: a \( 10^7 \) M\(_\odot\) SMBH binary (Section 3.3) and a \( 10^6 \) M\(_\odot\) binary whose orbital parameters are motivated by the blazar 0f 287 (Section 3.4). In Section 4, I provide rough estimates for the fraction of galaxies that could host SMBH binaries producing quasi-periodic transient flares. Observational implications, including prospects for detecting the flares and distinguishing them from TDEs are discussed in Section 5. I conclude by summarizing the findings in Section 6.

## 2 ACCRETION FLOW GEOMETRY

Let us consider a prograde accretion disc around an SMBH binary of mass\(^3\) \( M_\star \), semimajor axis \( a \) and orbital period \( P \). The Lindblad resonance clears the gas around the binary’s orbit and inhibits the infall of gas inwards of a radius \( \sim 2a \), excavating an annular gap (Artymowicz & Lubow 1994; but such a gap may close for low-mass binaries – see Kocsis, Haiman & Loeb 2012a,b). For binaries with comparable BH masses, the gas can cross inwards of \( \sim 2a \) only once per orbit on nearly radial trajectories, at a somewhat suppressed time-averaged rate – typically \( \sim 10–100 \) per cent of the accretion rate at larger radii (e.g. Ochi, Sugimoto & Hanawa 2005; MacFadyen & Milosavljević 2008; Cuadra et al. 2009; D’Orazio et al. 2012). It is convenient to think of the accretion flow in terms of two dynamically distinct components separated by the gap:\(^4\) an

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1. Large Synoptic Survey Telescope http://www.lsst.org/lsst/.
2. extended ROentgen Survey with an Imaging Telescope Array http://www.mpe.mpg.de/eROSITA.
3. Throughout this work, I use \( M \) denote the mass of a single SMBH, \( M_\star \), for the total mass of an SMBH binary and \( M_\odot \) for the mass of either member of a binary.
4. These components are not completely independent of each other. The gas that leaks into the cavity can return to and interact with the disc-cavity boundary (D’Orazio et al. 2012; Roedig et al. 2012; Shi et al. 2012).
outer, geometrically thin and optically thick circumbinary disc at \( R \gtrsim 2a \), and an inner, low-density region at \( R \lesssim 2a \). In this section, I present a rough physical description of each component.

2.1 The outer disc

2.1.1 Accretion disc around a single SMBH

To best illustrate the effect of the central circumbinary cavity on the observational appearance of the accretion disc, I will briefly review the standard theory for the spectral emission of a thin accretion disc around a single SMBH.

Under the simple assumption that disc is a superposition of annuli that emit as isotropic greybodies with a radial temperature profile \( T_p(R) \) for the thermalization photosphere, the emitted SED \( L_\nu \) is given by

\[
L_\nu = 2 \int 2\pi R F_\nu(T_p) \, dR,
\]

where

\[
F_\nu(T_p) = \frac{2\epsilon_v}{1+\epsilon_v} B_\nu(T_p)
\]

is the emergent flux per disc face, \( \epsilon_v \) is the ratio of the absorption opacity to the total opacity (see e.g. Blaes 2004), and \( B_\nu \) is the Planck function.

The photospheric temperature profile \( T_p(R) \) is given by

\[
\Xi(R, T_p) \sigma_{SB} T_p^4(R) = \frac{3}{8\pi} \left( 1 - \sqrt{\frac{R_{\text{ISCO}}}{R}} \right) M \Omega_k^2.
\]

Above, \( R_{\text{ISCO}} \) is the radius of innermost stable circular orbit, and the dimensionless factor \( \Xi(R, T_p) \) quantifies the deviation of the emission from a blackbody (Tanaka & Menou 2010); at low temperatures (large disc radii), \( \Xi \approx 1 \). The Keplerian angular velocity is denoted as \( \Omega_k \) and \( M \) is the mass accretion rate, which I will parametrize as

\[
\dot{M} = \frac{m}{\epsilon c^2} \dot{E}_{\text{edd}},
\]

with \( m \) a dimensionless parameter quantifying \( \dot{M} \) in terms of the Eddington luminosity \( \dot{E}_{\text{edd}}(M) = 1.25 \times 10^{38} (M/M_\odot) \) erg s\(^{-1}\) and a radiative efficiency \( \epsilon \), for which I adopt \( \epsilon = 0.1 \) throughout this paper.

The SED \( \nu L_\nu \) peaks at a frequency

\[
\nu_{\text{peak}}^{(\text{single})} > 1.2 \times 10^{16} \left( \frac{M}{10^7 M_\odot} \right)^{-1/4} \dot{m}^{1/4}
\]

\[
\times \left( \frac{R_{\text{ISCO}}}{6 GM/c^2} \right)^{-3/4} \text{Hz},
\]

which is in the far-UV or soft X-ray for SMBHs accreting at a significant fraction of Eddington. In equation (5), the inequality is due to greybody spectra having higher frequency peaks than blackbodies; the inequality symbol ‘\( > \)’ can be replaced by ‘\( \approx \)’ for blackbody SEDs.

The key point to take away from the above equations is that the innermost regions of the accretion disc are responsible for both the vast majority of the total emitted power, as well as for the highest energy thermal photons.

2.1.2 Circumbinary disc truncated by tidal torques

To a first approximation, the circumbinary disc can be thought of as a standard AGN disc that is simply truncated by the cavity. There are correcting factors – such as deformation of the surface density profile outside the cavity (Syer & Clarke 1995; Ivanov, Papaloizou & Polnarev 1999; Kocsis et al. 2012b), non-Keplerian potential variations and pressure gradients at the disc-cavity boundary (MacFadyen & Milosavljević 2008) and tidal heating of the edge of the disc (Lodato et al. 2009b) – but these do not significantly affect the theoretical exercise below, and I will neglect them for its purpose.

The cavity size is expected to be much larger than \( R_{\text{ISCO}} \). This means that circumbinary accretion discs are ‘missing’ the innermost regions that produce high-energy thermal photons, and will thus be intrinsically dim at optical, UV and soft X-ray frequencies compared to a disc around a single SMBH with the same mass. The wider the binary, the larger the cavity and greater the decrement in high-energy photons and luminous output.

In general, the size of the cavity \( R_{\text{cav}} \) with respect to the binary’s orbital separation \( a \) is thought to lie in one of two distinct regimes, depending on the balance between the time-scale on which the binary’s separation decays, \( t_{\text{dec}} \equiv |a/(da/dt)| \), and the viscous diffusion time-scale of the gas just outside the cavity, \( t_\nu \). For binaries decaying more gradually than the disc’s viscous diffusion time-scale \( i.e. \) if \( t_{\text{dec}} > t_\nu \), the cavity is located at the resonance radius \( R \approx 2a \).

For very compact binaries, gravitational-wave emission causes the orbital separation to decay in a runaway fashion \( (da/dt \propto a^{-3/2}; \) Peters 1964); at a separation \( a_{\text{dec}} \) where \( t_{\text{dec}} \approx t_\nu \), the binary ‘decouples’ from the circumbinary disc, rapidly decaying and merging before the gas outside the cavity can significantly evolve (Milosavljević & Phinney 2005; Tanaka & Menou 2010). Although some of the gas may be able to follow the binary during this brief stage and produce some high-frequency emission (Tanaka, Menou & Haiman 2012), a strong density peak remains at the location \( \sim 2a_{\text{dec}} \). Consequently, the peak of the SED of the circumbinary disc does not evolve significantly between decoupling and merger, and the SED brightens and hardens in earnest only after the binary has merged.

