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SUPERMASSIVE BINARY BLACK HOLES - POSSIBLE OBSERVATIONAL EFFECTS IN THE X-RAY EMISSION*

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Abstract. Here we discuss the possible observational effects in the X-ray emission from two relativistic accretion disks in a supermassive binary black hole system. For that purpose we developed a model and performed numerical simulations of the X-ray radiation from a relativistic accretion disk around a supermassive black hole, based on the ray-tracing method in the Kerr metric, and applied it to the case of the close binary supermassive black holes. Our results indicate that the broad Fe Kα line is a powerful tool for detecting such systems and studying their properties. The most favorable candidates for observational studies are the supermassive binary black holes in the galactic mergers during the phase when the orbital velocities of their components are very large and exceed several thousand $\mathrm{km\,s^{-1}}$.

1. Introduction

It is well known that mergers play an essential role in the evolution of galaxies and therefore coalescences of supermassive black holes (SMBHs) should be common in the Universe. We see the consequences of past supermassive binary black holes (SMBs) in the light curve profiles of so-called 'core ellipticals' and a small number of SMBs have been detected [1, 2]. However, the evolution of SMBs is poorly understood and it is hard to detect them on the sub-parsec scales (see e.g. [1, 2] and the references therein).

Theory predicts that SMBs should spend a substantial amount of time orbiting at velocities of a few thousand kilometers per second. If the SMBs are surrounded by gas, some observational effects might be expected due to accretion onto one or

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both of the SMBHs. This could result in a binary Active Galactic Nucleus (AGN) system with a strong X-ray emission. In the X-ray spectrum of Type 1 AGNs the broad Fe Kα line at 6.4 keV is often observed (see e.g. [3, 4]).

The broad Fe Kα spectral line which originates from the innermost regions of relativistic accretion disks around central supermassive black holes of galaxies, represents a powerful tool for studying the black hole masses and spins, space-time geometry (metric) in their vicinity [5], their accretion physics [6, 7], probing the effects of their strong gravitational fields, and for testing the certain predictions of General Relativity (see e.g. [8, 9]). Besides, gravitational microlensing turned out to be very helpful in these studies (see e.g. [10, 11, 12, 13, 14, 15]). For reviews of our previous investigations of emission lines as the observational signatures of single and binary SMBHs see e.g. [16, 17] and [2].

Here we study the possible observational signatures in the Fe Kα line emitted from two relativistic accretion disks in a binary system of SMBHs. The paper is organized as follows: in the second section we describe a model of a relativistic accretion disk around a SMBH and the simulations of its X-ray radiation, in the third section we present the results of our simulations, and finally in the fourth section we outline our main conclusions.

2. Model of a relativistic accretion disk around a SMBH

We developed a model of a relativistic accretion disk around a supermassive black hole, based on the ray-tracing method in the Kerr metric, and applied it to the case of SMBs, We used the pseudo-analytical integration of the geodesic equations which describe the photon trajectories in the general case of a rotating black hole having some angular momentum J (see [18, 19] for more details). In such case space-time geometry is described by the Kerr metric which depends on the spin a of the black hole, i.e. on its angular momentum J normalized to its mass M ($a = J/Mc,\ 0 \leq a \leq 1$):

$$ds^2 = -\left(1 - \frac{2Mr}{\Sigma}\right) dt^2 - \frac{4Mar}{\Sigma} \sin^2\theta dt d\phi + \frac{A}{\Sigma} \sin^2\theta d\phi^2 + \frac{\Sigma}{\Delta} dr^2 + \Sigma d\theta^2, \tag{2.1}$$

where

$$\Sigma = r^2 + a^2 \cos^2\theta, \quad \Delta = r^2 + a^2 - 2Mr, \quad A = (r^2 + a^2)^2 - a^2 \Delta \sin^2\theta. \tag{2.2}$$

Above definition is given in Boyer-Lindquist coordinates for $c = G = 1$. In the case of a non-rotating black hole, i.e. for $a \to 0$, Kerr metric reduces to the Schwarzschild one.

In the ray-tracing method one takes into account only those photon trajectories which reach the observer's sky plane by dividing the image of the disk on the observer's sky into a number of small elements (pixels), for which the photon trajectories are then traced backward from the observer by following the geodesics in a Kerr space-time, until they cross the plane of the disk. Computationally, this is much more efficient than the direct integration of the geodesic equations. A photon trajectory in the Kerr metric can be described by three constants of motion (the energy at infinity and two constants related to the angular momentum, respectively) which have the following forms when natural units $c = G = M = 1$ are assumed [19]:

$$E = -p_t, \quad \Lambda = p_\phi, \quad Q = p_\theta^2 - a^2E^2cos^2\theta + \Lambda^2cot^2\theta. \tag{2.3}$$

Here, (r, θ, ϕ, t) are the usual Boyer-Lindquist coordinates and p is the 4-momentum. As the trajectory of a photon is independent on its energy, it may be expressed using the two dimensionless parameters $\lambda = \Lambda/E$ and $q = Q^{1/2}/E$ which are very simply related to the two impact parameters α and β describing the apparent position on the observer's celestial sphere:

$$\alpha = -\frac{\lambda}{\sin\theta_{obs}}, \quad \beta = \pm\left(q^2 + a^2\cos^2\theta_{obs} - \lambda^2\cot^2\theta_{obs}\right)^{\frac{1}{2}}, \tag{2.4}$$

where the sign of β is determined by $\left(\frac{dr}{d\theta}\right)_{obs}$.

