Composite profile of the Fe Kα spectral line emitted from a binary system of supermassive black holes✩

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Abstract

We used a model of a relativistic accretion disk around a supermassive black hole (SMBH), based on ray-tracing method in the Kerr metric, to study the variations of the composite Fe Kα line emitted from two accretion disks around SMBHs in a binary system. We assumed that the orbit of such a binary is approximately Keplerian, and simulated the composite line shapes for different orbital elements, accretion disk parameters and mass ratios of the components. The obtained results show that, if observed in the spectra of some SMBH binaries during their different orbital phases, such composite Fe Kα line profiles could be used to constrain the orbits and several properties of such SMBH binaries.

Keywords: black holes: black-hole binaries; galaxies: active; accretion and accretion disks; spectral lines; X-ray emission spectra

1. Introduction

Binary systems of supermassive black holes (SMBHs) originate in galactic mergers, and it is believed that their coalescences represent the most powerful sources of low-frequency gravitational-waves (from 0.1 to 100 mHz) which could provide a significant amount of information not only about the SMBH binaries themselves (see e.g. De Paolis et al., 2003), but also about the early universe, the structure and nature of spacetime, and formation and structure of galaxies. They are expected to be detected in near future by space-based interferometers, such as New Gravitational-Wave Observatory (NGO), also known as evolved Laser Interferometer Space Antenna (eLISA) (see e.g. Amaro-Seoane et al., 2013), as well as by ASTROD I (Braxmaier et al., 2012). These measurements of gravitational radiation will be used for testing General Relativity with higher sensitivity, improving our understanding of gravity, and will complement traditional astronomical observations based on the electromagnetic spectrum.

On the other hand, electromagnetic radiation in different spectral bands emitted during such coalescences of SMBHs represents the most direct evidence for the formation of their binary systems, as well as their essential observational signatures (see e.g. Bogdanović et al., 2009a). At some stage during galactic merger, two SMBHs initially carried within the bulges of their host galaxies, will become gravitationally bound and will start to orbit around their center of mass with velocities of a few thousand km s⁻¹. In such cases, accretion of the surrounding matter on both SMBHs could be expected, and as a result, a strong X-ray emission in the broad Fe Kα line at 6.4 keV might be observed.

It was first showed by Fabian et al. (1989) that the broad Fe Kα emission line could be well modeled by fluorescent emission from the inner parts of a relativistic accretion disk around a SMBH, and that those regions of the disk could be mapped using the shape and variability of the line, since both of them are affected by Doppler and gravitational redshifts produced in vicinity of the central SMBH (for more details see e.g. reviews by Reynolds & Nowak, 2003; Fabian & Ross, 2010). The first convincing observational proof for the existence of the relativistically broadened Fe Kα line was found by Tanaka et al. (1995) in the X-ray spectra of Seyfert 1 galaxy MCG-6-30-15, ob-
tained by Japanese ASCA satellite.

The disks in binaries with arbitrary eccentricity and mass ratio are truncated due to ordinary and eccentric Lindblad resonances, and their sizes depend on binary mass ratio and eccentricity (see e.g. Lin & Papaloizou, 1979a,b; Artymowicz & Lubow, 1994; Hayasaki, 2011, and references therein). Therefore, stability of the orbits of the SMBH binaries could limit the sizes of the accretion disks around the components, as well as the size of their circumbinary accretion disk. Thus, the Fe Kα line emitting regions could have different structures, depending on the mass ratios of such binaries, properties of their accretion disks and separation between their components. In some cases, the secondary SMBH could be embedded in the accretion disk around the primary SMBH causing an empty annular gap in it which, as a consequence, could produce imprints in form of ripples in the observed Fe Kα line profile (see e.g. McKernan et al., 2013). In other cases, the binary clears a low density "hole" or cavity in the center of a circumbinary disk (see e.g. Bogdanović et al., 2009a,b, 2011, and references therein), and the Fe Kα line emission arising from the accretion disks around primary and secondary SMBHs is then affected by the Doppler shifts due to the orbital motion of the binary. Sesana et al. (2012) have shown that such double Fe Kα lines could be in principle identified and used to estimate the properties of the SMBHs, given the high spectral resolution observations with a next generation X-ray observatory. Such SMBH binaries are of special significance because a technique for their detection which utilizes the Doppler shifts in their spectra, although not unique, is one of the simplest and the most straightforward (see e.g. Bogdanović et al., 2009a). In further text we will refer to the total Fe Kα line emission from both primary and secondary disks of such a system as "composite", and to the emission from each of individual disks as "constituent".

