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ACCRETION DISK FLUX MODULATION: NEWTONIAN VERSUS GR EFFECTS.

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Abstract. Compact objects are prone to the most extreme gravity fields and it is generally accepted that the motion of plasma in their close neighborhood is only properly described in the framework of general relativistic magnetohydrodynamics (GR-MHD). Nevertheless, a lot of the models trying to explain the origin of the fast flux modulation observed in X-rays do not take into account the full GR. Using a simple analytical model for non-axisymmetric structure in a thin disk we compute the observed flux and compare the results obtained in the Newtonian case with a full GR account of a Schwarschild black hole. This allows us to see that, while the purely newtonian approach does give a modulation and was enough of a proof of principle, we are missing several aspects.

Keywords: black hole, GR

1 Introduction

Accreting black holes exhibit variabilities on a wide range of timescales spanning from years down to milliseconds. While the change in the accretion rate probably causes the variability on timescales longer than days (Lasota 2001), the cause for behavior happening from the tens of seconds to milliseconds is likely rooted in some instabilities in the inner part of the accretion disk itself (Remillard *et al.* 2002). The disk in those systems is not resolved, therefore its structure cannot be directly imaged. A long standing question is how any unresolved structure in those disks can give rise to a detectable modulation of the observed flux. An early attempt (Varniere & Blackman 2005) showed a proof of principle in the newtonian case. But those objects are subject to strong gravity and ultimately we ask the question of the impact of full general relativity (GR) and, more importantly for observation, in which cases is it required to use full GR to study this modulation. Indeed, some of the lower frequencies would be associated with structures orbiting far enough in the disk for GR effects to be negligible. We will map out different cases to see when that is actually the case and what could be the observational signature of the change from non-GR to GR.

1.1 Parametrizing non-axisymmetric structures in accretion disk

Rather than taking full MHD simulations of spiral-inducing instabilities in the different conditions we wish to explore, we decided to create a simple, analytical, model for the non-axisymmetric structure in order to test more cleanly the different parameters. Indeed, in a full simulation changing one parameter in the initial condition can have repercussions on several parameters and therefore it is harder to study the different effects separately.

Here we are trying to minimize the number of parameters to characterize non-axisymmetric structures in the disk. In that respect, we add to the disk axisymmetric thickness $h_o(r)$ a component that depends on the azimuthal angle and position $h_1(r, \vartheta) = d(r).s(r - r_s, \vartheta)$. We choose to decompose this additional component as a height function d that depends only on r and a shape function s which is finite only near the disc structure causing the non-axisymmetry. For simplicity we take the shape function to be gaussian and the thickness function to be a power-law of r-only and related to the equilibrium thickness $h_o(r)$. This provides a simple but useful framework to model non-axisymmetric structures.

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We modeled the non-axisymmetric structure by a spiral localized at $r_s = r_c e^{\alpha\vartheta}$ with r_c the position where the structure begins and α its opening angle.

$$h(r,\vartheta) = h_o(r) \cdot \left(1 + \gamma \left(\frac{r_c}{r}\right)^{\beta} \cdot e^{-0.5\left(\frac{r-r_s}{\delta}\right)^2}\right) \tag{1.1}$$

β measures how fast the thickness decreases from the maximum, δ parametrizes the radial extent of the structure, while γ relates to the unperturbed thickness of the disk. From that we simply compute the temperature assuming hydrostatic equilibrium.

In the cases presented here most of the above parameters are fixed in order to focus on the difference between newtonian and GR cases in function of a few key parameters. We take a thin disk with an unperturbed aspect-ratio of 10^{-2}, the spiral is taken to have a corotation radius $r_c = 2r_{in}$ where r_{in} is the position of the inner edge of the disk and an opening of $\alpha = 0.15$. This was taken so that we can easily distinguish the spiral from the unperturbed disk. For the same reason we have $\gamma = 2$, $\delta = 0.05$ and $\beta = 1$ which gives a rather large spiral on the disk. Using these rather extreme parameters we are not trying to reproduce *realistic* observations but rather have a strong signal on which we can see the GR effect clearly.

It was shown in Varniere & Blackman (2005) that spirals could be at the origin of the flux modulation even when they are unresolved. To go beyond that we look at the exact origin of the modulation. It appears that the key component to the modulation is due to the velocity in the disk, indeed special relativity cannot be neglected in the inner region of those accretion disks, which causes a sufficient time delay between the impact time of the geodesics that reach the observer.