Thus, during the lifetime of the binary, the surface density of the circumbinary disc peaks at a radius \( \sim \max (2a, 2a_{\text{dec}}) \). The peak frequency of the SED depends on the binary separation (or equivalently, orbital period) until the binary decouples from the disc, as

\[
\nu_{\text{peak}}^{(\text{binary})} (a \geq a_{\text{dec}}) \sim 10^{14} \left( \frac{M_\ast}{10^7 M_\odot} \right)^{1/4} \dot{m}^{1/4}
\]

\[
\times \left( \frac{P}{10 \text{ yr}} \right)^{-1/2} \text{Hz},
\]

Between decoupling and merger, \( \nu_{\text{peak}} \) is frozen at the value corresponding to \( a \sim a_{\text{dec}} \). Although the exact decoupling separation depends on the properties of the binary and the disc, several studies estimate \( a_{\text{dec}} \sim 100 GM/c^2 \) for a wide range of parameters (Milosavljević & Phinney 2005; Haiman et al. 2009; Tanaka & Menou 2010). Thus,

\[
\nu_{\text{peak}}^{(\text{binary})} (a \leq a_{\text{dec}}) \sim 1.7 \times 10^{15} \left( \frac{M_\ast}{10^7 M_\odot} \right)^{1/4} \dot{m}^{1/4}
\]

\[
\times \left( \frac{a_{\text{dec}}}{100 GM/c^2} \right)^{-3/4} \text{Hz}.
\]

Note that in contrast to discs around a single SMBH, in circumbinary discs the deviation from blackbody is small \( (\Xi \approx 1) \) and the thermal SED has virtually zero dependence on the spin of either SMBH.

In Fig. 1, I have plotted model greybody spectra for thin accretion discs around a single SMBH of mass \( M \) extending to \( R_{\text{ISCO}} = 3 GM/c^2 \) (dashed lines) and binary SMBHs with the same
the circumbinary disc can be much higher than in discs around SMBHs of the same total mass) without the bolometric luminosity exceeding $L_{\text{bol}}$. There is some parameter degeneracy between the binary and single SMBH values for $v_{\text{peak}}$, so that circumbinary discs of low-mass SMBH binaries can have SEDs that are similar in appearance to very massive single SMBHs with low accretion rates – e.g. an $M_{\bullet\bullet} \sim 10^7 M_\odot$, $m = 1$ binary near decoupling has $v_{\text{peak}}$ and $vL_\nu$ similar to that of an $M \sim 10^9 M_\odot$, $m = 0.01$ single SMBH. Such degeneracies may be broken through independent determinations of the engine mass, or if either the gravitational-wave emission from the merger or the subsequent UV/X-ray brightening of the SED (Milosavljević & Phinney 2005; Tanaka, Haiman & Menou 2010) is observed.

The above contrast between discs around binary and single SMBHs is a crude one, motivated by the most basic implementation of the theory of geometrically thin, optically thick accretion discs. In reality, observed AGN SEDs can deviate greatly from the simple picture painted above. Obscuration and dust-reddening of optical and UV photons can impede simple comparisons motivated by the analytic theory, especially if SMBH binaries preferentially reside in recently merged and heavily enshrouded galaxy environments.

2.2 Central cavity and leaked streams

The SEDs presented in Fig. 1 represent only a part of the total emission. As stated above, the outer disc leaks gas periodically into the cavity, and to predict the thermal emission from the whole system we must understand what happens to this leaked gas. Numerical simulations show that the leakage takes place in discrete streams that enter the cavity once per binary period on nearly radial free-fall trajectories and preferentially accretes on to the secondary (Artymowicz & Lubow 1996; Cuadra et al. 2009).

How far from either SMBH is the stream pericentre? In a simulation of accretion on to an SMBH binary with a 1:3 mass ratio, Cuadra et al. (2009) found the accretion across a radius of 0.1a from either SMBH to be highly punctuated and periodic, indicating that pericentre lies inside this radius. Sesana et al. (2012) resolve, in their simulations of a binary with a 0.35:1 mass ratio, small accretion discs with radii $\sim 0.005a$ around both SMBHs, suggesting a similar upper limit to the pericentre radius. (That is, the inner discs would be larger if the pericentres of the streams were farther from the SMBHs. Note that 0.1a is smaller than the canonical Hill stability radius, $R_{\text{hill}} \lesssim a(1-\epsilon)[M_*/(3M_\bullet)]^{1/3}$, where $M_\bullet$ is the mass of either SMBH and $M_\bullet$ is the total binary mass.) Similarly, the simulations of Hayasaki et al. (2008) for a 1:1 system – under the assumption that the streams cool efficiently and the entire accretion flow on to the binary is isothermal – form small, dense discs with radii $\sim 0.1a$.

If the streams accrete on time-scales longer than the binary period, then over time the leaked gas will form persistent, small, optically thick accretion discs around one or both individual SMBHs (as in Hayasaki et al. 2008). In this scenario, the inner disc(s) would emit in the UV, but more weakly than in single-BH AGN due to the lower gas content (Gütekün & Miller 2012; Tanaka, Menou & Haiman 2012). The binary could also exhibit periodic optical/UV flares as the incoming periodic streams interact with the pre-existing inner disc(s) (Tanaka, Menou & Haiman 2012) or the cavity wall (D’Orazio et al. 2012; Roedig et al. 2012; Shi et al. 2012).

An alternate possibility, which I explore further in this paper, is that the leaked gas is consumed by one or both SMBH(s) on
a time-scale faster than the binary’s orbital period. In this case, no persistent discs are present inside the cavity, and the streams instead fuel transient accretion flows that produce optical/UV/X-ray flares once per binary orbit. In between streams, the accretion flow would exhibit low intrinsic UV flux and unusual spectral shape as discussed in Section 2.1, and the system may appear as an odd AGN or even masquerade as a quiescent nucleus. As I discuss further in the next section, a key motivation for postulating that the streams accrete rapidly is the large amount of gravitational energy that they have at pericentre, due to the streams being marginally gravitationally bound to the binary.

The low-density cavity would be optically thin, and the diffuse gas there is unable to cool efficiently. Thus, in between the periodic leakage of the streams, the central cavity should resemble the underluminous, advection dominated accretion flow (ADAF) state (Ichimaru 1977; Narayan & Yi 1994, 1995). It is interesting to note that the conditions at the boundary between the gap and the circumbinary disc – such as steep gradients in temperature, pressure and radial velocity, as well as super-Keplerian orbital velocities near the boundary – satisfy the theoretical requirements for consistent solutions with an ‘outer disc, inner ADAF’ configuration (Honma 1996; Liu et al. 1999; Mannmoto & Kato 2000). Despite producing virtually zero emission in the optical to soft X-ray frequencies, the optically thin accretion flow inside the cavity may help generate outflows (Narayan & Yi 1995; Blandford & Begelman 1999; Meier 2001; Tanaka & Menou 2006; Narayan & McClintock 2008), which may be observable as radio sources or contribute to blazar emission (e.g. Falcke & Biermann 1999; Cao 2002).

3 MODELLING THE PERIODIC FLARES

I now turn to modelling the accretion of the leaked streams on to the individual SMBH(s), and the resulting emission. I divide the accretion on to the binary SMBH in terms of three distinct components, as follows.

(i) Circumbinary disc. The disc has a cavity maintained at \( R \sim 2a \), and has a surface density profile that corresponds to a mass supply rate \( \dot{m}_\text{CB} \equiv \dot{m}(R \gg 2a) \). The thermal SED of the disc is dim and soft compared to discs around a single SMBH with comparable mass and accretion rate.

(ii) Leaked streams. Once per period, gas leaks into the cavity in the form of elongated streams on nearly radial orbits. Simulations indicate that the pericentres of the streams occur inside \( \lesssim 0.1a \). The amount of gas in the streams is equal to or less than \( P \times \dot{M}_\text{CB} \). The streams shock-heat near pericentre, and their bulk orbital energy is dissipated as heat. Some fraction of the gas circularizes its orbit around one or both SMBHs and begin to accrete through viscous diffusion, with the rest being flung back out towards the circumbinary disc or ejected as an outflow.

