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X-ray variability of accreting supermassive binary black holes approaching coalescence

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Abstract

The next generation of X-ray observatories (e.g. the Advanced Telescope for High ENergy Astrophysics, ATHENA) will offer possibilities for the first multi-messenger observation in X-rays and gravitational waves (GWs, provided by the Laser Interferometer Space Antena, LISA) of supermassive binary black hole (BBH) merger systems. Here, we summarize some recent results of simulations for predicting their X-ray variability. First, at the circumbinary disk scale, several variability patterns are expected, including a modulation produced by an overdensity (the 'lump'). However, the circumbinary disk emission will dominate in the UV/optical rather than in the X-ray band for most systems, unlike the individual accretion structures ('mini-disks'). Nevertheless, these structures disappear as the system approaches merger so the associated X-ray emission disappearance can act as a signature of forthcoming coalescence. Meanwhile, the aforementioned circumbinary disk variability is found to survive, again in the UV/optical. This emphasizes the need for multi-wavelength signatures and campaigns to detect those supermassive BBHs as they approach coalescence.

1 Introduction

With a possible overlap between the missions LISA (gravitational waves, $0.1 - 100$ mHz), ATHENA (X-rays) and possibly the Transient High Energy Sky and Early Universe Surveyor (THESEUS, X-rays, gamma, infrared) around 2035-2040, accreting supermassive binary black holes (BBHs) have the potential to become multi-messenger sources. Multi-messenger observations would inform us on the growth of BHs and galaxies, and could lead us to witness, for the first time, the re-birth of an active galactic nucleus. In this contribution to the Spanish Astronomical Society meeting, we discuss some possible origins for the X-ray (and multi-wavelength) variability to help us detecting those systems.

In order to predict the electromagnetic variability, we need to understand the accretion flow properties. Fluid simulations have mainly focused on the circumbinary accretion and converged on a qualitative picture, assuming a circumbinary disk (CBD) has formed. The CBD inner edge is truncated at about twice the orbital separation, forming a low-density cavity, except for two spiral streams feeding the individual accretion structures. In the CBD, spiral waves propagate outwards, and close to the CBD edge an overdensity, dubbed the 'lump' [14], forms.

2 Variability of the circumbinary disk emission – away from merger

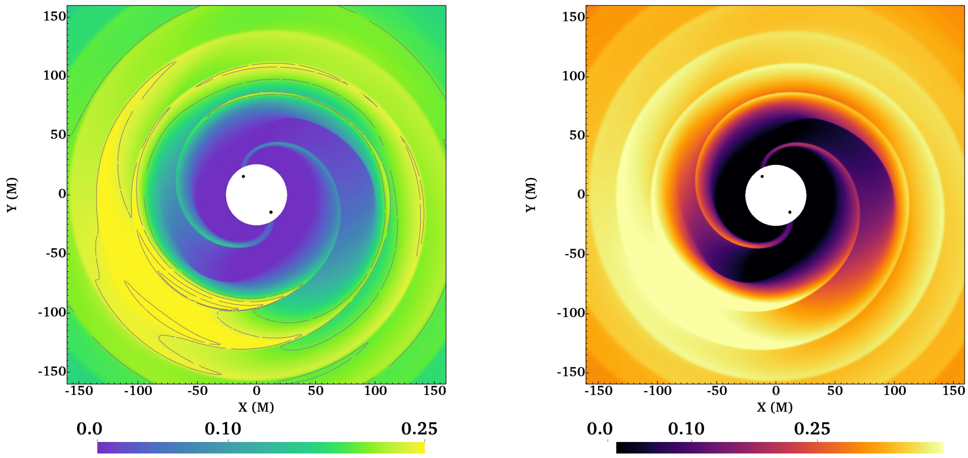

Figure 1: Surface density map and contours (left) and temperature (right) in code units in the circular-orbit case for $q = 1$, separation $b = 36$ M. The lump is in the bottom-left corner.

