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HOW TO DISTINGUISH BINARY VARIABILITY FROM SINGLE BLACK HOLE

P. Varniere[3,1], R. Mignon-Risse[3,2] and F. Casse[3]

Abstract. Since the first detection of gravitational wave signals from binary black holes (BBHs), the hunt for their pre and post-merger electromagnetic counterparts has started. In particular, numerical simulations have been looking for a signal unique to BBHs, their 'smoking gun', that could help identify pre-merger systems with certainty. With several characteristic signals already put forward, we now concentrate on their uniqueness. This is especially important as a disk instability has been proposed to explain the strong timing feature associated with pre-merger binary black holes Here we will use general-relativistic hydrodynamical and ray-tracing simulations to compute the observables associated with BBH systems and see in which cases they could be distinguished from more standard black-hole variability such as quasi-periodic oscillations (QPOs). In particular, we will continue with a model-dependent approach for the QPOs to see if a better knowledge of QPOs would offer some distinction from a typical pre-merger BBH lightcurve.

Keywords: binary black hole

1 Introduction

Since the first detection of gravitational wave (GW, Abbott et al. 2017) signals from binary compact objects, observers have been on the hunt for binary black hole (BBH) pre and post-merger electromagnetic counterparts which would give us a new insight into the effect of their strong and fast evolving gravity on accretion-ejection structures. This kind of study is made difficult with the lack of 'early warning' with existing ground detectors (LIGO, Virgo, Kagra) or, in the future, the large detection box of space-based telescopes (LISA). Hence the need to better constraint BBHs observables in order to identify candidates even before their GW detection.
This is where general-relativistic fluid simulations of pre-merger BBH come into play to predict what those systems look like. The most studied case involves a circumbinary disk, which often exhibits a 'lump' at its edge and a two-arms spiral, with a cavity in which two streams are feeding each black hole (MacFadyen & Milosavljević 2008; Shi et al. 2012; Noble et al. 2012; D'Orazio et al. 2013; Gold et al. 2014; Shi & Krolik 2015; Armengol et al. 2021; Tiede et al. 2021; Liu 2021). Some intermittent accretion structures form around each black hole if their separation is sufficiently large.

In this paper we want to explore the observables coming from the circumbinary disk, especially the presence of this 'lump' and its associated timing variability. In particular we want to see how easy it would be to reproduce them with a single black-hole system and if there are ways to distinguish them.

2 Reproducing circumbinary disk observable with a single black-hole system

2.1 Circumbinary disk observables

Thanks to numerical fluid simulations (see e.g. the code comparison by Duffell et al. 2024) we have a good picture of the key features of circumbinary disks and how they could translate into observables.

[1] Université Paris-Saclay, Université Paris Cité, CEA, CNRS, AIM, 91191, Gif-sur-Yvette, France
[2] Department of Physics, Norwegian University of Science and Technology, NO-7491 Trondheim, Norway
[3] Université Paris Cité, CNRS, Astroparticule et Cosmologie, F-75013 Paris, France

One of the most promising feature to date is the strong periodic modulation expected from the 'lump' orbiting at the edge of the circumbinary disk and the smaller one comparable to the orbital period of the binary. Another interesting aspect is that the flux modulation is not constant all over the electromagnetic spectrum but involves a pivoting of the higher energy emission of the circumbinary disk coming from the orbiting 'lump'.

2.2 *Fitting the circumbinary disk with a simpler system*

While a circumbinary disk is essentially a disk far from its last stable orbit and should therefore be easily fitted by a disk around a single black-hole (SBH) system with the same mass, it is still important to see if the presence of structures and the fact that the photons are propagating through a binary black-hole metric instead of a SBH metric has a detectable impact on the overall spectrum.

The left of Fig.1 shows how the spectra of the highly structured circumbinary disk can be fitted by a simple, axisymmetric, disk orbiting a non-spinning SBH if the inner edge of that disk is at a similar distance from the SBH than the circumbinary disk is from the center of mass of the binary (which is about twice the binary separation in the stage studied here).
One problem with that fit is the need to explain the truncation, and slight movement, of the inner edge of the disk around that SBH. Although, such moving truncated disks are seen in microquasars with regularity (Remillard & McClintock 2006) and a similar mechanism could be inferred for a SMBH.
A way to lift that requirement is to impose that the inner edge of the fitted disk be at its last stable orbit, which translates into a mass for the SBH of: $\mathrm{M_{SBH}} = \left(r_{\mathrm{in}}^{\mathrm{BBH}}/r_{\mathrm{g}}^{\mathrm{BBH}}\right)^{3/2}\left(r_{\mathrm{g}}^{\mathrm{SBH}}/r_{\mathrm{LSO}}^{\mathrm{SBH}}\right)^{3/2}\mathrm{M_{BBH}}$, with each radius given in their respective gravitational radius $r_g = GM/c^2$. The resulting fit gives a similar SED as shown on the left of Fig.1 but with masses of a few $10\,\mathrm{M_{BBH}}$ which might be incompatible with existing constraints on the mass of that source.
In the absence of an independent mass measurement for the system, we might still be able to refute that case as we need a different mass at different times of observation which might lead to tension in the fit. For example, in the case of a separation of $20\,r_{\mathrm{g}}$ presented here, this leads to a small variation comprised within $15.5 \pm 1.5\ \mathrm{M_{BBH}}$ but it would be larger for wider binaries, hence increasing potential fit tension until we obtain an independent mass measurement which would disagree with the mass needed by this SBH model.