(iii) Post-shock accretion flow. The resulting hot, bound, post-shock gas fuels a transient, luminous flare (or two flares) as it accretes on to either SMBH, until it is depleted and becomes optically thin. Then, the system is soft and dim again, until the next pair of streams enter the cavity.

3.1 Viscosity prescription

As the stream falls on a marginally bound orbit into the cavity, it becomes tidally elongated. Upon passing the point of nearest approach to an SMBH, the leading end will collide with the rest of the stream, shock-heating the gas; additional heating may occur due to tidal compression, as well as the enhanced velocity gradients and viscous shear at pericentre. The expected result is that a moderate fraction of the stream’s bulk kinetic energy is converted to radiation (see Kim, Park & Lee 1999; Strubbe & Quataert 2009 for similar calculations in the context of TDEs).

Upon entering pericentre, the stream has a kinetic energy density

\[
\frac{1}{2} \sqrt{1 - e_{\text{stream}}^2} \rho v_k^2, \quad \text{where} \quad e_{\text{stream}} \sim 1 \quad \text{is the eccentricity of the stream with respect to the SMBH to which it makes the closest passage,}
\]

\( \rho \) is the gas density and \( v_k \) is the local circular Keplerian velocity. The amount of energy that is converted to heat for whatever portion of the stream that becomes (nearly) circularized is thus \( \frac{1}{2}(1 - \sqrt{1 - e_{\text{stream}}^2}) \rho v_k^2 \). Radiation pressure dominates over gas pressure in the post-shock gas, and the temperature \( T_{\text{shock}} \) is related to the local gravitational potential as

\[
\frac{1}{2} \left( 1 - \sqrt{1 - e_{\text{stream}}^2} \right) \rho v_k^2 \sim \alpha a T_{\text{shock}}^4, \quad \text{or (8)}
\]

\[
\frac{1}{2} \rho v_k^2 \sim 3 \rho c_s^2, \quad \text{(9)}
\]

where \( c_s \) is the isothermal sound speed. As alluded to in the previous section, the amount of orbital energy that is available to shock-heat the accretion flow is very large; for the same depth of the gravitational potential, the post-shock pressure in the gas is higher than that a steady-state canonical \( \alpha \)-disc model (Shakura & Sunyaev 1973) by a factor

\[
\frac{T_{\text{shock}}}{T_{SS}} \approx \frac{4}{27} \left( \frac{H c_s}{\alpha R c} \right)^{-1}, \quad \text{(10)}
\]

where \( \tau \) is the optical depth of the disc and \( H = c_s/\Omega_k \) is the scale-height. For realistic disc properties, the above ratio is well in excess of unity. Thus, if the viscous stress scales with the internal pressure of the fluid, then the circularized post-shock gas will accrete much more rapidly than gas in a steady-state disc.

What is the mass \( M_{\text{flare}} \) that is accreted in this fashion? As stated above, the time-averaged mass flux into the cavity is of the order of \( \sim 10–100 \) per cent of the mass accretion rate \( M_{\text{CB}} \equiv M(R \gg 2a) \) in the circumbinary disc, so the combined mass of the streams for each cycle is of the order of \( \sim (0.1-1) \times M_{\text{CB}} \). However, only a fraction of this mass will ultimately be bound to and accreted by the SMBHs. I therefore parameterize the mass of the post-shock gas that accretes on to either SMBH in terms of this a priori unknown fraction \( f < 1 \):

\[
M_{\text{flare}} = f M_{\text{CB}} P
\]

\[
= 0.2 \frac{f}{0.1} \frac{\dot{m}_{\text{CB}}}{10} \frac{M_{\text{SS}}}{10^7 M_\odot} \frac{P}{10 \text{ yr}} M_\odot. \quad \text{(11)}
\]

Whatever leaked mass is not accreted immediately may be rejected into the circumbinary disc (see footnote 4), fall back on to either SMBH at a later time, interact with and reprocess the photons produced by the flare, contribute to the ADAF/corona within the cavity, or ejected via thermally, radiatively or magnetically driven outflows. While the unaccreted gas could have observable features, the flare must be the energetically dominant event, at least in the UV and soft X-ray frequencies, because it is the component that taps into the deepest parts of the binary’s potential well.

Given the range of dynamic scales of the problem and the number of relevant physical processes involved – steep thermodynamic and density gradients, asymmetries, the precise thermal and kinetic state of the post-shock bound gas, the possible onset of viscous
and thermal instabilities, the importance of radiative forcing and photon trapping, magnetohydrodynamic treatment of the viscosity mechanism, to name a few — performing a fully consistent and detailed calculation for the evolution and accretion signature of the post-shock gas is a daunting task. Here, I instead construct a toy model of the problem, employing an idealized viscosity prescription which normalizes the viscosity through the canonical $\alpha$ prescription and assumes that the fluid elements have Keplerian circular orbits. This approach is admittedly crude; it is meant only to serve as a proof of concept that the post-shock accretion event can develop and decay rapidly and produce a luminous outburst. The toy treatment presented here could also provide an analytic foundation within which future, more detailed studies may be framed.

The post-shock gas that is bound to either SMBH will spread as turbulent viscosity transports angular momentum and dissipates orbital energy. The kinematic viscosity $\nu$ is the product of the gas sound speed and the size of the largest turbulent eddies. The latter cannot be larger than the disc scaleheight $H = c_s / \Omega_K$, so I parametrize the viscosity in the familiar fashion, $\nu = \alpha H c_s = \alpha c_s^2 / \Omega_K$, with $\alpha < 1$ (Shakura & Sunyaev 1973). Using the relationship between the sound speed and the local Keplerian circular velocity in the post-shock gas in equation (9), I prescribe

$$\nu = \alpha \frac{c_s^2}{\Omega_K} \sim \frac{\nu}{\Omega_K} \propto R^2 \Omega_K.$$  

(12)

Empirical estimates of $\alpha$ in AGN typically give $\alpha \sim 0.01-0.1$, and simulations of the magnetorotational instability suggest similar values (Pessah, Chan & Psaltis 2007). There are indications that outbursting systems have higher values, $\alpha \sim 0.3$ (e.g. Dubus, Hameury & Lasota 2001; Starling et al. 2004; King, Pringle & Livio 2007); dissipations of supersonic shocks or other instabilities could drive macroscopic turbulence with $\alpha \sim 1$ (e.g. Carciofi et al. 2012). In magnetohydrodynamic simulations of circumbinary discs, Shi et al. (2012) and Noble et al. (2012) find Reynolds and Maxwell stresses equivalent to $\alpha > 1$ near the cavity edge.

The $\alpha$ prescription in equation (12) should be viewed as an approximate normalization of the magnitude of the viscous stresses in the post-shock accretion flow. In reality, the effective value of $\alpha$ is unlikely to be a constant with respect to time or radius, owing to the inhomogeneities and sharp thermodynamic gradients; similarly, the radial viscosity profile may evolve to deviate from the $\nu \propto R^{1/2}$ post-shock profile. In addition, the post-shock accretion flow may be susceptible to thermal or viscous instabilities (Lightman & Eardley 1974; Pringle 1976; Shakura & Sunyaev 1976; Piran 1978; Hirose, Krolik & Blaes 2009; Jiang, Davis & Stone 2013). If the accretion flow in question is unstable, it may undergo runaway heating and be accreted more rapidly than in the idealized calculation presented here.

