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PREDICTING THE ELECTROMAGNETIC SIGNATURES OF PRE-MERGER BINARY BLACK HOLES

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Abstract. The many recent detections of gravitational waves (GWs) of binary black hole (BBHs) mergers, and the first detection of an EM counterpart to neutron star merger, have opened the way for future multi-messenger compaigns. One expected result, not achieved yet, is the detection of the electromagnetic (EM) counterpart to BBH merger, ideally in the pre-merger phase to ensure optimal follow-up. However, the pre-merger EM signal is not firmly identified because few numerical codes are able not only to model the gravitational impact of the BBH on its circumbinary disk but also to compute its observational consequences, in General Relativity (GR). In this proceeding, we use `e-NOVAs` ("extended Numerical Observatory for Violent Accreting systems") to compute the circumbinary disk evolution in GR-hydrodynamics in an analytical BBH metric, and to compute synthetic observations in the same metric via GR ray- tracing. We find the central region to be cleared of material by the BBH torques, thus forming a low-density cavity. As a consequence, the energy spectrum resembles that of a truncated disk. The circumbinary disk hosts several non-axisymmetries: spiral arms and an overdensity, the so-called 'lump'. They produce a two-timescale modulation of the EM lightcurve for non-face-on observers; this could be the smoking-gun for pre-merger BBHs.

Keywords: black hole physics, accretion discs, hydrodynamics, gravitational waves, multi-messenger astronomy

1 Introduction

While the gravitational wave (GW) detection associated with a neutron star merger (Abbott et al. 2017a) and the associated gamma-ray burst observation (Abbott et al. 2017b) have set the stage for a new era in multi-messenger astrophysics, the electromagnetic (EM) counterpart to binary black hole (BBH) pre- and post-merger remains undetected. A pre-merger detection would allow for optimal EM follow-up, and a subsequent GW-EM co-detection would be precious in many ways, for several branches of physics/astrophysics. It would allow us to test General Relativity (GR) in strong and dynamical spacetimes and to measure the speed of gravity by comparing the arrival time of GW and photons, thus testing GR. In the case of supermassive BBHs, systems evolving on longer timescales and more likely to offer opportunities for pre-merger EM detection, it would also benefit cosmology: measuring the host galaxies' redshift together with the GW luminosity distance could help relieving the Hubble tension (e.g. Piro et al. 2022).

Currently, stellar-mass BBH mergers are being detected by ground-based GW detectors (LIGO/Virgo/Kagra). The future Laser Interferometer Space Antena (LISA, Amaro-Seoane et al. 2017) and Pulsar Timing Arrays (PTA, e.g. Babak et al. 2016) are/will be sensitive to the low-frequency GWs produced during supermassive BBH mergers of total mass $M{\sim}10^{4-7}\mathrm{M}_{\odot}$ and $M > 10^{8}\mathrm{M}_{\odot}$, respectively. While a new generation of EM facilities is being under preparation (e.g. Athena in X-ray, THESEUS in IR/X-ray/gamma) or becoming available (Vera Rubin Observatory in optical), the EM signature of pre-merger BBHs to look for in the location box given by the GW signal for sufficiently slowly inspiralling systems remains elusive, and relies on theoretical predictions.

This problem has been addressed via numerical simulations of the circumbinary, gaseous environment around pre-merger BBHs, or more generally, binaries. Artymowicz & Lubow (1994) have shown that binary systems accreting from a circumbinary disk clear a central cavity of low-density gas, from which two accretion streams

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can feed the individual objects. As a consequence, several authors reported a deficit at high energy in the thermal SED of the circumbinary disks and mini-disks surrounding the individual objects (e.g. Roedig et al. 2014). Circumbinary disks are far from axisymmetric: they develop two spiral arms and their inner edge is the site of an orbiting overdensity dubbed ‘lump’ (Shi et al. 2012), whose origin is not fully understood yet although we found its appearance to be concomitant with the development of the Rossby Wave Instability (Mignon-Risse et al. 2023a). The observational appearance of circumbinary disks is rarely obtained from a (computationally- and memory-expensive) full GR treatment in the same BBH spacetime, and rather relies on approximations. Those include cooling/heating models to compute the luminosity (Farris et al. 2015), applying relativistic boosts analytically in post-processing rather than ray-tracing (Tang et al. 2018), or computing ray-tracing assuming that light travels faster than the fluid and the spacetime (D’Ascoli et al. 2018, Gutiérrez et al. 2022). Here we propose to fill this gap by studying circumbinary disks surrounding pre-merger BBHs in the full GR framework provided by `e-NOVAs`.

2 GRHD simulations of the circumbinary disk

In the first step of `e-NOVAs`, we follow the circumbinary disk evolution in 2D GRHD with the `GR-AMRVAC` code (Casse et al. 2017) incorporating an approximate, analytical BBH spacetime (Mignon-Risse et al. 2022). In this spacetime, we solve the equations of conservation of baryon density and momentum on a spherical grid, at the center of which the BBH is located (see Fig. 1). The circumbinary material is initially axisymmetric, close to gravito-centrifugal equilibrium (on an equivalent single BH of mass M). We use an adiabatic equation-of-state. Several setups are considered, varying the orbital separation, circular-orbit versus GW-driven inspiral, or mass ratio.

