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GRAVITATIONAL WAVES OR ELECTROMAGNETIC COUNTERPART? NO NEED TO CHOOSE

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Abstract. Theoretical investigations on potential electromagnetic (EM) counterparts to gravitational waves (GW) detection generally consist in looking for EM signals emitted by the GW-emitting system, e.g. short gamma-ray bursts produced by neutron star mergers. Here, we take a different and original approach: we study whether the GWs themselves, while propagating through the accretion environment around the GW-emitting system, could leave an observable imprint. We perform this study with eNOVAs, the extension of our Numerical Observatory to dynamical spacetimes, in which we implement an approximate binary black hole (BBH) spacetime accounting for GW propagation. After showing that the GWs leave a weak but non-axisymmetric imprint onto the BBH circumbinary disk, we find the system's lightcurve to be modulated at the semi-orbital period. As expected, the amplitude of the modulation is small (<1%), larger for highly-inclined systems, regardless of the BBH mass, but is fundamentally different from the lightcurve produced by an axisymmetric disk around a single BH.

Keywords: gravitational waves, accretion, black holes

1 Introduction

The search for electromagnetic (EM) counterparts to gravitational wave (GW) detection is motivated by the additional science that a joint observation can achieve, e.g. the measurements of the speed of gravity. In the pre-merger phase of binary black holes (BBHs), it can allow us to follow the accretion flow in a dynamical spacetime, which is not possible with X-ray binaries (for which the spacetime is Kerr's spacetime) and may provide new tests for general relativity, down to the possible birth of a new active galactic nucleus. Such observations would be crucial for our understanding of galaxy evolution because it is tightly linked to the central supermassive black hole feedback. The detection of binary black hole systems relies on theoretical EM signatures, to be looked for with EM facilities and distinguished from other sources (typically single accreting BHs but also any transient source in the sky). Those predictions are often obtained numerically (e.g. Gutiérrez et al. 2021), due to the complexity of the system to be modelled - plasma dynamics in a magnetized, radiative environment and strong gravity -, which is even more complex than for single black holes due to the dynamical spacetime around BBHs. Such studies focused on the inner parts of the accretion flow: the innermost region of the circumbinary disk (see e.g. Mignon-Risse et al. 2022c) and the possible individual disks feeding the two BHs. In the present study, we take a complementary approach and look at the outermost regions of the circumbinary disk, beyond a gravitational wavelength.

In that view, we extended the Numerical Observatory for Violent Accreting systems, `NOVAs`, made of the general-relativistic (GR) magneto-hydrodynamical code `GR-AMRVAC` (Casse et al. 2017) and of the GR ray-tracing code `GYOTO` (General relativitY Orbit Tracer of the Observatoire de Paris, Vincent et al. 2011), to dynamical spacetimes. We dubbed it `eNOVAs`, and it is the first European pipeline made of GRMHD simulations and GR ray-tracing in a *dynamical spacetime*, second worldwide (after `HARM-3D` post-processed with `BOTHROS` in the US, d'Ascoli et al. 2018, Gutiérrez et al. 2021). As a first application of `eNOVAs`, we investigate the influence of outgoing GWs emitted by inspiralling BBHs on the system's circumbinary disk and the potential EM signature

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associated to such phenomena. GWs are taken into account thanks to an analytical, approximate BBH spacetime construction valid down to a given orbital separation (see below).

In the following, we use the practical system of geometrical units where G = c = 1, so distances and time scales are given in units of the total binary mass M.

2 Imprint of GWs on the circumbinary disk

In order to study the propagation of GWs and how they impact the circumbinary disk around an inspiralling, spinning binary black hole (BBH), we implemented an analytical, approximate BBH spacetime (Ireland et al. 2016) into the general-relativistic magneto-hydrodynamical code `GR-AMRVAC`, once we generalized it to any spacetime (e.g. non-stationary, non-axisymmetric, non-diagonal spatial metric, unlike the Kerr metric in Boyer-Lindquist coordinates; more details in Mignon-Risse et al. 2022b). This analytical spactime is composed of several zones, depending on the distance to the BBH. In this study, we focus on the so-called "Far Zone", located further away than a gravitational wavelength from the BBH. The spacetime in the Far Zone is that of Minkowski perturbed by outgoing GWs emitted by the inspiralling BBH: the purpose of this work.