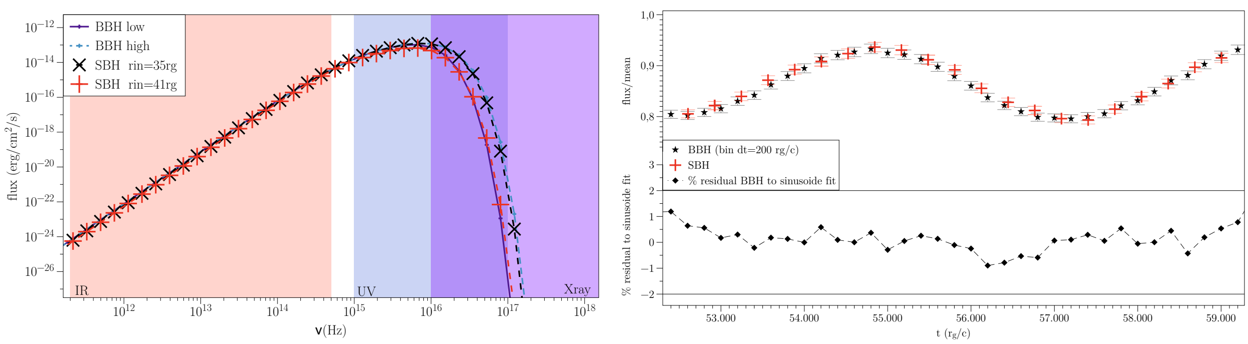

Fig. 1. Left: Fit of the BBH SED, at its low and high variability extrema, by a moving truncated disk around a SBH. **Right:** top: comparison between the BBH pulse profile and the one coming from a disk instability around a SBH. bottom: residual from the fit of the BBH pulse profile with a sinusoid.

Another observable, which has gain a lot of traction in the recent years, is the strong variability coming from the orbiting lump at the edge of the circumbinary disk. As we recently proposed a disk instability as the origin of the lump(Mignon-Risse et al. 2023), it is necessary to compare the pulse profile of the 'lump' variability with the one coming from the same instability at the edge of a SBH disk in order to see if they can be distinguished. On the top right of Fig. 1 we see that it will not be feasible, based purely on the LC at that time resolution, to differentiate between a disk instability and the 'lump' variability. Similarly, the bottom right of Fig. 1 shows the residual from a sinusoidal, hence model independent, fit of the LC. Not only it is a good fit, but there is no structure in the residual hinting at the need of a more complex model.

This means, that while the presence of the 'lump' variability is required, it can easily be explained/fitted without needing a BBH, hence it cannot be used to firmly identified BBH systems.

3 Timing variability and QPOs.

While neither the SED nor the LC gives us a firm constraint on the binarity of the central object(s), we now turn to the unique aspect linked with a BBH, namely its binary orbital period. We recently showed that, depending on the mass ratio, the LC has a secondary, smaller in amplitude, modulation that is either the (semi-)binary period or the beat between the binary period and the lump. The left of Fig. 2 shows how this second modulation can become visible if we have 1) a good time resolution and 2) a good signal-to-noise ratio (SNR) as this modulation has an amplitude of about 1%.
This could become a way to test BBH candidates by searching for this second period by either folding data lacking the SNR at the lump frequency to see if any substructures are visible or directly if the frequency is such that we can follow it with a high enough precision during one observation.