In order to predict the electromagnetic variability of the CBD, we conducted a series of 2D general-relativistic hydrodynamical simulations [9], solving the equations of mass, momentum and entropy conservation in an approximate BBH spacetime valid in the CBD region[1] [8]. For that reason, we excised the innermost region of the cavity, focusing on the CBD emission. Afterwards, we post-process these data with a general-relativistic ray-tracing code [16] in order to obtain synthetic observations (lightcurve, spectrum) in thermal blackbody emission. We do not include cooling/heating models in the fluid simulation as we mostly focus on the CBD dynamics and the appearance of dense non-axisymmetries once relativistic effects are

[1]This metric is built as a Minkowski (flat) metric with a post-Newtonian perturbation: the expansion parameter is $\mathrm{r}_{\mathrm{g},i}/r \ll 1$ (*weak field* approximation), with $\mathrm{r}_{\mathrm{g},i} \equiv \mathrm{G}M_i/\mathrm{c}^2$ the gravitational radius of the i−th BH, and r the BBH separation *or* the distance to each one of them: thus, it is restricted to the CBD region.

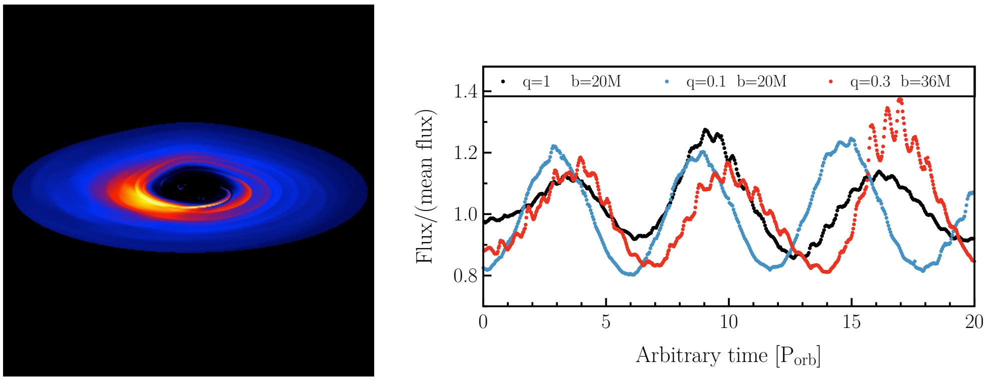

Figure 2: Left panel: example of an emission map in thermal blackbody radiation from the circumbinary disk region. Right panel: lightcurves in the circular-orbit case for various runs, all dominated by the lump modulation.

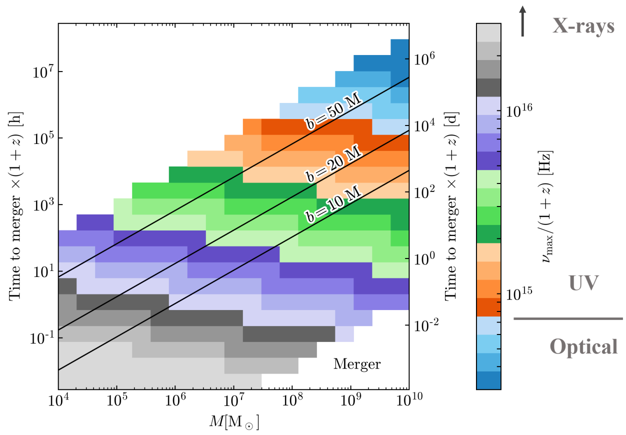

Figure 3: Frequency at the peak of the CBD spectrum, i.e. where the lump modulates the flux, as a function of the BBH mass and the time to merger (in hours on the left axis, more suited for low-mass systems, and days on the right). Accretion rate: $\dot{M} = 0.5\dot{M}_{\rm Edd}$.

accounted for. For that reason we simply assume a temperature $T{\sim}\Sigma^{\gamma-1}$ with Σ the surface density and $\gamma = 5/3$ the adiabatic index, adapted to thermal pressure-dominated plasmas.