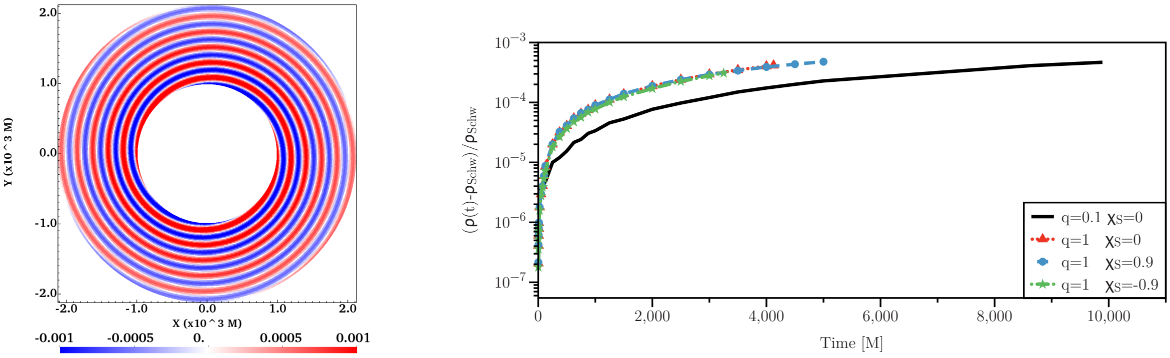

Fig. 1. Left: Density deviation $(\rho(t) - \rho_{\rm Schw})/\rho_{\rm Schw}$ at the end of the simulation, where $\rho_{\rm Schw}$ is the density in the Schwarzschild, single BH, case. **Right:** Temporal evolution of $(\rho(t) - \rho_{\rm Schw})/\rho_{\rm Schw}$ for various runs, varying the mass ration and the BH spin. The deviation is nearly spin-independent, but is affected by the mass ratio.

Our simulations are performed on a 2D cylindrical grid in the disk plane, with the BBH being located at the center (e.g. outside of the grid). Those are initialized with an axisymmetric, circumbinary disk density structure which mainly follows a decreasing power-law profile in the radial direction. This disk is set to be at equilibrium if it was around a single, hence non-GW emitting, BH, whose mass is equal to the total binary mass. The grid goes from 18.75 M to 5000 M in the radial direction but we focus our study on the region beyond 1000 M as we are interested in the zone impacted by GWs. The spatial resolution allows us to have more than 20 cell per gravitational wavelength. We follow the inspiral motion of the BBH from an orbital separation of 15 M to about 8M, below which the approximate spacetime construction is no longer valid. This corresponds to a time-to-merger of a few days for a $10^7 {\rm M}_\odot$ BBH and this time is proportional to the total binary mass. Several values of BBH parameters are covered: for the spinless case, we vary the mass ratio q between 0.1 and 1. In the equal-mass ratio case ($q = 1$) we vary the symmetric spin parameter $\chi_{\rm S}$ between -0.9 and 0.9.

Left panel of Fig. 1 shows how the density at the end of the simulation deviates from the density distribution around a Schwarzschild, single BH (which also corresponds to the initial density distribution), expressed as $(\rho(t) - \rho_{\rm Schw})/\rho_{\rm Schw}$, in the equal-mass case ($q = 1$), spinless case. As expected from the GWs being small perturbations of spacetime, the density deviation is small, of the order of 0.1%. The deviation takes the form of a spiral whose wavelength is the BBH gravitational wavelength $\lambda{\sim}\pi\sqrt{r_{12}^3/M}$, where r_{12} is the orbital separation. The temporal evolution of $(\rho(t) - \rho_{\rm Schw})/\rho_{\rm Schw}$ is shown in the right panel of Fig. 1 for various mass ratios and spin parameters. This quantity increases with time, as a progressive response of the disk to the metric not being that of a single BH but that of a BBH. The density deviation is stronger for a higher mass ratio. It is, however, found to be nearly independent of the spin parameter. Interestingly, because the inspiral does not occur at the same speed for each of these cases, the effect induced by GWs is integrated for shorter or longer times (recall that we do not cover a given time period but a given portion of the inspiral trajectory).

In the end, the $q = 0.1$ simulation is integrated about twice longer than the $q = 1$ (spinless) simulation, and $(\rho(t) - \rho_{\rm Schw})/\rho_{\rm Schw}$ reaches a comparable value.

Overall, we showed that GWs propagating through the circumbinary disk of an inspiralling BBH affects the density distribution in a non-axisymmetric manner. The influence is the largest for the equal-mass ratio of any spin value.

3 Is this imprint observable?

In the previous section, we showed that the GWs passing through the BBH circumbinary disk leave a weak but non-axisymmetric imprint in the disk density distribution. Here, we investigate whether this imprint translates into observable features distinct from single BH sources. Indeed, spiral structures in disks have been found to cause a modulation of the lightcurve, with a greater impact at high inclination (e.g. Varniere & Vincent 2016). Hence, we post-process the aforementioned simulations with `GYOTO` in the same BBH metric. This is the first time `GYOTO` is used in a dynamical spacetime.

We assume the EM radiation to be fully due to thermal emission. Using `GYOTO` we compute the energy spectrum and lightcurve of this circumbinary disk*. First of all, the energy spectrum (not shown here) is too weakly affected to be distinguishable from a disk around a single BH whose innermost radius would be set at the same location as the circumbinary disk innermost radius. On the other hand, the lightcurve, normalized by the mean flux value, is displayed in the left panel of Fig. 2, for inclination angles 20 deg and 70 deg, where 0 deg corresponds to the face-on inclination. A modulation of the flux is visible at the semi-orbital period (≈200 M). The amplitude of the modulation, as expected from the impact on the density distribution (Fig. 1), is weak (<1%). The right panel of Fig. 2 shows how the lightcurve varies with the mass ratio, at a fixed inclination (here 60 deg, an intermediate value sufficient to observe the modulation). We find that the modulation period and amplitude are very weakly affected by the mass ratio (and by the spins, not shown here for conciseness, but see Mignon-Risse et al. 2022a). This suggests that the lightcurve modulation is linked to the existence of the spiral.