### 3.2 Viscous spreading

Treating the post-shock, bound accretion flow as a superposition of annuli centred around either SMBH, I use the standard equation for Keplerian, viscous thin discs (e.g. Pringle 1981), which gives the evolution of the vertically integrated density $\Sigma$:

$$\frac{2\pi R}{\Omega} \frac{d}{dt} \Sigma(R, t) = \frac{\partial}{\partial R} \left[ 2R^{1/2} \frac{d}{dR} \left( 3\pi \nu R^{1/2} \right) \right].$$  

(13)

The idealized viscosity form in equation (12), $\nu \propto R^{1/2}$, has well-documented exact solutions for arbitrary initial profiles of $\Sigma$ (Lüst 1952; Lynden-Bell & Pringle 1974; Pringle 1991; Tanaka 2011) that I will employ throughout the rest of this paper.

Initially, the post-shock accretion flow will be moderately geometrically thick, with $H^2/R^2 \sim c_s^2/v_K^2 \sim 1/6$. The pressure is dominated by radiation, and the main source of opacity is electron scattering.

The viscous diffusion time-scale of the gas is

$$\tau_v(R) = \frac{R}{v_{\nu}} = \frac{4}{\alpha} \left[ 1 + 2 \frac{d}{d\ln R} \left( \frac{\nu}{\Sigma} \right) \right]^{-1} \Omega_K^{-1}.$$  

(14)

For an initial mass distribution initially concentrated at a radius $R_0$,

$$\tau_v(R_0) > \frac{2}{\alpha^2 \pi} \left( \frac{M_*}{M_{**}} \right)^{1/2} \left( \frac{R_0}{a} \right)^{3/2}.$$  

(15)

That is, the accretion flow will be depleted on a time-scale shorter than the binary orbital period (cf. Sesana et al. 2012) if it is initially deposited at a radius

$$R_0 < 0.3 \left( \frac{\alpha}{0.1} \right)^{2/3} \left( \frac{M_*}{M_{**}} \right)^{1/3} a$$

$$\sim 1.0 \left( \frac{0.4}{1-e} \right) \left( \frac{\alpha}{0.1} \right)^{2/3} R_{\text{full}}.$$  

(16)

Above, I set $e \sim 0.6$ as a reference value for the binary eccentricity (Roedig et al. 2011). As discussed in the previous section (Section 2.2), inequality 16 is amply satisfied by the orbital trajectories of the leaked streams in numerical studies.

The regions where the accretion flow is optically thin cannot be treated by the thin-disc equation (13), and will have negligible viscous transport and radiative output compared to the optically thick regions. I compute $\tau = \theta K \Sigma$, where $\theta = 0.2$ is a porosity factor (Turner 2004), and neglect the emission from the regions where $\tau < 1$. Because the accretion flow spreads so that the surface density at large radii is lower than near the centre (see e.g. Tanaka 2011), the outer regions of the disc become optically thin first.

Let us now apply this model to a specific example. I consider a binary of total mass $M_*=10^5 M_\odot$, with a period of $P = 30$ yr ($a = 0.010$ pc). I set $m_{\text{CB}} = 1$ and $f = 0.05$, which fixes the total mass in the bound, post-shock accretion flow at $M_{\text{flow}} = 0.33 M_\odot$. I assume accretion on to the secondary SMBH with $M_{**}/M_* = 1/10$ and $R_{\text{ISCO}} = 3 G M_*/c^2$. I solve the viscous evolution of the post-shock annulus for two different initial surface density distributions. One is a $\delta$-function ring initially located at a radius $R_0 = 0.05a \approx 10^4 G M_*/c^2$ from the SMBH. The second initial profile is a torus with constant gas volume density (i.e. $\Sigma \propto R^{-1}$) that extends from 0.5 $R_0$ to 1.52 $R_0$. The dimensions of the second profile were chosen so that both initial conditions share the same values for the total orbital angular momentum and gas mass.

In the top panel of Fig. 2, I plot the mass flux

$$M(R, t) = 3\pi \nu \Sigma \left[ 1 + 2 \frac{d}{d\ln R} \left( \frac{\nu}{\Sigma} \right) \right] \left( 1 - \sqrt{R_{\text{ISCO}} / R} \right)^{-1}$$  

(17)

evaluated at $R = 10 G M_*/c^2$, for an individual accretion episode on to the secondary SMBH. The evolution of the $\delta$-function ring

---

5 The results of the present analysis should not be significantly affected if the bound gas forms an eccentric accretion disc; see Syer & Clarke 1992; Lyubarskij et al. 1994; Ogilvie 2001.
is plotted with a thin curve, and that of the constant-density torus is plotted with a thick curve. For both initial profiles, the accretion rate peaks at nearly the same time, and the subsequent decay behaviour is virtually identical. Note that although the accretion rate reaches values above the ‘critical’ Eddington value (i.e. $m > 1$), the luminosity produced by the accretion event is capped at near $L_{\text{Edd}}$ (see Section 3.3 below) due to radiative advection.

For our viscosity prescription, the late-time mass accretion rate scales as $\dot{M} \propto t^{-4/3}$, 
\[
\frac{d \ln \dot{M}}{d \ln t} \approx -1 - \left(4 - 2 \frac{d \ln \nu}{d \ln R} \right)^{-1} = -\frac{4}{3},
\]  
(18) 
due to the late-time behaviour of the central surface density profile (Tanaka 2011). This is quite similar to the canonical late-time behaviour $\dot{M} \propto t^{-5/3}$ for TDEs (Rees 1988; Phinney 1989), which arises from the orbital energy distribution of the disrupted stellar material. For both the transient flares discussed in this paper (see Section 3.3 below) and TDEs (Lodato, King & Pringle 2009a; Shen & Matzner 2012; Guillochon & Ramirez-Ruiz 2013), the light curve at any given frequency is not expected to follow the same power-law decay as the mass accretion rate. Thus, for either type of transient, it is unlikely that the underlying mass accretion rate could be accurately deduced from the observed emission. In other words, it may not be possible to distinguish a cavity-accretion flare ($\dot{M} \propto t^{-4/3}$ in this idealized treatment) from a TDE ($\dot{M} \propto t^{-5/3}$) solely from the decay in the light curve.

A key model assumption with respect to the light curve is that the accretion flow forms promptly, i.e. on time-scales shorter than ~10 percent of the binary orbital period. The fact that the dynamical times are much shorter where the stream shocks ($R < 0.1a$) favours this hypothesis, but this should be confirmed by numerical simulations. If the fuelling accretion flow materializes on time-scales longer than the fuel depletion time-scale, then the light curves would rise more slowly. Because a promptly rising light curve is a key smoking-gun feature of TDEs, if cavity-accretion flares develop more gradually, this could be used to distinguish the two types of transients.

In the bottom panel of Fig. 2, I plot the fraction of the initial gas mass that is optically thick ($\tau > 1$). For fiducial parameter values, the entire stream becomes optically thin on a time-scale shorter than $P$, at which point the entire flow will have transitioned into a radiatively inefficient and underluminous state. The amount of time it takes for the gas to be depleted in this way depends on the total amount of gas in the flow. For very high accretion rates into the cavity, the post-shock flow may not be depleted before the next stream arrives at pericentre; in this case, persistent mini-discs would form around one or both SMBHs and the flares would be less dramatic. The exact fraction of time the system spends in quiescence (as an odd-coloured or underluminous AGN) depends on the amount of the leaked streams that is consumed by the SMBH(s) (i.e. on $M_{\text{CB}}$ and the unknown parameter $f$), as well as the binary period $P$.

