Binary Black Hole Accretion During Inspiral and Merger

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ABSTRACT

We present the results of 2D, moving mesh, viscous hydrodynamical simulations of accretion onto merging supermassive black hole (SMBH) binaries. We include viscous heating, shock heating, and radiative cooling, and simulate the transition from the “pre-decoupling” epoch, where the inspiral timescale is longer than the viscous timescale, to the “post-decoupling” epoch, where the inspiral timescale is shorter than the viscous timescale. We find that there is no abrupt halt to the accretion at decoupling, but rather the accretion shows a slow decay, with significant accretion well after the expected decoupling. Moreover, we find that the luminosity in X-rays is significantly higher prior to the merger, as orbital energy from the SMBH binary is converted to heat via strong shocks inside the cavity, and radiated away. Following the merger, the cavity refills viscously and the accretion rate relaxes to the Shakura-Sunyaev value, while the X-ray luminosity drops as the shocks quickly dissipate.

1 INTRODUCTION

Supermassive black holes are currently believed to reside in nearly all galactic nuclei (Kormendy & Ho 2013; Ferrarese & Ford 2005). When such galaxies merge, a combination of dynamical friction, gravitational slingshot interactions with stars, and interactions with gas can bring the black holes close enough to become gravitationally bound, forming a SMBH binary system in the merged galaxy remnant (Naved 2013). The nuclei of merged galaxy remnants are expected to contain an abundance of dense gas (Barnes & Hernquist 1996; Armitage & Natarajan 2002; Milosavljević & Phinney 2005; Springel, Di Matteo & Hernquist 2005), which may form a circumbinary accretion disk (Artymowicz & Lubow 1992; Armitage & Natarajan 2002; Milosavljević & Phinney 2005).

The standard picture for the evolution of the system is as follows: For large binary separations $a$, the inspiral time due to gravitational wave (GW) emission is much longer than the viscous time ($t_{GW} \gtrsim t_{vis}$), so that the disk settles into a quasi-stationary state. For equal-mass BHs, the binary tidal torques carve out a partial hollow in the disk (Artymowicz & Lubow 1994; Milosavljević & Phinney 2005; MacFadyen & Milosavljević 2008; Kocsis, Haiman & Loeb 2012) of radius $\sim 2a$ and excite spiral density waves throughout the disk, that dissipate and heat the gas. However, gas can penetrate the hollow in response to the time-varying tidal torque (MacFadyen & Milosavljević 2008; Havasak, Mineshige & Ho 2008; Farris, Liu & Shapiro 2011; Kocsis, Haiman & Loeb 2012; Noble et al. 2014; Roedig et al. 2013). At sufficiently small separations $t_{GW} \lesssim t_{vis}$, and the BHBH decouples from the disk as the viscosity is unable to refill the cavity quickly enough to follow the shrinking picture. As a result, it has been proposed that the final SMBH binary merger takes place in a vacuum, and that the associated EM signature can only appear after the cavity refills from the decoupling radius on a viscous timescale (Milosavljević & Phinney 2005; Shapiro 2010; Tanaka & Menou 2010).

Such binaries may provide a unique opportunity to observe electromagnetic signatures originating from the interaction of the binary with the surrounding accretion disk. The gravitational radiation originating from the SMBH binary inspiral should also be detectable by Pulsar Timing Arrays (PTAs) (Hobbs et al. 2010; Kocsis & Sesana 2011; Tanaka, Menou & Haiman 2012; Lommen 2012; Sesana et al. 2012) or by a space interferometer such as eLISA (Amaro-Seoane et al. 2013), provided the binary has maintained a circumbinary disk past the decoupling epoch (Barausse & Rezzolla 2008; Noble et al. 2012; Kocsis, Haiman & Loeb 2012).

Recent simulations of such binaries in the pre-decoupling epoch have called this picture into question. Prior to decoupling, simulations have shown that the cavity can be significantly lopsided so that gas is able to approach the BHs much closer than $\sim 2a$. Moreover, the cavity is penetrated by accretion streams with surface densities comparable to that of the circumbinary disk itself, which allow the binary to accrete freely, with very little suppression due to the gravitational torques of the binary (Artymowicz & Lubow 1994; MacFadyen & Milosavljević 2008; Sesana et al. 2012; Shi et al. 2012; Noble et al. 2013; D’Orazio, Haiman & MacFadyen 2012; Farris et al. 2014a). In this paper, we simulate viscous accretion onto a binary, allowing the binary orbit to shrink due to gravitational radiation such that our simulations pass through the “decoupling” epoch and proceed all the way to merger. We estimate the extent to which accretion is diminished due to...
decoupling. We also examine time-dependent signatures of the merger which may appear in the spectrum.

We consider equal-mass, nonspinning binaries. While the BH mass scales out, we are primarily interested in total masses \( M \approx 10^5 M_\odot \) and low density disks for which the tidally induced inspiral is subdominant, and the disk self-gravity is negligible.