Because the flux has been normalized to its mean value, this lightcurve is independent of the BBH mass and distance. Changing the BBH mass would require to scale the disk temperature, shifting it to higher value for a smaller BH mass (see e.g. Alston et al. 2022). Consequently, the energy spectrum would peak at lower energies; for BH mass values from solar-mass to supermassive (up to 10^{10}M$_\odot$), the peak progressively shifts from the soft X-ray to the UV band.

Overall, we report a weak observable imprint from the propagation of GWs through the GW-emitting BBH system's circumbinary disk: its takes the form of a small amplitude (<1%) modulation at the semi-orbital period.

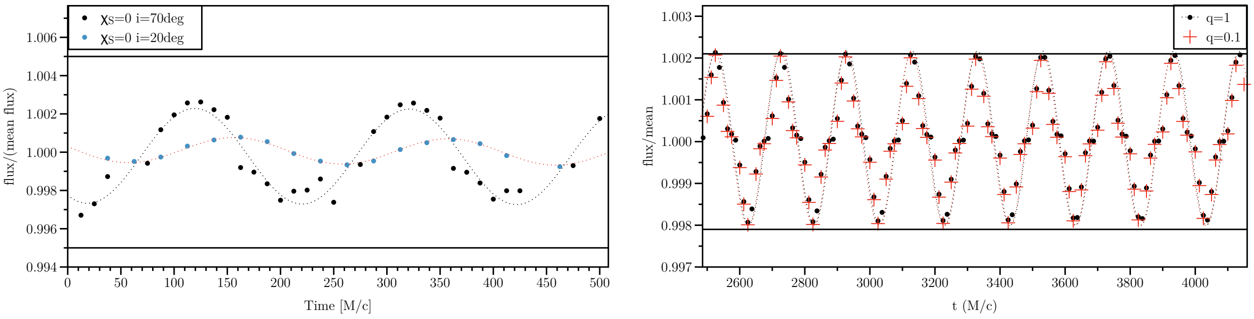

Fig. 2. Left: Lightcurve normalized to the mean flux (hence independent of the binary mass), computed in the equal-mass case and for two source inclinations: 20 deg and 70 deg (0 deg being face-on). A modulation at the semi-orbital period (≈ 200 M) is visible. Its amplitude is larger at higher inclination. **Right**: Similar lightcurve but for mass ratios 0.1 and 1, at inclination 60 deg. The amplitude and periods of the modulation are similar.

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*For computing the energy spectrum and having an idea about the whole emission produced by the disk, we took into account the entire disk, not just the region beyond 1000 M.

4 Conclusions

In this paper, we have investigated the impact of gravitational waves emitted by inspiralling binary black holes (BBH) on the system's circumbinary disk. To do so, we used `eNOVAs`, our Numerical Observatory now generalized to dynamical spacetimes. The effect of GWs was taken into account via an approximate, analytical spacetime of BBHs. We initialized our 2D general-relativistic hydrodynamical `GR-AMRVAC` simulations with an axisymmetric disk which would be at equilibrium around a single BH. We followed the disk evolution on a portion of the BBH inspiral trajectory (about a factor of two in orbital separation).

We found that the circumbinary disk density distribution deviates from its initial value - which is the equilibrium value for a disk around a single BH. This deviation takes the form of a spiral whose wavelength is the BBH gravitational wavelength. The deviation increases with time but is small at the end of the simulations (about 0.1%). In addition, it is nearly independent of the BBH spin but larger for a mass ratio closer to 1.

In order to see whether this non-axisymmetric imprint would be observable from an observed located at infinity, we post-processed those simulations with the general-relativistic ray-tracing code `GYOTO` in the same BBH metric. The energy spectrum is not distinguishable between the different cases (single BH, BBH of various spins and mass ratio), but the lightcurve is affected by the spiral. Indeed, the lightcurve is modulated at the semi-orbital period and the amplitude of the modulation is slightly smaller than 1%, which corresponds to the lowest amplitude quasi-periodic oscillations ever detected in low-mass X-ray binaries (Remillard et al. 2002). While weakly modulated, the lightcurve is intrinsically different from that of an axisymmetric disk around a single BH.

This work presents a potential source of electromagnetic counterpart in the pre-merger phase of BBHs. The amplitude of the time feature we report in the lightcurve is independent of the total BBH mass, while its period is the semi-orbital period of the BBH. Hence, these findings are of current interest for EM counterpart search associated to the LIGO-Virgo-Kagra for stellar-mass BBHs GW detection but also for future studies associated to LISA for supermassive BBHs.

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