### 3.3 Energetics and emission

To model the emergent spectrum, I now estimate the radial temperature profile of the disc. I assume that the accreting gas is able to promptly dispose of the viscously generated heat via greybody radiation and advection:

\[
Q_{\gamma} \sim Q_{\nu} + Q_{\text{adv}},
\]  
(19) 
where
\[
Q_{\nu} = \frac{9}{4} \Sigma v^2 \nu^2,
\]  
(20) 
\[
Q_{\nu} = 2 \times \frac{4 \sigma_{SB} T^4}{3 \pi} \text{ and}
\]  
(21) 
\[
Q_{\text{adv}} = -\frac{\dot{M}}{2 \pi R^2} c^2 \left(12 \frac{d \ln T}{d \ln R} - 4 \frac{d \ln \rho}{d \ln R}\right)
\]  
(22) 
represent viscous heating, radiative cooling and advective cooling (Abramowicz et al. 1988), respectively. Outer regions of the accretion flow (where the surface density is lower) that are optically thin are assumed to be radiatively inefficient, and excluded from the emergent flux calculation.

In Fig. 3, I present toy-model light curves, along with several snapshots of the emergent spectrum, for the accretion event modelled earlier in Fig. 2. The binary mass is $M_{\bullet} = 10^7 M_{\odot}$, the period is $P = 30$ yr and the accretion occurs on to the secondary SMBH with $M_2 = 10^6 M_{\odot}$. I have included for reference the emission from the circumbinary disc, with $\dot{m}_{\text{CB}} = 1$, $\alpha = 0.1$ and a cavity at $R < 2a$.

The top panel shows the bolometric light curve (black, solid curve) along with several monochromatic ones: $R$-band (700 nm; red, dotted curve), $U$-band (365 nm; blue, short dashed curve), far-UV (1500 Å; magenta, long dashed curve) and 0.5 keV (cyan, dash-dotted curve). As in Fig. 2, thick lines show the light curves for the $\delta$-function initial density profile, and thin curves show those for the constant-density profile. Both light curves converge near their peaks, occurring at roughly $t = 0.01P$. The subsequent emission drops off steeply as the gas is depleted and the outer accretion flow becomes optically thin and radiatively inefficient.
between them, and that
$U_t = 10$
Toy light curves (top panels) and spectrum snapshots (bottom panels) for an $M_{\text{disc}} = 10^5 M_\odot$ binary with a 1:10 mass ratio. The binary has a period of 30 yr, which places the peak emission frequency of the circumbinary disc in the infrared. In this example, the flares peak in the UV and soft X-ray frequencies and last several months before decaying rapidly over several years. Neither the bolometric nor the monochromatic light curves obey the $r^{-4/3}$ decay of the central accretion rate.

None of the light curves follow an $L \propto r^{-4/3}$ power-law decay of the central mass accretion rate (Fig. 2); as is the case with TDEs, it is unlikely that the underlying accretion rate can be deduced from the observed light curves (see Section 3.2). The peak bolometric luminosity is roughly equal to the Eddington luminosity of the secondary, even though the accretion rate is supercritical by an order of magnitude. This is consistent with models of slim accretion discs (e.g. Watarai et al. 2000; Ohsuga et al. 2005, in which advection helps to stabilize the disc against radiative self-destruction even when $\dot{m} \gg 1$.

In the bottom panel of Fig. 3, I show several snapshots of the SED, calculated as a greybody spectrum from the temperature profile as in the circumbinary SEDs in Fig. 1. On the lower-left corner is the emission of the circumbinary disc, which in this example peaks in the infrared and is optically dim. This is the emission from the system most of the time, in between the flares. The composite (flare plus circumbinary disc) spectrum at the peak ($t = 0.01P$) and just as the flare is fading ($t = 0.26P$) are also shown to demonstrate that, in principle, the time evolution of the emission properties can be quite dramatic. In this toy example, the binary spends $\approx 70$–90 per cent of its time in quiescence, with the flares decaying to less than $\approx 10$ per cent of the peak luminosity within $\approx 0.1P$. However, in addition to the viscous and thermal evolution of the accreting gas, the duration of the flare is also sensitive to the raw amount of mass deposited via the stream.

### 3.4 An alternate binary model for OJ 287

The BL Lacertae object OJ 287 is known to produce pairs of optical outbursts every 11–12 years. The outbursts occur in pairs whose peaks are separated by a nearly constant interval of approximately 2 yr. While the flux amplification values from episode to episode, the optical brightness is observed to rise by as much as 5 mag during a flare.

Beginning with Sillanpaa et al. (1988), many studies have interpreted this system as an SMBH binary. In particular, Lehto & Valtonen (1996), Valtonen et al. (2006) and Valtonen et al. (2008) have modelled the flares as resulting from a secondary SMBH impacting a circumbinary accretion disc. In this disc-impact model, the secondary’s orbit is elliptical and inclined with respect to the accretion disc, so that two impacts occur near pericentre. Valtonen, Ciprini & Lehto (2012) take the primary and secondary masses to be $1.8 \times 10^6$ and $1.2 \times 10^6 M_\odot$, respectively.

Here, I also interpret OJ 287 as an accreting binary with a period of 11.7 yr (9 yr in the binary’s reference frame, for redshift $z = 0.3$) but with two substantive differences from the model of Valtonen et al. First, the binary’s orbit is coplanar with a circumbinary accretion disc, and the disc has a circumbinary cavity with a radius of $2a$. Secondly, I use a total binary mass of $10^9 M_\odot$, more consistent with independent observational results than the $> 10^{10} M_\odot$ value in the binary model (e.g. Xie et al. 2002; Liang & Liu 2003; Fan & Cao 2004; Gupta et al. 2012). The accretion rate in the circumbinary disc is taken to be $\dot{m}_{\text{CB}} = 5$, by matching the optical-wavelength flux in between outbursts with the circumbinary disc output. (As noted in Section 2.1.2, because the cavity drastically reduces the total disc power, the circumbinary disc can have $\dot{m}_{\text{CB}} > 1$ without being Eddington limited.) I take the primary and secondary masses to be $8 \times 10^8$ and $2 \times 10^8 M_\odot$, respectively. I suppose, arbitrarily, that they accrete $f = 5$ per cent of $\dot{m}_{\text{CB}}$ between them, and that the fraction consumed by each SMBH is inversely proportional to their mass ratio. I take $\alpha = 0.5$ and $R_0 = 0.05a$ for the post-shock accretion flows (note the observational indications that $\alpha \approx 1$ for violent accretion events of this type; Section 3.2), and assume that the flares are offset by 2 yr in the observer’s frame, based on the observed delay between the two peaks.

I present the light curves and SED snapshots of this model in Fig. 4. The observable flux is computed from the source emission assuming a luminosity distance of 1600 Mpc to correspond to the source redshift. The bolometric luminosity (black solid curves, top panel) fluctuates by an order of magnitude between quiescence and flaring. The $B$-band monochromatic flux (blue dotted curves) varies by two orders of magnitude. SEDs during quiescence ($'A'$) and the peak of each flare ($'B'$, $'C'$) are shown in the bottom panel. The first flare, due to accretion on to the secondary, lasts longer because I have assumed that this SMBH accretes more gas than the primary.

Many different spectra and light curves can be produced by varying the model parameters, but the production of two recurring flares at near-Eddington fluxes is a generic feature for the cavity-accretion flares discussed here. Given the approximate nature of the model, I undertake no special effort to obtain a detailed fit to the observed properties of OJ 287. Rather, the goal of this exercise is merely to demonstrate that this simple picture – periodic streaming of gas into the disc cavity and subsequent shock-heating and rapid accretion on to the SMBHs – can provide an explanation for the cadence, duration and energetics of the optical flares.

With respect to OJ 287, the present model has several notable features. First, the interpretation does not require a primary mass of $\gtrsim 10^{10} M_\odot$, which is over an order of magnitude larger than several empirical estimates, as well as the $M_* - \sigma$ relation. Second, the cavity naturally explains the optical dimness of the system in between outbursts. In fact, the steep dropoff in the SED at optical frequencies arises simply from an $m \gtrsim 1$ disc around an $M \sim 10^5 M_\odot$ binary being truncated at $R \sim 2a$. However, this
that a galaxy merger precedes SMBH binary formation, as well as a robust theoretical foundation for the hierarchical growth of galaxies. Below, I will make use of this theoretical knowledge to make educated estimates for the global event rate of cavity-accretion flares.