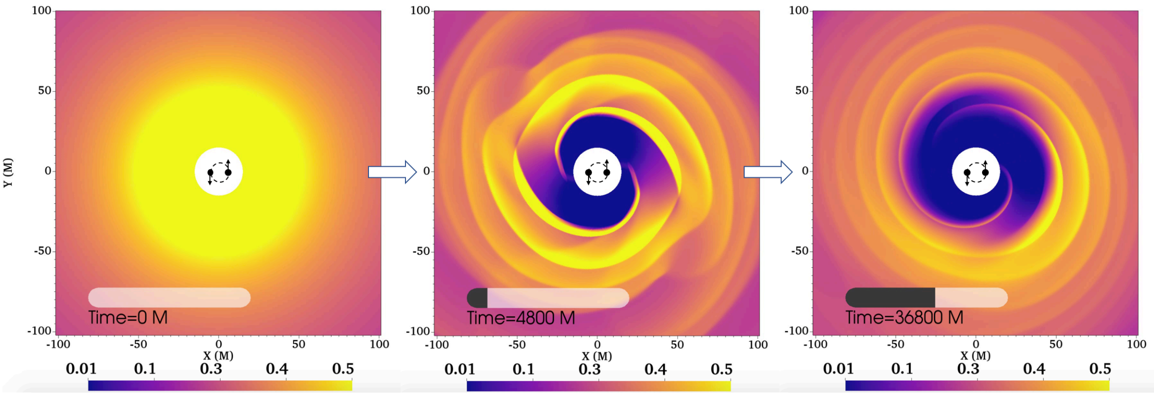

Fig. 1. Time sequence of the density (given in code units) in the mass ratio $q = 1$, circular-orbit, $b = 20\,\mathrm{r_g}$, case. The BBH is located within the inner boundary of the domain.

Figure 1 shows the time-evolution of the density in the circumbinary disk in the $q = 1$, circular-orbit, $b = 20\,\mathrm{r_g}$ case ($\mathrm{r_g}$ being defined with the total BBH mass M). This orbital separation value, if accounting for GW-driven inspiral, corresponds to a time-to-merger $\sim 1\,(M/10^6\mathrm{M_\odot})$ day. In less than one binary period, axisymmetry is broken. We recover accretion structures already reported in the literature: a low-density *cavity* of radius about twice the orbital separation, *accretion streams* crossing the cavity to feed the BBH, *spiral arms*, and after more than 50 binary orbits, an azimuthal $m = 1$ overdensity becomes visible: this is *the lump* feature, which orbits at the local Keplerian frequency $\Omega_{\rm lump}$, a fraction of the binary orbital frequency.

The accretion rate through the surface $r = 2$ b which roughly corresponds to the cavity surface is shown in the top-left panel of Fig. 2. It is modulated at twice the beat frequency between the mean orbital frequency of the lump $\bar{\Omega}_{\rm lump}$ and the orbital frequency of the binary $\Omega_{\rm orb}$, i.e. $2\,\Omega_{\rm beat} = 2\,(\Omega_{\rm orb} - \Omega_{\rm lump}) \approx 1.7\,\Omega_{\rm orb}$.

3 Electromagnetic counterparts

3.1 Variability

In order to investigate whether any of these accretion structures would translate into observable EM signatures of pre-merger BBHs, we post-process those simulations in `e-NOVAs` with the `GYOTO` code (Vincent et al. 2011) in the same BBH spacetime, assuming thermal emission. From this, we obtain multi-wavelength thermal emission maps (right panel of Fig. 2) and lightcurves (bottom-left panel of Fig. 2), here for an inclination angle 70° (0° being face-on). In order to make this lightcurve mass-independent, we have integrated the flux around the SED peak frequencies, then we normalized it to the averaged flux. The SED peak is typically located in the optical to UV bands; the peak frequency increases with the accretion rate normalized to the Eddington value, with the decreasing orbital separation (hence time-to-merger), with the decreasing BBH mass. The most prominent feature of the lightcurve is the modulation at the lump orbital period, on top of a second modulation, smaller in amplitude, at the binary semi-orbital period. It is amplified by relativistic beaming: a non-axisymmetric feature (azimuthal $m = 2$: spiral arms; or azimuthal $m = 1$: the lump) appears brighter as it approaches the observer and dimmer as it gets away from the observer (see e.g. Vincent et al. 2013). Since the lump is also responsible for the SED peak emission, the lightcurve modulation originates from the highest-energy part of the circumbinary disk spectrum only. These results apply qualitatively for q ranging between 0.1 and 1, $b = 20\,\mathrm{r_g}$ and $b = 36\,\mathrm{r_g}$.

Most notably, there is a mismatch between the accretion rate and lightcurve modulations, as visible in Fig. 2. Therefore, the accretion rate variability is not a good proxy for the EM variability. More details can be found in Mignon-Risse et al. (2023b).