Our setup consists of an axisymmetric disk close to centrifugal equilibrium but leads to the self-consistent formation of a cavity, spiral arms and overdense lump, as depicted on the left panel of Fig. 1 for $q = 1$ ($q \equiv M_2/M_1 \leq 1$). The lump is denser than its surroundings, which implies, with our simple thermodynamical model, a higher temperature[2] (right panel of Fig. 1). One emission map in thermal blackbody radiation is shown in the left panel of Fig. 2. As shown here, once ray-traced back to the observer, with a non-face-on inclination

[2]This enhanced temperature could have multiple origins in practice, e.g. an enhanced optical depth to the ambient radiation field. Alternatively, the lump's impact on the accretion could generate non-axisymmetric 'viscous' heating or be a region of enhanced shocks [14].

($i = 70°$ here), the emission of hot non-axisymmetries is boosted by relativistic Doppler effect. Thus, the emission from the lump (but also from the spiral arms) is enhanced when it comes towards us and dimmed when it recedes from us. As a consequence, the lightcurve exhibits a main modulation[3] at the lump period, $\sim 6\,\mathrm{P_{orb}}$ here, as shown in the right panel of Fig. 2.

The lump's emission contributes to the highest-frequency and most luminous part of the CBD multi-color blackbody spectrum. In Fig. 3 we display this peak frequency, which would be the typical frequency to observe the lump modulation, as a function of the BBH mass and time-to-merger (equivalent to the separation) for $q = 1$, from analytical models [13]. We can see that it corresponds to UV radiation for LISA-like BBHs ($10^{4-7}\mathrm{M_\odot}$; optical for PTA-like BBHs, i.e. $10^{7-10}\mathrm{M_\odot}$). Thus, we conclude that the CBD thermal emission, although variable, is not the ideal X-ray target we are looking for. What about the individual disks within the cavity?

3 Variability of the individual disks' emission

As our aforementioned BBH metric is not valid close to the BHs, we cannot model these individual disks yet. Thus, we discuss here some results from the recent literature regarding their expected X-ray variability. It can be expected, from analytical models again and from simulations (e.g. [5]) that the mini-disks of LISA BBHs should emit in the soft X-ray band.

As the lump passes close to one component of the binary, accretion onto the mini-disks can be enhanced and could modulate the X-ray flux. This occurs at the beat frequency (or twice the beat frequency as $q \to 1$) between the binary system orbit and the lump's orbit, i.e. $\Omega_\mathrm{beat} \equiv \Omega_\mathrm{orb} - \Omega_\mathrm{lump}$ that gives $P_\mathrm{beat}{\sim}1.2P_\mathrm{orb}$ [10], i.e. a period quite similar to the orbital period. A second possible cause of variability is the 'self-lensing flare' (e.g. [2]), for accreting BBHs seen (close to) edge-on. As one BH passes in front of the other BH's disk, the disk emission is boosted gravitationally, producing a flare at the orbital period (or semi-orbital period as $q \to 1$). Finally, relativistic Doppler boost can also act on the individual disks' emission [3], again for systems closer to edge-on view, and occurs at the orbital period (or semi-orbital period as $q \to 1$). Those variabilities are mutually non-exclusive.

However, as each disk's inner and outer radius is set by their Innermost Stable Circular Orbit (ISCO, a few r_g) and the tidal truncation radius ($\sim b/3$), respectively, the region of existence of individual disks shrinks as the BBH approaches merger. Thus, their X-ray emission disappears $\sim$1 day before merger for $q=1$, $M=10^6\,\mathrm{M_\odot}$ ([6], [5]). This X-ray drop could be the signature to look for, if the source is entirely monitored during the drop, or monitored before and after. However, we might observe these systems when the X-ray flux is already below sensitivity level. Indeed, while the scaling of the lightcurve to other masses is unsure, the time-to-merger at which the ISCO radius and the tidal truncation radius are equal directly scales with the BBH mass. Hence, this would be $\sim$10 days before merger for $M=10^7\,\mathrm{M_\odot}$, when the localization contours given by LISA still cover more than $10^3\,\mathrm{deg}^2$ (at $z=1$, [7]), making such detections challenging. Therefore, we need to rely on a) multi-wavelength campaigns, as the system will not be an X-ray source anymore and b) on some

[3]For more details on the smaller-amplitude modulation we refer the reader to [10].

other accretion structure than the individual disks to exhibit characteristic signatures.