1.2 the GYOTO code

In order to simulate the observed light-curve, we use the open-source general relativistic ray-tracing code GYOTO (Vincent *et al.* 2011). We assume the spiral to be at rest in a reference frame corotating with the disk at the Keplerian velocity at radius r_c. Null geodesics are integrated backward in time from a distant observer to the disk. When the disk is hit, the outgoing flux is assumed to follow the blackbody law at the local temperature. Two kinds of ray-tracing have been performed. The first kind (*Schwarzschild* or *full-GR* case in the following) takes into account the Schwarzschild metric, thus all special and general relativistic effects for a non-rotating black hole. The second kind (*Newtonian* in the following) assumes straight geodesics, without any special or general relativistic effects. Unless otherwise stated, the inclination angle is taken to be 45° which is a very intermediate value. Our goal is to determine in what cases the Newtonian integration gives a similar result with the full-GR case and what are the main differences.

2 Case of a non-axisymmetrical structure at $10r_{LSO}$

To start we take a disk relatively far from the last stable orbit with an inner radius at $r_{in} = 5r_{LSO}$ while the non-axisymmetrical structure starts at $r_c = 10r_{LSO}$.

Fig. 1. shows the light curve for both the Newtonian (in black) and Schwarschild (in red) cases. The flux normalization is the same for all the plots and is associated to the case where the disk is at the last stable orbit, namely the maximum emission. Indeed, as the disk gets further away from the last stable orbit its temperature and therefore its total emission decreases. As the structure gets further away from the last stable orbit, it is expected that GR will become negligible and a newtonian calculation will be enough to get an accurate measurement. What we see here is, that for a spiral corotation located at $10r_{LSO}$, GR effects are not negligible when looking at the total flux modulation. The base effect is a special relativity effect but, not only the GR add to the time delay, we also have the beaming effect becoming important.

3 Case of a non-axisymmetrical structure at $2r_{LSO}$

In Fig. 2 we now look at a "strong gravity" case, where the inner edge of the disk is located at the last stable orbit and the non-axisymmetrical structure starts at twice that distance, we obtain, as before, a stronger modulation in the GR case but we also see that the light curves are not in phase anymore.

It will be interesting to see if such shift in the phase could be detected as the inner edge of the disk moves closer to the last stable orbit. It could lead to a new explanation for some of the unusual time-lag in

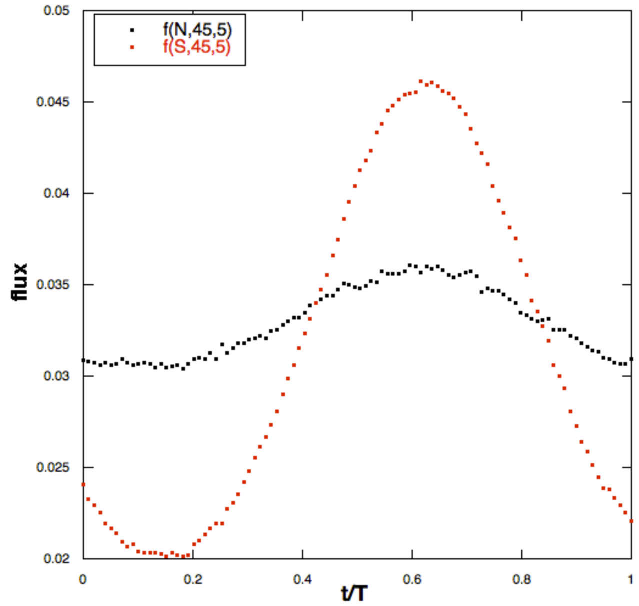

Fig. 1. Comparison of the light curve obtained when looking at 45° and the inner edge of the disk is at $5r_{LSO}$. N stands for Newtonian and S for Schwarschild.

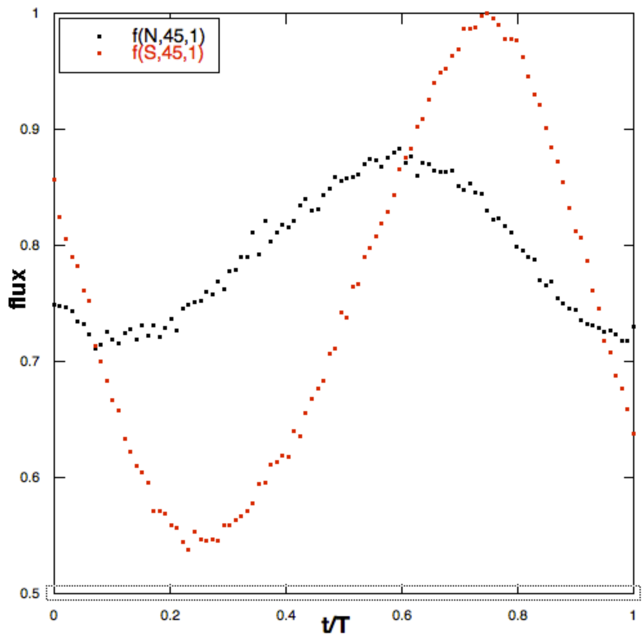

Fig. 2. Comparison of the light curve obtained when the inner edge of the disk is at r_{LSO}.

microquasars, especially as this effect will probably be amplified when taking into account the spin of the black hole.