Fakhouri, Ma & Boylan-Kolchin (2010) found that the mean merger rates of dark matter haloes in the Millennium Simulations (Springel et al. 2005; Boylan-Kolchin et al. 2009) can be described by a simple analytic fitting formula. For mergers with halo mass ratios between unity and 30:1, the merger rate (per halo per unit time) evaluates to

$$\Gamma_{\text{merger}} \approx 2.1 \left( \frac{M_{\text{halo}}}{10^{13} M_{\odot}} \right)^{0.13} (1+z)^{0.095} \frac{dz}{dt},$$

(23)

for a given halo mass $M_{\text{halo}}$ and redshift $z$. I compute $dz/dt$ in the standard cold dark matter cosmology with $h = 0.70$, $\Omega_{\Lambda} = 0.72$ and $\Omega_m = 0.28$ (Hinshaw et al. 2012).

By relating the stellar velocity dispersion $\sigma_*$ of galaxies to the dark matter halo mass, one can attempt to convert the observed $M$–$\sigma_*$ relation (Ferrarese & Merritt 2000; Gebhardt et al. 2000; Gültekin et al. 2009; Graham et al. 2011) to a relation between $M$ and the host halo mass $M_{\text{halo}}$ (Ferrarese 2002; cf. Baes et al. 2003; Wyithe & Loeb 2003; Bandara, Crampton & Simard 2009). Following Graham & Scott (2013), we adopt a broken power law

$$\frac{M}{10^{12} M_{\odot}} \sim 3 \left( \frac{M_{\text{halo}}}{7 \times 10^{12} M_{\odot}} \right)^{0.8} (1+z)^{3/2},$$

(24)

where the slope $\alpha_M$ equals 5/3 if $M_{\text{halo}} < 7 \times 10^{12} M_{\odot}$ (or $M < 3 \times 10^{12} M_{\odot}$) and 6/5 at higher masses. Although this relation is known to have a large intrinsic scatter, it serves to provide an order-of-magnitude estimate. Combining equations (23) and (24), one can estimate the rate at which two SMBHs with combined mass $M_*$ end up in a single halo.

Some fraction of such pairs will form binaries embedded in circumbinary discs. There are (semi-) analytic formulations of how such binaries evolve towards merger (Syer & Clarke 1995; Ivanov et al. 1999; Haiman et al. 2009; Liu & Shapiro 2010). In the simplest description, the evolution can be written as

$$\frac{da}{dt} = \dot{a}_{\text{GW}} + \dot{a}_{\text{disc}}.$$

(25)

At large separations, the binary evolves by depositing its orbital angular momentum into the circumbinary accretion disc ($\dot{a}_{\text{disc}}$), and at close separations by emitting gravitational waves ($\dot{a}_{\text{GW}}$). For the former, we are interested in secondary type-II migration, where the binary opens a central cavity in the disc. I take the simple prescription given by Syer & Clarke (1995),

$$\dot{a}_{\text{disc}} = - \frac{a}{t_c} \left[ \frac{2n(1+q)^2}{q} \frac{t_c}{t_{\text{fall}}} \right]^k,$$

(26)

where $q \leq 1$ is the secondary-to-primary mass ratio, $t_c = 2R^2/(3\nu)$ is the viscous diffusion time-scale evaluated at the cavity edge $R = 2a$, and the dimensionless quantity $k \approx 0.4$ depends on the surface density and viscosity profiles of the disc. I take $\nu$ to be given by a standard Shakura–Sunyaev disc with $\alpha = 0.1$ and $\dot{m}_{\text{inj}} = 0.3$ (typical for luminous AGN; e.g. Kollmeier et al. 2006). I assume $q = 0.1$ as a typical SMBH mass ratio in such binaries. The effects on the above prescriptions for varying the viscosity prescription and various system parameters (e.g. $q$, $m$, $\alpha$) can be found in Haiman et al. (2009); given the approximate nature of this exercise, I will not explore this parameter space. Note that Kocsis et al. (2012b)
find that the disc-driven migration of the binary could be significantly slower than the expression in equation (26); the actual lifetimes of SMBH binaries with circumbinary discs could be longer than estimated here. For the gravitational-wave-driven evolution, I take

\[
\frac{\dot{a}_{\text{GW}}}{GM/c^2} = \frac{64}{5} \frac{c^3}{GM} \frac{q}{(1+q)^2} \left( \frac{a}{GM/c^2} \right)^{-3}
\]

(27)

from Peters (1964), assuming circular orbits for simplicity.

The most liberal assumption possible is that once SMBH pairs are formed after a galaxy merger, all of them evolve towards coalescence while embedded in circumbinary discs. Thus, an upper limit for the average flaring rate per galaxy \( \langle \Gamma_{\text{flare}} \rangle \), averaged over all galaxies, can be estimated by counting the total number of flares (orbits) a binary makes while embedded in a disc, and then multiplying by the universal formation rate of binaries (i.e. the halo major merger rate):

\[
\langle \Gamma_{\text{flare}} \rangle \sim \langle P^{-1} \rangle < \Gamma_{\text{merge}}(M_*, z) \int \left( \frac{da}{dt} \right)^{-1} \frac{1}{P} \, da
\]

(28)

I have assumed one flare per binary orbit above, but it is trivial to generalize to two flares. Similarly, the maximum fraction of galaxies that host a flaring SMBH binary between observed orbital periods \( P_1 \) and \( P_2 \) can be estimated by multiplying the total time a binary spends evolving between those periods with the formation rate of binaries:

\[
f_{\text{**}}(P_{\text{obs}}) < \Gamma_{\text{merge}}(M_*, z) \int_{P_{1/2}}^{P_{2/2}} \left( \frac{da}{dt} \right)^{-1} \, dt
\]

(29)

Note that above, \( f_{\text{**}} \) is the fraction of objects that exhibit flares, not the fraction of time SMBHs spend flaring as opposed to quiescence. The \( z \)-dependence of the above expressions assumes that the timescale for the formation of a disc-embedded binary takes place on time-scales much shorter than a Hubble time.

I conservatively choose the upper limit of integration in equations (28) and (29) to be \( a_0 \equiv R(Q = 1)/2 \), i.e. that the disc does not extend to regions where it is canonically Toomre-unstable (Section 2.1); if the disc is stabilized by other mechanisms such as gravitational turbulence, the number of flaring objects and flares in the sky would be higher than estimated here. I limit the integration to a minimum orbital period in the observer rest-frame \( P_{\text{obs}} = (1+z)P_0 \) of one month, to focus on flares whose quasi-periodically recurring nature may be challenging to detect. (Objects whose flares recur on shorter time-scales would be identified as such shortly after being detected, in the course of standard monitoring of a TDE-like transient.) I do not count binaries that have already decoupled from their circumbinary discs, as such systems are expected to produce weaker flares (if marginally decoupled) or no flares at all. If some circumbinary gas is able to follow the binary in the gravitational-wave-driven regime (Tanaka, Menou & Haiman 2012), flaring SMBH binaries may also be detectable in gravitational waves by pulsar timing arrays. Note that we can immediately place an order-of-magnitude estimate that \( f_{\text{**}} \sim 10^{-3} \), since we know \( \Gamma_{\text{merge}} \sim \text{a few} \times \text{Gyr}^{-1} \) and that the timescale for an SMBH binary to evolve from \( a_0 \) to coalescence is \( \sim t_\text{c} \sim \text{Myr} \).