In our previous investigations we developed numerical simulations of X-ray emission from a relativistic accretion disk around a SMBH, based on ray-tracing method in Kerr metric, and successfully applied these simulations for studying: (i) properties of SMBHs in some observed Active Galactic Nuclei (AGN) from the shapes of their Fe Kα lines (Jovanović et al., 2011), (ii) observational effects of strong gravity in vicinity of SMBHs (Jovanović & Popović, 2008), (iii) photocentric variability of QSOs, as well as variability of their X-ray and optical lines, due to perturbations in their accretion disks (Jovanović et al., 2010; Popović et al., 2012), (iv) influence of gravitational microlensing on radiation from X-ray, UV and optical emitting regions of accretion disks of AGN (Jovanović et al., 2008, 2009; Popović et al., 2003a,b, 2005, 2006). For reviews of our previous investigations of influence of single and binary SMBHs in AGN on emission lines see e.g. Jovanović (2012); Jovanović & Popović (2009) and Popović (2012).

Here we use these simulations for studying the composite Fe Kα line profiles emitted from both components of a SMBH binary system. Usually the broad optical lines, like Hα and Hβ, are used for studying the SMBH binaries (see e.g. Bogdanović et al., 2008, 2009b; Bon et al., 2012; Popović, 2012). However, it is very difficult to identify the components in their profiles which vary due to Doppler shift. Such components are usually in the form of broad and faint "bumps" embedded in the line profile and their variability usually invokes a non-binary interpretation, since it has been seen in long-term monitoring of disk emitters, while at the same time, a SMBH binary interpretation is still considered just as a possible alternative (see e.g. Shen et al., 2013, and references therein). In contrast, the Fe Kα line has more asymmetric profile with much sharper peaks, and in principle, it should be easier to identify its constituent and varying components. Here we study whether this property of the composite Fe Kα line could be exploited for studying the SMBH binaries.

The paper is organized as follows: in the second section we present the models and parameters of a binary system of SMBHs and relativistic accretion disks around its components, in the third section we describe our simulations and the resulting composite profiles of the Fe Kα spectral line for several cases, and finally in the fourth section we outline our conclusions.

2. Iron Kα emission from SMBH binaries

2.1. Model of relativistic accretion disk around a SMBH

We modeled the emission from accretion disk by numerical simulations based on ray-tracing method in Kerr metric, taking into account only photon trajectories reaching the observer’s sky plane. For more details about this method see e.g. Fanton et al. (1997) and Čadež et al. (1998) and references therein, but briefly, in this method one divides the image of the disk on the observer’s sky into a number of small elements (pixels) and for all of them the photon trajectories are traced backward from the observer until their intersection with the plane of the disk, by pseudo-analytic integration of the corresponding geodesics in Kerr space-time. For each photon the ratio between the observed νobs and emitted νem frequencies (i.e. the redshift factor g) is calculated:

$$g = \frac{\nu_{\text{obs}}}{\nu_{\text{em}}} = \frac{1}{1+z}.$$  \hspace{1cm} \text{(1)}$$

A simulated image of an accretion disk, as would be seen by a distant observer by a high resolution telescope, is obtained by coloring all pixels according to the corresponding values of g. The corresponding simulated line profile F (g) is obtained from the total observed flux distribution at the observed energy Eobs (Fanton et al., 1997):

$$F(E_{\text{obs}}) = \int_{\text{image}} \varepsilon (r) g^4 \delta (E_{\text{obs}} - g E_0) d\Sigma,$$  \hspace{1cm} \text{(2)}$$

where \(\varepsilon (r) = \frac{\dot{M}}{4\pi r^3} \) is the surface emissivity of the disk which varies with radius as a power law with emissivity
index $p$, $d\Omega$ is the solid angle subtended by the disk in the observer's sky and $E_0$ is the rest energy of the line.