4 Preliminary report on what impacts the rms amplitude

From the purely observational point of view we are interested by what could impact the rms amplitude of the modulation. Using our simple model we already see two parameters, that we have access to through observations, have important consequences on the rms amplitude of the same disk structure.

4.1 Impact of the inner edge of the disk

If we now compare the normalized flux we get in the case of a Schwarschild black-hole depending on where the inner edge of the disk is, we see in Fig. 3 that, while the total flux is higher the closer we get to the last stable orbit, the relative importance of the spiral increases with distance. This gives the modulation a stronger rms amplitude when the disk is further away. It will be interesting to compare the evolution of the maximum rms amplitude as function of the inner edge of the disk with observations.

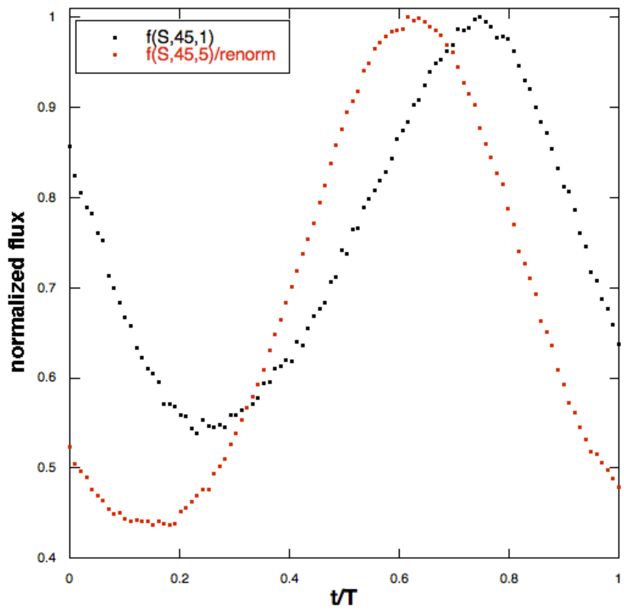

Fig. 3. Comparison of the light curve obtained when the inner edge of the disk is at r_{LSO} and at five times that distance. We renormalized the light curve in the case where the inner edge is at $5r_{LSO}$ to have the same max value at in the r_{LSO} case for easier comparison.

While it will be interesting to compare the evolution of the maximum rms amplitude as function of the inner edge of the disk with observations, this is beyond the scope of these preliminary results. Indeed, we need first to gather enough observational data and then compare how different spirals behave to see if the trends are similar. Adding a non-zero spin will also be needed and will add another degree of freedom which might prevent any firm conclusion.

4.2 Impact of the inclination angle

It was long hypothesized that higher inclination angles (more ”edge-on”) would lead to stronger modulation. This is what we observed when comparing the same disk at 45° and 85° as can be seen on Fig. 4.

But, in the high-inclination case, we also observed a distortion of the light-curve that could lead to the PDS of such signal having a complex harmonic structure while the ”real” signal is a simple $m = 1$ mode. It will be interesting to explore this in more detail and look at how much stronger the effect is for high spins. It might be an alternative explanation for the complex harmonic structure observed in microquasars.

5 Conclusions

Here we are presenting preliminary results on the impact of a full GR ray-tracing calculation when computing the flux from a disk harboring non-axisymmetric structures. We used a very simplified disk structure model and mainly showed the necessity, even for structures away from the last stable orbit, to take full GR into account.

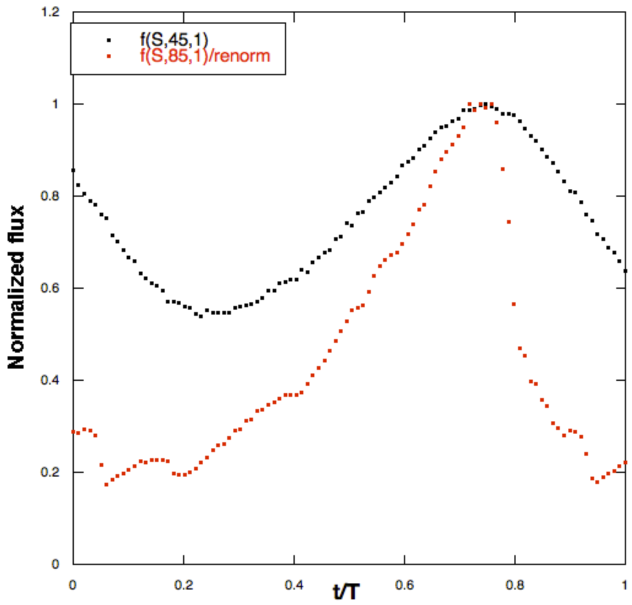

Fig. 4. Comparison of the light curve obtained at different inclination angle

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