I plot these upper limits for \( \Gamma_{\text{flare}} \) and \( f_{\text{**}} \) in Fig. 5, as a function of \( M_\text{} \), and for several different subsets of the binary SMBH population. From left to right, the vertical pairs of panels show binary populations at \( z = 0−2 \). The top panels show \( \langle \Gamma_{\text{flare}} \rangle \) (flares per unit time, per all galaxies, in the galaxy rest frame). The black, solid curves show all binaries embedded in Toomre-stable discs. The blue, dashed curves show the flaring rate from only the binaries whose circumbinary discs are luminous in the \( V \) band, and the red, dotted curves show those that are ultradim in the \( V \) band between flares. This was determined by evaluating whether the redshifted peak frequency in the spectral emission of the circumbinary disc was higher or lower than \( 10^{14} \text{ Hz} \) (equation 6). The figure shows that if all SMBH pairs merge via migration in a disc with a central cavity, then the event rate could exceed \( 10^{-3} \text{ yr}^{-1} \), compared to the TDE rate estimates of \( \Gamma_{\text{TDE}} \sim 10^{-3} \text{ yr}^{-1} \) (Magorrian & Tremaine 1999). In other words, if \( \sim 1 \text{ per cent of SMBH pairs produced cavity-accretion flares}, \) then their global event rate could be comparable to the rate of stellar TDEs. (However, as mentioned in Section 2.1.2, recently merged systems may preferentially be obscured by dust.) The overall fraction of flares occurring in systems with optically dim circumbinary discs increases with \( z \) as the peak disc frequency is redshifted.

The bottom panels of Fig. 5 show the upper limits for the fraction of all galaxies that host an accreting SMBH binary embedded in a Toomre-stable circumbinary disc. I have also plotted the maximum fraction of galaxies hosting SMBH binaries with periods 1 month < \( P_{\text{obs}} < 1 \text{ yr} \) (dotted red curves), 1 yr < \( P_{\text{obs}} < 10 \text{ yr} \) (short dashed blue curves) and 10 yr < \( P_{\text{obs}} < 100 \text{ yr} \) (long dashed purple curves). The figures suggest that flaring binaries should typically have orbital periods (flare frequencies) of several months to several years if the

![](https://academic.oup.com/mnras/article-abstract/434/3/2275/1035241/2275)
binary mass is less than \(\sim 10^8 \, M_{\odot}\), and \(\gtrsim 10^9 \, M_{\odot}\) (coincident, incidentally, with the flare period of OI 287).

These upper limits are, of course, highly speculative, given the large uncertainties regarding the formation rate and evolution of SMBH binaries, the fraction of these objects that form prograde circumbinary accretion discs, and the fraction of those objects that are unobscured. These calculations do, however, demonstrate the possibility that cavity-accretion flares from SMBH binaries might be a common occurrence, perhaps comparable to the incidence of luminous AGN activity. The existence of a population of flaring binaries could be hidden by the fact that they may resemble inactive galaxies in between flares. They could be discovered, alongside TDEs and other extragalactic transients, in upcoming surveys such as LSST and eROSITA.

5 DISCUSSION

Above, I have argued that an accreting SMBH binary with a prograde circumbinary disc may produce periodic X-ray/UV/optical flares at cadences of years or decades, that this may occur in nuclei that are optically quiescent in between outbursts, and that such events may be common in the transient sky. That is good and well as a piece of educated speculation, but the inverse problem – that is, supposing that such flares are observed, then discerning whether the cause is an accreting SMBH binary – is a much more difficult one.

It is well known that most AGN exhibit aperiodic optical/UV fluctuations at the \(\sim 10\) per cent level over time-scales of weeks to years (Ulrich, Maraschi & Urry 1997; Giveon et al. 1999; Collier & Peterson 2001). However, examples in which the AGN appears ‘turn on’ briefly from a previously quiescent state are rare (e.g. Gilli et al. 2000; Grupe, Thomas & Beuermann 2001). Transient AGN-like activity with rapidly rising and decaying optical and UV light curves are generally thought to be stellar TDEs (Komossa & Bade 1999; Komossa & Greiner 1999; Gezari et al. 2006, 2009; Esquej et al. 2008; Cappelluti et al. 2009; van Velzen et al. 2011; Cenko et al. 2012; Saxton et al. 2012).

Indeed, the flares proposed in this work are physically similar to TDEs, in that an amount of gas comparable to that of a star is deposited close to an SMBH (which may previously appear quiescent) – except that whereas the ‘fuel’ in TDEs is deposited at a distance of a few gravitational radii, the gas streams leaked from the circumbinary disc are typically deposited at thousands of gravitational radii (i.e. \(\lesssim 0.1\)z). One could also think of the flares as a gas-rich analogue of G2, the purported \(\sim 10^{-5} \, M_{\odot}\) gas cloud\(^6\) falling towards Sgr A\(^*\) (Gillessen et al. 2012).

The task of disentangling TDEs from SMBH binaries is further complicated by the fact that the two phenomena are not mutually exclusive. On the contrary, it has been suggested that SMBH binaries – or a recently merged binary (Komossa & Merritt 2008; Stone & Loeb 2011, 2012) – may even enhance the rate of TDEs, without the aid of an accretion disc (Chen et al. 2009, 2011; Wegg & Nate Bode 2011). Conversely, an accretion disc around a single SMBH may enhance the TDE rate without a central binary (Karas & Šubr 2007). Thus, the observation of multiple TDE-like transients in a single galactic nucleus will not be enough to claim that the cause is an accreting SMBH binary, even if corroborated by additional circumstantial indicators such as morphological evidence of a recent galaxy merger.

Fortunately, the cavity-accretion scenario proposed here has several basic predicted features (other than periodicity) that should help to distinguish flaring supermassive binaries from TDEs. The most significant prediction is that the flares can be produced by SMBHs with \(M_\bullet > \text{few} \times 10^8 \, M_{\odot}\), which are thought not to disrupt solar-type stars. Another is that it requires the presence of a circumbinary accretion disc with a cavity, which should have an anomalously red or optically dim SED that may be observed in the infrared. The cavity may also result in unusually weak broad emission lines in between flares. AGN with such properties are known to constitute a small fraction (\(\sim 1\) per cent) of the general population (Gibson, Brandt & Schneider 2008; Shemmer et al. 2009).

I have only discussed the thermal emission from the optically thick accretion flow. However, it is widely established that SMBH accretion can exhibit a wide range of emission features. The diversity of emission is shared by TDE candidates – e.g. the contribution of the outflowing wind (Strubbe & Quataert 2009, 2011), the production of relativistic jets (Bloom et al. 2011; Burrows et al. 2011; Zauderer et al. 2011) and associated radio transience (Giannios & Metzger 2011). Sesana et al. (2012) discussed the possibility that SMBH binaries may produce periodic variability in the Fe K\(\alpha\) emission line (but this may be difficult to observe if the accretion flows inside the cavity are short lived); the rapid onset of a hypercritical accretion flow may trigger radiatively driven jets or outbursts (Tanaka & Menou 2010). The cavity-accretion flares discussed in this paper, if they occur in nature, should have a similarly diverse variety of observable signatures.

In constructing the toy model of the accretion flare, I made several order-of-magnitude parametrizations and estimates, based on previous studies where possible, for quantities such as the mass deposited by each stream and the distance from the SMBH where the gas circularizes and begins to accrete. The actual light curves and SEDs will also depend on the detailed thermal and viscous evolution of the gas, including the possible onset of instabilities. The emission signatures presented here are based on idealized treatments of the accretion geometry and viscosity, and should be viewed only as a proof-of-concept demonstration based on order-of-magnitude normalizations. Finally, the toy model assumes that the fuelling accretion flow forms on a short time-scale much shorter than the binary orbital time-scale; cavity-accretion flares may develop more gradually if the fuelling flows are slow to form and circularize, and this could help to distinguish them from TDEs. The validity of the above theoretical treatments can be tested by future numerical simulations.