Here we use this model of accretion disk to study the composite Fe Kα line profiles emitted from SMBH binaries, taking into account Doppler shifts during their different orbital phases. For that purpose, and in order to study some more realistic cases, we modeled two disks (denoted as disk 1 and disk 2) with different radii and inclinations, because such disks emit significantly different profiles of the Fe Kα line (as it can be seen from the top part of Fig. 1). Both disks surround the slowly rotating Kerr SMBHs, having the same spin (i.e. angular momentum $J$ per unit mass $M$ of the SMBH) of $J/Mc = 0.1$. The first disk is extending from $R_{ms}$ to 30 $R_g$ (where $R_{ms}$ is radius of the marginally stable orbit, $R_g = GM/c^2$ is the gravitational radius, and $G$ and $c$ are well known constants) and has inclination of 60° (disk 1). The second one is extending from 10 $R_g$ to 100 $R_g$ and has inclination of 30° (disk 2). We assumed that the inclinations of the disks do not change with the time, or along the orbit, as well as that both of them have the same emissivity index of $p = 2$ (see e.g. Jovanović & Popović, 2009, and references therein). Also, since the Fe Kα line originates from the innermost parts of an accretion disk close to the marginally stable orbit around a SMBH (see e.g. Jovanović, 2012, and references therein), a circumbinary disk is assumed not to contribute to the total Fe Kα line emission of the system.

Figure 1: An illustration of two accretion disks around the components of a binary system of SMBHs, rotating along a Keplerian orbit. Disk 1 and disk 2, as well as the corresponding simulated profiles of the Fe Kα spectral line emitted from them, are zoomed in the top part of the figure. See Table 1 for the disk parameters.
2.2. Keplerian radial velocity curves of SMBH binaries

It is well known from the theory of close binary stars that the radial velocities \( V_{i,2}^{\text{rad}} \) of a binary system can be calculated from the following orbital elements: eccentricity \( e \), inclination \( i \), longitude of pericenter \( \omega \), separation between the components \( a \) and their masses \( M_{1,2} \), according to the following expression (see e.g. Hilditch, 2001):

\[
V_{i,2}^{\text{rad}}(\theta) = K_{1,2} [\cos(\theta + \omega) + e \cdot \cos \omega] + \gamma.
\]  

(3)

In previous equation \( \theta \) is true anomaly, \( \gamma \) is systemic velocity and \( K_{1,2} \) are semiamplitudes of the velocity curves:

\[
K_{1,2} = \frac{2 \pi a_{1,2} \sin i}{P \sqrt{1 - e^2}}.
\]  

(4)

where the semimajor axes \( a_{1,2} \) are found from: \( a = a_1 + a_2 \) and \( M_1 a_1 = M_2 a_2 \). Radial velocity curves as functions of time can be calculated from (3) using Kepler’s equation, and orbital period of the binary system can be determined from the third Kepler’s law:

\[
P^2 = \frac{4 \pi^2 a^3}{G(M_1 + M_2)}.
\]  

(5)

An illustration of a Keplerian orbit of a SMBH binary is shown in bottom part of Fig. 1. In all our simulations, we assumed that the masses of primary and secondary SMBHs are \( M_1 = 1 \times 10^8 \, M_\odot \) and \( M_2 = q \, M_1 \), where the mass ratio \( q \) is taken to be 1 or 0.5 (see e.g. Bon et al., 2012). In order to avoid and neglect the self-lensing effects between the components in the binary system (see e.g. Gould, 1995), we studied only significantly inclined orbits with \( i = 30^\circ \) and \( i = 60^\circ \), and with relatively large separation between the components of \( a = 0.01 \, \text{pc} \). Therefore, we modeled two binary systems of SMBHs (denoted as \( \text{binary 1} \) and \( \text{binary 2} \)) with different mass ratios, orbital inclinations and eccentricities. In the case of the first one: \( q = 1, \ i = 60^\circ, \ e = 0.75 \) (binary 1), while in the case of the second one: \( q = 0.5, \ i = 30^\circ, \ e = 0 \) (binary 2). In both cases \( \omega = 90^\circ \) and systemic velocity \( \gamma = 0 \). The corresponding Keplerian radial velocity curves are presented in Fig. 2.

2.3. Composite profiles of the Fe Kα line

Taking into account that for Keplerian orbits \( V_{i,2}^{\text{rad}} \ll c \), the corresponding contributions of Doppler effect to the redshift \( z \) in expression (1) are \( \approx V_{i,2}^{\text{rad}}/c \). Hence, a composite profile \( F(g) \) of the Fe Kα line emitted from both accretion disks at some orbital phase, can be calculated from two constituent unshifted profiles \( F_1(g) \) and \( F_2(g) \) according to:

\[
F(g) = F_1 \left( \frac{1}{g} - \frac{V_{1}^{\text{rad}}}{c} \right)^{-1} + F_2 \left( \frac{1}{g} - \frac{V_{2}^{\text{rad}}}{c} \right)^{-1}.
\]  

(6)

Figure 2: Keplerian radial velocity curves for two binary systems of SMBHs: \textit{binary 1} (top) and \textit{binary 2} (bottom). See Table 2 for the parameters of these systems.