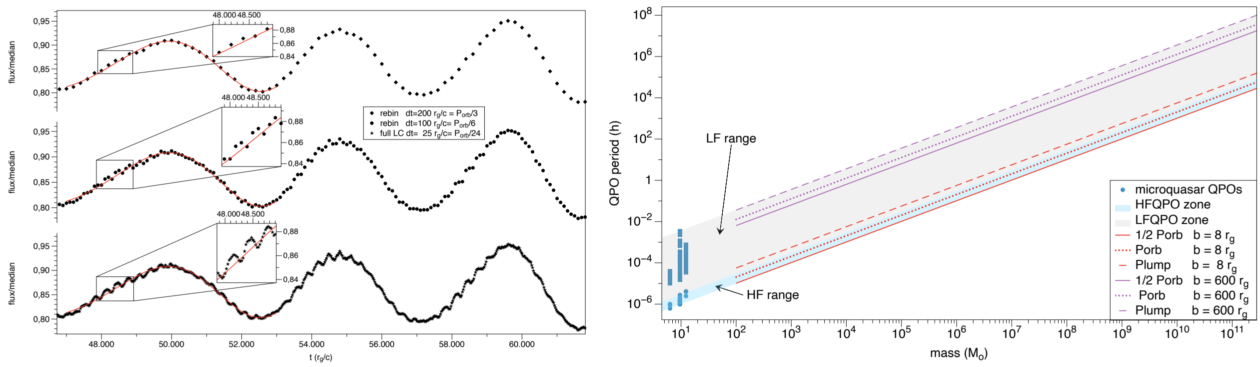

Fig. 2. Left: BBH lightcurve at different time bins showing the presence of the secondary modulation related to the binary period. **Right:** Extension of observed LMXB QPOs to higher mass systems. We also plot what would be the binary parameters for the BBH variability to be in that range.

While finding both of those frequencies in the lightcurve of a BBH candidate would be a great step toward identification, we now face another problem as the existence of a shorter, weaker modulation on top of a strong one is not unique to BBHs. Indeed, those are a common feature of the variability of Low-Mass X-ray Binaries (LMXB) harbouring a BH and are dubbed Quasi-Periodic Oscilations. As most of the models for those QPOs scale with the BH mass, we show, with the shaded area, on the right of Fig. 2 which domain of timescales would the scatter of observed LMXB QPOs (for microquasars GRS 1915+105, XTE J1550-564 and GRO J1655-40) be for SMBH systems. We also plot the evolution of the lump and binary period as function of the BBH mass for two extreme separations, showing how any realistic circumbinary disk features would fall into the potential extension of LMXB QPOs to higher BH masses.

4 How to go beyond

The only way to lift the degeneracy between the extension of QPOs and the BBH circumbinary disk features requires to improve our understanding of QPOs in order to ascertain their origin and rate of occurrences in SMBHs. Indeed, if, through QPO-model-dependent methods, we can prove that:

- either the system, if a single black-hole, would not be prone to QPOs
- or if the parameters inferred from the QPO model for the disk would make it in contradiction with the SED

then we can rule out QPOs as a source for that double variability, hence leaving us with a BBH system as the only valid solution.
While the first option could be done by comparing with similar systems purely observationally, the second option can only be done by using QPO models whose result might be refuted by using other QPO models. A first step here might be to check a few QPO models to explore the viability of the inferred ‘single system’, especially against the energy spectrum and other observables, such as the presence of jets/wind, having known association with QPOs in LMXB.

For example, if one wants to explain the double variability of the left of Fig.2 with QPO models such as the one based on the Accretion-Ejection Instability (AEI) and the Rossby-Wave Instability (RWI) (for an example

of the co-existence of those instability in one disk, see Varniere et al. 2011) then it gives constraint on the position of the inner edge of the disk and the mass of the BH which would then be incompatible with the energy spectrum of the source.
All in all, we need to have a better understanding of quasi-periodic variability in SMBHs if we want to use the BBH variability as a key to find them.

5 Conclusions

In this paper we showed how easily the spectrum and temporal variability of the circumbinary disk of a BBH can be fitted with the much simpler system of a single black hole and its disk. Some of the ways to reproduce the BBH observables involve either having the same black-hole mass with a disk truncated away from its last stable orbit as is observed in some LMXB or by changing the mass of the single black-hole to have the disk at its last stable orbit.

This highlights the need for a good, independent, mass estimate for all of the sources showing the kind of variability presented here if we want to assess the presence of a binary. Though, ultimately, we need to improve our understanding of QPOs in SMBHs as the only way to distinguish them from the circumbinary disk variability will be QPO-model-dependent.
As an example of this, we presented one set of QPO models, first studied in LMXB but that were proven compatible with the disk of SMBHs (Varniere 2023), that would allow to distinguish between QPOs in a SBH system and the variability of a BBH circumbinary disk. Using those QPO models could be an added test of BBH candidates, especially when based on their variability.

Data Availability

The data that support the findings of this study are available from the corresponding author, P.V., on request and will also be part of a data release in 2024*.

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*Which will be available for download at `https://apc.u-paris.fr/~pvarni/eNOVAs/LCspec.html`