6 CONCLUSION

In this paper, I explored the possibility that the periodic leakage of circumbinary gas on to an SMBH binary produces luminous transient flares that may interrupt intervals of apparent quiescence. The underlying mechanism behind this hypothesis consists of two characteristics of prograde accretion discs found in numerous simulations: (i) the presence of a central, circumbinary cavity in a prograde accretion disc, which reduces the emergent flux of the system at frequencies above the optical; and (ii) the periodic, punctuated leakage of the disc gas into the cavity, which would trigger UV and soft X-ray emission as it accretes on to one or both SMBHs. The main findings for these ‘cavity-accretion flares’ from SMBH binaries are as follows:

\(^6\)Murray-Clay & Loeb (2012) and Scoville & Burkert (2013) suggest that G2 is instead a low-mass star with an associated disc or outflow.
The hypothesis that accreting SMBH binaries produce quasi-periodically recurring, transient luminous flares is based on the comparison of the depletion time-scale of the gas that enters the cavity with the binary’s orbital period. As long as the streams are circularized inside a radius comparable to the SMBH’s Hill sphere, the orbital energy available to heat the gas is sufficiently large so that the post-shock accretion flow should have a viscous accretion time-scale shorter than the binary’s orbital period. The post-shock accretion flow is expected to be marginally geometrically thin and strongly advective, similar to the slim-disc class of accretion-disc solutions. As is generally the case with such optically thick accretion, the thermal emission of the flare is expected to peak in the UV or soft X-rays, and extend to optical frequencies.

One or two transient flares may be produced per binary orbit, depending on whether one or both SMBHs develop optically thick accretion flows.

Unlike TDEs, these flares can be powered by SMBHs of arbitrary mass, including those in the $10^5 M_\odot$ class.

Because the presence of the cavity reduces the high-frequency thermal emission of the circumbinary disc, in between the outbursts such a system may appear as an anomalously coloured AGN or be mistaken for a quiescent galactic nucleus. The circumbinary disc may also have unusually weak broad-line or X-ray emission.

The flares and the intervening quiescence could manifest themselves as periodic optical outbursts, such as those exhibited by OJ 287. The cavity-accretion interpretation of OJ 287 differs from the disc-impact model proposed by Valtonen et al. (2006) in several ways: the required SMBH mass is smaller ($10^2 M_\odot$); the optical dimness in between outbursts is a direct consequence of the cavity, as opposed to reddening by dust; whereas the disc-impact model strongly constrains the flare timing based on the binary orbit solution, temporal stochasticity is expected in the cavity-flare model due to the accretion dynamics. One or both optical flares may be associated with a radio-loud episode, depending on the spins of the SMBHs. As stated above in (iii), the initial shock that circularizes the accretion flow in the cavity-flare model could explain the ‘precursor flare’ events observed in this system.

If the gas sound speed in the post-shock accretion flow scales with its Keplerian velocity (i.e. if its thermal profile is virial), then the corresponding viscosity prescription will drive a central accretion rate that decays as $\dot{M} \propto t^{-4/3}$. As with TDEs ($\dot{M} \propto t^{-5/3}$ canonically), the monochromatic and bolometric light curves are not expected to follow a simple power-law. Thus, it may not be possible to deduce the mass accretion rate from the light curve.

Most flaring SMBH binaries will have periods of $\sim 100$ yr, if the production of flares is contingent upon the Toomre stability of the circumbinary disc. More massive systems are capable of more luminous outbursts having longer cadences. For binaries with $M \lesssim 10^3 M_\odot$, the orbital periods may be months or shorter; however, such low-mass binaries may not produce flares because the cavity may close (Kocsis et al. 2012b).

Depending on the fraction of galaxy mergers that produce sub-parsec SMBH binaries with prograde circumbinary discs, the global rate of cavity-accretion flares may be high enough to be detected serendipitously by existing and future deep, high-cadence observatories such as eROSITA or LSST. Under the most liberal assumptions — that most galaxy mergers result in the formation of such binaries and that the flares are not preferentially obscured due to the recent merger of the hosts — the global rate of cavity-accretion flares from SMBH binaries may exceed the theoretical rate of TDEs.

If they occur in nature, cavity-accretion flares from SMBH binaries should be discovered by future surveys such as LSST and eROSITA alongside TDEs and other extragalactic transients. In the meantime, additional constraints may be placed on the prevalence of this mechanism by monitoring (candidate) TDE host galaxies for recurrent activity. The results presented here reinforce the notion that accreting SMBH binaries may be a common source of luminous astrophysical transients (Haiman et al. 2009; Tanaka et al. 2010).

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REFERENCES

Abramowicz M. A., Czerny B., Lasota J. P., Szuszkiewicz E., 1988, ApJ, 332, 646
Artyomowicz P., Lubow S. H., 1994, ApJ, 421, 651
Artyomowicz P., Lubow S. H., 1996, ApJ, 467, L77
Baes M., Buyle P., Hau G. K. T., Dejonghe H., 2003, MNRAS, 341, L44
Bandara K., Crampton D., Simard L., 2009, ApJ, 704, 1135
Barth A. J., Benz M. C., Greene J. E., Ho L. C., 2008, ApJ, 683, L119
Belgenman M. C., Blandford R. D., Rees M. J., 1980, Nat, 287, 307
Bianchi S., Chiaberge M., Piconcelli E., Guainazzi M., Matt G., 2008, MNRAS, 386, 105
Blaes O. M., 2004, in Beskin V., Henri G., Menard F., Pelletier G., Dalibard J., eds, Accretion Discs, Jets and High Energy Phenomena in Astrophysics. Springer, New York, p. 137
Blandford R. D., Begelman M. C., 1999, MNRAS, 303, L1
Bloom J. S., Holz D. E., Hughes S. A., Menou K., 2009, in Astro 2010: The Astronomy and Astrophysics Decadal Survey. Science White Papers, No. 20
Bloom J. S. et al., 2011, Sci, 333, 203
Bogdanovic T., Eracleous M., Sigurdsson S., 2009, ApJ, 697, 288
Boroson T. A., Lauer T. R., 2009, Nat, 458, 53
Boylan-Kolchin M., Springel V., White S. D. M., Jenkins A., Lemson G., 2009, MNRAS, 398, 1150
Burrows D. N. et al., 2011, Nat, 476, 421
Cao X., 2002, ApJ, 570, L13
Cappelluti N. et al., 2009, A&A, 495, L9
Carcioli A. C., Bjorkman J. E., Oetro S. A., Okazaki A. T., Stefl S., Rivinius T., Baade D., Haubois X., 2012, ApJ, 744, L15
Cenko S. B. et al., 2012, MNRAS, 420, 2684
Chen X., Madau P., Sesana A., Liu F. K., 2009, ApJ, 697, L149
Chen X., Sesana A., Madau P., Liu F. K., 2011, ApJ, 729, 13
Chornock R. et al., 2009, Astron. Telegram, 1955, 1
Collier S., Peterson B. M., 2001, ApJ, 555, 775
Colpi M., Dotti M., 2011, Adv. Scie. Lett., 4, 181
Comerford J. M., Griffith R. L., Gerke B. F., Cooper M. C., Newman J. A., Davis M., Stern D., 2009, ApJ, 702, L82
Cuadra J., Armitage P. J., Alexander R. D., Begelman M. C., 2009, MNRAS, 393, 1423
D’Orazio D. J., Haiman Z., MacFadyen A., 2012, preprint (arXiv:1210.0536)
Done C., Davis S. W., Jin C., Blaes O., Ward M., 2012, MNRAS, 420, 1848