4 Variability of the circumbinary disk emission – close to merger

While the individual disks vanish close to merger, the CBD does not. A natural question is, however, how the fast inspiral impacts the CBD dynamics (and subsequent observables), especially beyond the so-called 'decoupling' point [1], i.e. the point in time when the BBH's inspiral velocity exceeds the CBD gas inward velocity and the CBD 'lags behind' the BBH.

Using the same methods as in Sec. 2, we investigated the survival of the lump modulation past decoupling (for more details, see [11]). For this, we restarted a circular-orbit simulation (Fig. 1) with the inspiral activated. We considered two cases: $q = 1$ ($b = 36$ M initially), and $q = 0.3$ ($b = 33$ M initially so the time-to-merger is the same) and we activated cavity cells on-the-fly. Since we do not include *ad hoc* viscosity model, angular momentum is purely transported via the non-axisymmetric hydrodynamics and these simulations somehow correspond to the low-viscosity limit, i.e. decoupling the earliest, in a similar manner as [4].

As shown in the left panel of Fig. 4 which corresponds to less than $0.1(M/10^6\mathrm{M}_\odot)$ day before merger, the lump survives post-decoupling (for $q = 1$ and $q = 0.3$), confirming the trend found for $q = 1$ in viscous disks ([15], [5]). As a consequence, the lightcurve, shown in the right panel of Fig. 4 exhibits the lump modulation until the end of the simulation, i.e. $\sim 10(M/10^6\mathrm{M}_\odot)$ minutes before merger. As in the circular case, the modulation is observable in the UV/optical, corresponding to the CBD spectrum peak frequency.

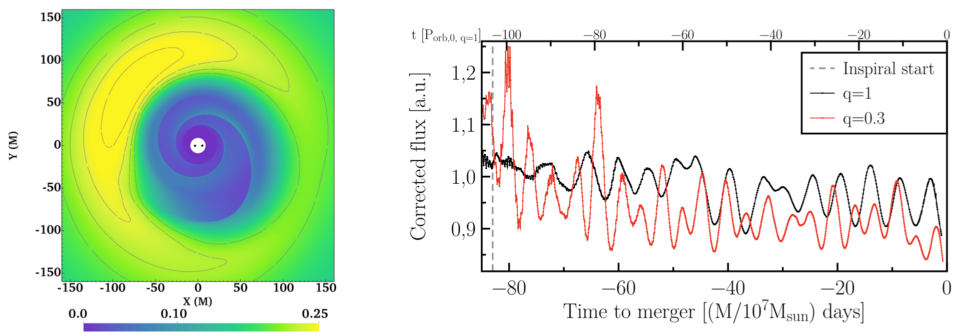

Figure 4: Left panel: surface density map in the inspiral case for $q = 1$, less than $0.1(M/10^6\,\mathrm{M}_\odot)$ day before merger. Right panel: lightcurves in the inspiral case for $q = 1$ and $q = 0.3$. The flux decreases gradually because of our limited-mass reservoir.

5 Conclusion

In the context of preparing multi-messenger missions (LISA, ATHENA, THESEUS...), we aim at predicting the X-ray variability of accreting, supermassive binary black holes. In the setup we considered, the lightcurve from the circumbinary disk thermal emission exhibits a UV/optical modulation at the orbital period of the overdense lump. Meanwhile, the individual disks are expected to emit in the soft X-ray band, of interest for the ATHENA and THESEUS missions, from theoretical arguments and up-to-date numerical simulations. As those disks progressively disappear close to coalescence, a drop in X-ray flux is predicted and could help us detecting those systems. If detected too late, the drop would not be captured however. We show that even close to merger – that is, after the circumbinary disk decouples from the binary –, the lump modulation of the circumbinary disk survives (still in UV/optical) and could provide the only remaining observable signature. This all highlights the need for multi-wavelength campaigns (e.g. with also the Rubin Observatory, and dedicated follow-up strategies) and the complementarity of the various signatures predicted by simulations.

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