3. Results and discussion

We first simulated the constituent Fe Kα lines emitted by \textit{disk 1} and \textit{disk 2} (see top part of Fig. 1). The parameters used in these simulations are summarized in Table 1. In order to quantify the widths of the obtained constituent lines, we measured their full width at half maximum (FWHM). In the case of \textit{disk 1} we obtained: \( \text{FWHM}_1 \approx 36000 \, \text{km s}^{-1} \) and in the case of \textit{disk 2}: \( \text{FWHM}_2 \approx 20000 \, \text{km s}^{-1} \), both being in the range of the corresponding values typically observed in AGN (see e.g. Nandra et al., 1997, 2007).

In the next step, we simulated radial velocity curves of \textit{binary 1} and \textit{binary 2} (see Fig. 2), using the parameters presented in Table 2. As it can be seen from Fig. 2, both SMBH binaries have orbital periods of approximately 7 years and velocity semiamplitudes of several thousand km s\(^{-1}\). In the case of \textit{binary 1}, the radial velocities of both components reach \( \approx \pm 6000 \, \text{km s}^{-1} \) at certain orbital phases, which is approximately 17% of FWHM_1 and 30%
Figure 3: Composite profiles of the Fe Kα line emitted during different orbital phases of the binary. Model of accretion disk around each component is denoted in the caption of each subpanel.

Table 1: The parameters of two simulated accretion disks: $J/Mc$ - spin of the central SMBH, $\theta_{obs}$ - disk inclination, $R_{in}$ - inner radius of the disk, $R_{out}$ - outer radius of the disk, $p$ - power law emissivity index.

|        | $J/Mc$ | $\theta_{obs}$ (°) | $R_{in}$ ($R_g$) | $R_{out}$ ($R_g$) | $p$ |
|--------|--------|---------------------|------------------|-------------------|-----|
| disk 1 | 0.1    | 60                  | 5.67             | 30                | 2   |
| disk 2 | 0.1    | 30                  | 10               | 100               | 2   |

Table 2: Mass ratios and orbital elements of two simulated SMBH binaries: $q$ - mass ratio (for $M_1 = 1 \times 10^8 M_{\odot}$), $a$ - separation between the components, $i$ - inclination, $e$ - eccentricity, $\omega$ - longitude of pericenter and $\gamma$ - systemic velocity.

|        | $q$ | $a$ (pc) | $i$ (°) | $e$ | $\omega$ (°) | $\gamma$ (km/s) |
|--------|-----|----------|--------|-----|--------------|------------------|
| binary 1 | 1   | 0.01     | 60     | 0.75| 90           | 90               |
| binary 2 | 0.5 | 0.01     | 30     | 0   | 90           | 0                |

of FWHM$_2$. Hence, the Fe Kα line emitted from such a binary could be significantly affected by the Doppler effect due to orbital motion. The smaller Doppler shifts are expected in the case of binary 2, since the radial velocity of its primary reach $\approx \pm 1300$ km s$^{-1}$ and of the secondary $\approx \pm 2700$ km s$^{-1}$, which is $\lesssim 10\%$ of FWHM$_1$ and FWHM$_2$.

For both SMBH binaries we then simulated the composite Fe Kα line profiles in the following four cases for accretion disks around the primary and secondary components:

1. disk 1 (primary) and disk 1 (secondary);
2. disk 2 (primary) and disk 2 (secondary);
3. disk 1 (primary) and disk 2 (secondary);
4. disk 2 (primary) and disk 1 (secondary).
The obtained composite profiles during nine different orbital phases are presented in Figs. 3 and 4. Due to higher radial velocities, the larger Doppler shifts are expected in the case of binary 1, which can be seen by comparing the corresponding panels of Figs. 3 and 4. As it can be also seen from Figs. 3 and 4, these Doppler shifts cause ripple effects and clefts in the composite Fe Kα line profiles which oscillate with orbital period.