2 METHODS

Our initial disk configurations are similar to that of Farris et al. (2014b), and consist of a steady-state Shakura-Sunyaev disk solution, modified by adding a hollow cavity within \( r \lesssim r_0 \equiv 2.5a \). We assume a geometrically thin, gas pressure dominated, optically thick accretion disk, with electron scattering as the dominant opacity. In the early stage of our simulations, the inner cavity wall migrates inward due to viscosity, accretion streams form, and a quasi-steady state is reached. The fluid evolves according the the 2D viscous Navier Stokes equations, assuming an \( \alpha \)-law viscosity prescription.

Following Peters (1964), we account for shrinkage of the binary separation \( a \) due to gravitational radiation to leading order,

\[
a = a_0 \left(1 - \frac{t - t_0}{\tau}\right)^{1/4} \tag{1}
\]

where \( a_0 \) is the separation at initial separation at time \( t_0 \), and \( \tau \) is the characteristic merger timescale. Throughout the inspiral, we assume that the binary remains on a circular orbit. Because \( \tau \) depends on \( a_0 \), and our simulations can be rescaled to any separation, we need only choose \( \tau \) large enough so that \( \tau > t_{\text{vis}} \) so that the fluid near the binary can relax to a quasistationary configuration before “decoupling” occurs and the shrinkage begins to outpace the viscous refilling of the cavity. Thus, we choose \( \tau = 5t_{\text{vis}} \).

The DISCO code (Duffell & MacFadyen 2014) allows one the freedom to specify the motion of the computational cells. For this problem we choose a rotation profile which matches the nearly Keplerian fluid motion outside the cavity, while transitioning to uniform rotation at the binary orbital frequency inside the cavity. The radius at which this transition occurs shrinks with the binary according to

\[
\Omega_{\text{cell}} = \frac{r^{n-3/2} + a_n^{n-3/2}}{r^n + a_n^n} \tag{2}
\]

where \( n = 8 \). After the binary merges and \( a = 0 \), all cells move at the Keplerian rate. Profiles of \( \Omega_{\text{cell}} \) at various epochs are displayed in Fig. 1.

For each simulation, we use a \( \Gamma \)-law equation of state of the form \( P = (\Gamma - 1)\rho \epsilon \), where \( P \) and \( \epsilon \) are the \( \rho \)-integrated pressure and internal energy, respectively, and \( \Gamma = 5/3 \) is the adiabatic index. Viscous heating and radiative cooling are incorporated naturally through the energy equation, as described in Farris et al. (2014b).

3 RESULTS

Our initial disk contains an artificial cavity of radius \( \approx 2.5a \). Viscosity in the circumbinary disk transports angular momentum outward, causing the cavity to refill. Gravitational torques from the binary tend to drive matter outward, and a quasistationary balance between competing gravitational and viscous torques is achieved after \( \sim 2t_{\text{vis}} \). The quasisteady state is similar to that of Farris et al. (2014b), in that well collimated, narrow accretion streams form which penetrate the cavity, efficiently delivering fluid to the BHs. The cavity also becomes lopsided, as described in Farris et al. (2014a) and Shi et al. (2013). One may naively think that when \( t_{\text{vis}} = t_{\text{merg}} \), decoupling should occur and the accretion rate should drop essentially to zero. We find this not to be the case. Rather, we find a gradual decline in \( M \) beginning when \( t_{\text{vis}} \approx t_{\text{merg}} \), but with significant accretion persisting until much closer to merger. This can be seen by examining the snapshot in Fig. 2 in which accretion streams and minidisks are clearly present as late as \( t - t_{\text{merg}} = -0.1t_{\text{vis}} \), where \( t_{\text{merg}} \) is the merger time, and in Fig. 3 where we see that the accretion rate has only been reduced by a factor of \( \approx 0.5 \) by this time. We attribute the persistence of accretion at late times to the high-density accretion streams which are very effective at delivering gas into the cavity, and are not treated properly in axisymmetric 1D calculations.

In order to examine changes in the spectrum throughout the inspiral and merger, we calculate the spectrum assuming thermal blackbody emission at surface patch in the disk,

\[
L_\nu = \int \frac{2h_\nu^3}{c^2 \exp \left( \frac{h_\nu}{kT_{\text{eff}}(r, \phi)} \right) - 1} dA \tag{3}
\]

where the effective temperature \( T_{\text{eff}}(r, \phi) \equiv (q_{\text{cool}}(r, \phi) / \sigma)^{1/4} \), and \( q_{\text{cool}} \) is the radiative cooling rate. In our simulations we allow heat generated through viscosity and shocks to be radiated at the blackbody rate instantaneously, without accounting for the time necessary for photons to diffuse through the optically thick disk.