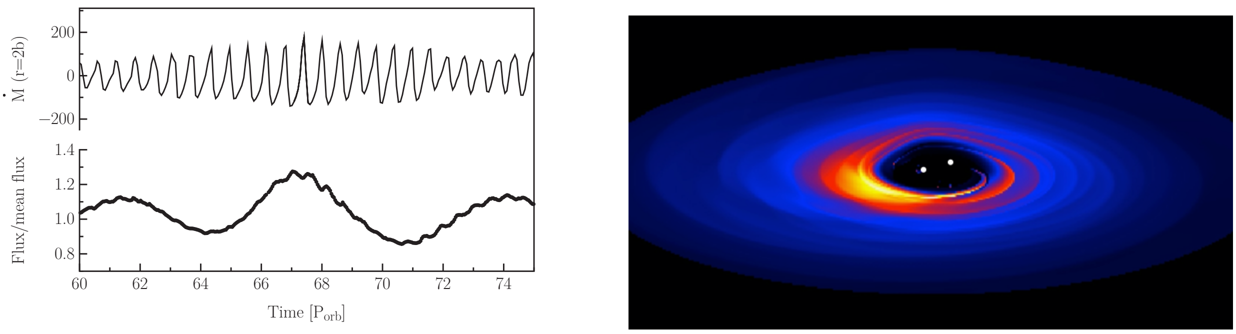

Fig. 2. Accretion rate through the surface $r = 2$ b (similar to that found at the domain inner boundary) and lightcurve (left panel); thermal emission map (right panel). Those are given for the simulation shown in Fig. 1, with an observer inclination angle of 70°.

3.2 Spectral energy distribution

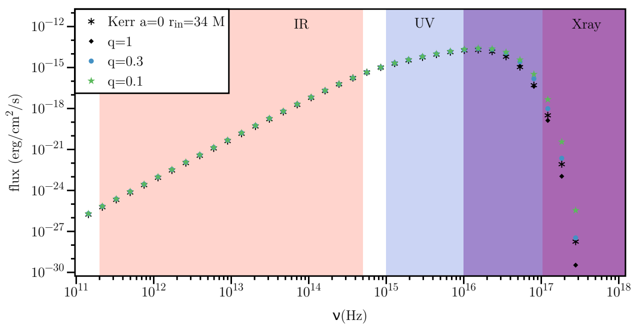

Fig. 3. Energy spectrum of: a circumbinary disk around a $10^5\,\mathrm{M_\odot}$ BBH with $q = [0.1, 0.3, 1]$ (here shown for a BBH inspiralling from $b = 15\,\mathrm{r_g}$ to $b = 8\,\mathrm{r_g}$) and a single $10^5\,\mathrm{M_\odot}$ BH disk of inner radius located at $34\,\mathrm{r_g}$.

Here we investigate the observational impact of the cavity, that is the lack of emitting material in the central region of the circumbinary disk. The energy spectrum of a circumbinary disk around a $10^5\,\mathrm{M_\odot}$ is shown in Fig. 3 for q varying between 0.1 and 1. Interestingly, the spectrum is hardly distinguishable between different values of q, and with a single BH disk whose edge would be set at 34 M, which roughly corresponds to twice the initial separation $b = 15\,\mathrm{r_g}$, i.e. the approximate cavity radius. Thus, compared to a single BH (of mass equal to the total BBH mass) disk that would reach the innermost stable circular orbit (ISCO), located at a few r_g (depending on the BH spin), the spectrum appears as that of a truncated disk. This has been often referred to as a 'notch' between the circumbinary disk spectrum and the mini-disk spectrum when accounted for (e.g. Shi & Krolik 2016), that the streams do not compensate. In other words: a single BH source whose disk inner radius – as given from spectrum fitting – is away from the ISCO, could actually be a BBH. More details can be found in Mignon-Risse et al. (2022).

4 Conclusions

In this proceeding, we reported recent efforts to predict the EM signatures of circumbinary disks around pre-merger BBHs. To do so, we have computed the fluid evolution and emission in a full GR framework provided by the numerical observatory `e-NOVAs`, incorporating an approximate BBH spacetime. We have recovered the main accretion structures already reported in the literature: *a low-density cavity, accretion streams, spiral arms*, and the orbiting overdensity, *the lump* feature. In thermal emission, we found the circumbinary disk lightcurve to be dominated by the orbiting spiral arms and lump emission, thus producing a two-timescale modulation. This modulation is observer-dependent and cannot be obtained via scalar arguments (still valid for face-on views) assuming a one-to-one correspondance between the accretion rate variability and the EM variability. Meanwhile, as a consequence of the cavity, the spectrum is similar to that of a truncated disk around a single BH (of mass equal to the total BBH mass). Thus, the energy spectrum of a single BH disk whose inner edge would be away from the ISCO is hardly distinguishable from a BBH circumbinary disk spectrum. To allow for such a comparison, an accurate BBH mass measurement from GW signal and/or EM observations is required.

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