In the case of binary 1 these effects are very strong, mostly due to great mass ratio $q$, and sometimes cause so deep clefts in the composite line profiles that the corresponding constituent profiles can be almost completely resolved. This is especially the case when the secondary SMBH is surrounded by disk 2, which emits narrower line (see the panels (b) and (c) of Fig. 3), and to a lesser extent when the secondary is accreting through disk 1, which emits broader line (see the panels (a) and (d) of the same figure). This difference indicates that, besides the mass ratio $q$, the disk inclination also has a significant impact on the composite profile variability, since a more inclined disk emits a broader line (see top part of Fig. 1). The similar result was obtained by Yu & Lu (2001), who also studied a possibility to probe the SMBH binaries by their observed Fe Kα line profiles. However, in contrast to Yu & Lu (2001), our results demonstrate that the orbital motion of the SMBH components should not be neglected, since it could cause detectable Doppler shifts in the constituent Fe Kα line profiles.

If such composite profiles of the Fe Kα line with resolvable constituent components were observed, it would be possible to measure their Doppler shifts, which could be then used for reconstructing the radial velocity curves of the SMBH binary (as shown in Bon et al., 2012). One could then fit Keplerian orbits to these velocity curves in order to determine the orbital elements and mass ratio of the components. Providing an independent estimate for
orbital inclination, the masses of both components, as well as their semimajor axes could be also inferred (Bon et al., 2012).

In the case of binary 2, which is more realistic due to smaller mass ratio $q$, the ripple effects in the composite line profiles are much weaker, and hence it is more difficult to resolve the constituent profiles and measure their Doppler shifts (see Fig. 4). The weak ripples occur mostly in the line core (see the first three panels of Fig. 4), except when the constituent line originating from the primary disk is much narrower than the corresponding profile emitted from the secondary disk (see the last panel of Fig. 4). In the latter case, both wings of the composite profiles (especially the "blue" one) could be also affected by formation of the "bump"-like structures which vary due to Doppler shifts. In the former case of variability in the Fe Kα line core, one should keep in mind that the relatively narrow line core in the case of AGN could have multiple origins which, besides an accretion disk, also include a parsec-scale molecular torus and, to a lesser extent, the optical broad-line region (Nandra, 2006). Therefore, the mixing of the broad emission from the accretion disk with the narrow emission from the other regions could limit the possibility to detect the ripple effects due to Doppler shifts caused by orbital motion of the SMBH binary.

However, even in such cases when the ripple effects are weak, it could be possible to study the amplitudes and periods of their oscillations through the analysis of the light curves of different parts of the composite Fe Kα lines, assuming that these oscillations are consequence of the binary SMBHs and not of some other phenomena, such as orbiting bright spots in the disk (see e.g. Iwasawa et al., 2004; Jovanović et al., 2010). For instance, a recent reverberation study of the Fe Kα light curves by Zoghbi et al. (2013) for several different AGN demonstrated the feasibility of these type of investigations. As a result, the constraints to the mass ratios $q$ and orbital periods $P$ could be obtained, provided that the observed X-ray spectra of the studied SMBH binaries have sufficient signal to noise ratio.

As it can be seen from Figs. 3 and 4, two assumed models of the accretion disks around the SMBHs in a binary system resulted with a variety of the composite Fe Kα line profiles. However, one should keep in mind that for different parameters of two accretion disks (e.g. for different boundaries of the Fe Kα line emitting region), the resulting composite line profiles could be even more diverse.

4. Conclusions

In this paper we simulated the composite profiles of the Fe Kα spectral line emitted from two relativistic accretion disks in a binary system of SMBHs during its different orbital phases, in order to find whether such profiles and their variations could be detected and used for studying the properties of the SMBH binaries. From our investigations we can outline the following conclusions:

1. The performed simulations showed that the composite Fe Kα lines with rippled profiles could provide evidence about the presence of the binary SMBH systems, and could be used for studying their properties and orbits;

2. The most favorable candidates for such studies are the binaries with high mass ratios and radial velocities which reach $\gtrsim 10\%$ of the constituent line FWHMs;

3. Mass ratios of the components and inclinations of their accretion disks have significant impact on detected composite Fe Kα line variability caused by Doppler shifts due to orbital motion;

4. Such variability is in the form of ripple effects which oscillate with orbital period;

5. In the case of SMBH binaries with mass ratios approaching to 1, these ripple effects are very strong and the corresponding constituent profiles, as well as their Doppler shifts, could be resolved;

6. Besides the variability of the composite Fe Kα line profiles, the properties of the observed SMBH binaries could be also constrained by studying the light curves of the different parts of the composite line, and in some cases, the radial velocity curves of the constituent line profiles originating from the primary and secondary accretion disks.

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