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As a result, some of the heat generated in the accretion streams may actually be retained and dissipated non-locally. The magnitude of this effect should be studied through future comparisons with 3D models which include radiative transfer. In Figure 3 we plot spectra at $t/t_{\text{vis}} = -2.0, -1.0, 0.0, 1.0, 2.0$. We find that prior to merger, there is a strong enhancement in emission at high frequencies due to the shock heated minidisks. As in Farris et al. (2014b), we find no noticeable “notch” in the spectrum, as the low-frequency tail of the emission from the hot minidisks and the hot streams effectively washes out any deficits arising from the missing gas in the cavity. Scaled to a $10^8 M_\odot$ binary with a separation near decoupling at $a/M = 100$, we find that the enhancement is significant in soft and hard X-rays. Following the merger, there is a dramatic drop in high-frequency emission, as the shocks quickly dissipate in the absence of any binary torques.

In each curve in Fig. 3 we note that there is a cutoff at high-frequencies. Physically, this corresponds roughly to the effective temperature at the BH horizon, which is the hottest region of the disk. We account for these horizons by masking out emission within a distance of $2M$ from each point mass, assuming that $a_0 = 100M$, which is of the order of the decoupling separation. This is admittedly a crude prescription, and we expect that the precise frequency at which the cutoff occurs will be modified in a fully relativistic simulation which accounts naturally for accretion through each BH’s horizon. However, the qualitative result that this cutoff is at higher frequencies prior to merger, due to the shock heating of the minidisks and parts of the accretion streams, should be robust.

Comparing the spectra before and after merger, it is clear that the total bolometric luminosity is much greater prior to merger. This is somewhat counterintuitive, as circumbinary accretion disks have often been assumed in the literature to be dim as a result of binary torques choking off accretion. However, given the current understanding that accretion is not significantly diminished by binaries, the ability for gas in the cavity to tap into the large reservoir of orbital energy in the binary must be considered. As the precise amount of energy transferred from the binary depends on complicated 3 body interactions as well as the dynamics of the shock-heated gas in the cavity, a simple estimate for the magnitude of the bolometric luminosity enhancement prior to merger may not be possible. In our simulations, we find the enhancement to be roughly 2 orders of magnitude, but we caution that this result is very preliminary, and must be checked against simulations with more detailed treatments of dynamics of gas near the BH horizon. We also note that similar enhancements in bolometric luminosity due to tidal heating have been noted in previous analytic calculations (Kocsis, Haiman & Loeb 2012b,a).

While the EM emission from an accreting binary can be modified significantly over the course of the inspiral and merger, past work has often focused on the total bolometric luminosity, ignoring the fact that lightcurves can be highly frequency dependent. Calculations which did include frequency evolution have assumed a lack of high-frequency emission from within the cavity and have focused on post-merger brightening (see e.g. Milosavljević & Phinney 2003; Tanaka & Menou 2010). In our simulations, we find that emission from the relatively cool gas in the circumbinary
4 DISCUSSION

Prior work on SMBH binaries has emphasized a “post-decoupling” epoch, during which the binary separation shrinks due to gravitational radiation too quickly for the inner disk cavity to viscously refill, leading to mergers with very little gas present. We have performed 2D simulations of accretion onto a shrinking binary and shown that the “decoupling” process is actually very gradual, and that significant accretion can persist well after the expected decoupling epoch, including separations corresponding to orbital frequencies that place the binary inside the PTA and LISA bands. This is encouraging as it suggests that EM counterparts for PTA and eLISA sources should be observable.

We have shown several observable electromagnetic signatures of SMBH mergers. We have computed blackbody spectra from snapshots of our simulations and shown that the high-frequency enhancements in the spectra which arise from shock heated minidisks and accretion streams disappear following the merger, as the shocks are no longer present in the absence of the binary torques. This effect is also reflected in steep drop in the high-frequency lightcurves.
coinciding with the binary merger. We note that the enhancement in UV/soft X-ray may also lead to stronger broad lines prior to merger.

In our simulations, we find the total enhancement in bolometric luminosity during the pre-merger phase to be roughly a factor of $\eta \sim 100$, so that $L \sim \eta GM M/R_{isco}$. This extra energy is emitted by shock heated gas in the streams and minidisks, but ultimately comes from the orbital energy of the binary. In our calculations, we have neglected any changes to the binary orbit due to this effect, assuming it is small compared to the rate of energy loss due to gravitational waves, $L_{gw} \sim (GM/ac^3)M^3/a$. We can check our assumption by computing the ratio of these luminosities,

$$\frac{L}{L_{gw}} \sim 10^{-3} \left( \frac{\eta}{100} \right) \left( \frac{M_{bh}}{10^9 M_\odot} \right) \left( \frac{ac^2/GM}{100} \right)^3 \left( \frac{M c^2}{L_{edd}} \right).$$

Thus, we see that our neglect of energy loss from the binary due to interaction with the disk is warranted for our fiducial parameters. However, the above ratio is very sensitive due to interaction with the disk is warranted for our fiduciary viscous time. This is an encouraging finding for EM counterparts to GW sources.

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