In order to find the photon trajectories (null geodesics) which originate in the accretion disk at some emission radius r_{em} and reach the observer at infinity, one must solve the following integral equation [19]:

$$\pm\int\limits_{r_{em}}^{\infty}\frac{dr}{\sqrt{R\left(r,\lambda,q\right)}} = \pm\int\limits_{\theta_{em}}^{\theta_{obs}}\frac{d\theta}{\sqrt{\Theta\left(\theta,\lambda,q\right)}}, \tag{2.5}$$

where

$$\begin{gathered} R\left(r,\lambda,q\right) = \left(r^2 + a^2 - a\lambda\right)^2 - \Delta\left[\left(\lambda - a\right)^2 + q^2\right], \\ \Theta\left(\theta,\lambda,q\right) = q^2 + a^2\cos^2\theta - \lambda^2\cot^2\theta. \end{gathered} \tag{2.6}$$

The above integral equation (2.5) can be solved in terms of Jacobian elliptic functions, i.e. by a pseudo-analytical integration. For the exact expressions of the solutions, see e.g. [19].

Then, the flux density of the radiation emitted by the disk at each point, as well as the redshift factor of the photons are calculated. Due to relativistic effects, photons emitted at frequency ν_{em} will reach infinity at frequency ν_{obs}, and their ratio determines the shift due to these effects: $g = \frac{\nu_{obs}}{\nu_{em}}$. The total observed flux at the observed energy E_{obs} is given by [18]:

$$F_{obs}\left(E_{obs}\right) = \int\limits_{image}\varepsilon\left(r\right)g^4\delta\left(E_{obs} - gE_0\right)d\Xi, \tag{2.7}$$

where $\varepsilon\left(r\right) \propto r^{-p}$ is the surface emissivity of the disk which varies with radius as a power law with emissivity index p, $d\Xi$ is the solid angle subtended by the disk in the observer's sky and E_0 is the rest energy.

In that way, one can obtain the color images of the accretion disk which a distant observer would see by a powerful high resolution telescope (see the left panels of Fig. 2.1). The simulated Fe Kα line profiles emitted from such a relativistic accretion disk, can be calculated taking into account the intensities and received photon energies of all pixels over the disk image (see the right panels of Fig. 2.1).

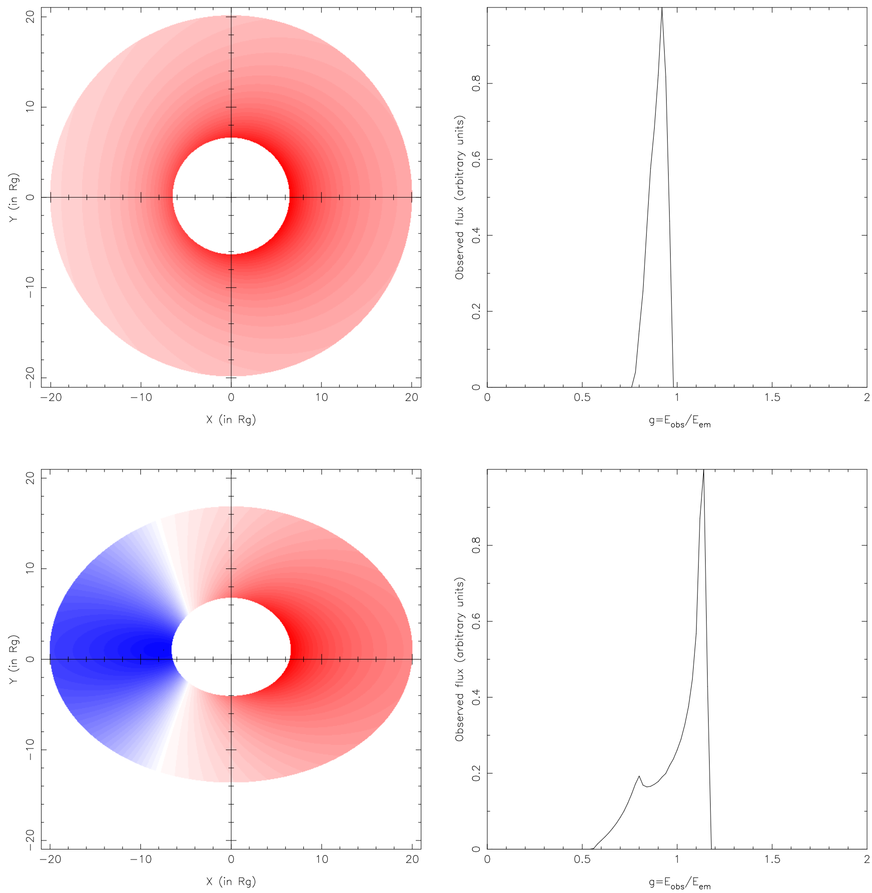

FIG. 2.1: The simulations of the accretion disks and corresponding Fe Kα line profiles for the same dimensions of the disk $R_{out} = 50\ R_g$, but for different inclination of 5° (top) and 45° (bottom).

3. Results: the X-ray emission from SMBs

Assuming that each of SMBHs in a binary system has an accretion disk that emits the broad Fe Kα spectral line, we explored different parameters of their disks and different distances between them. An example is presented in Fig. 2.1, where we assumed an emission from one nearly face-on inclined disk with the inclination of 5° (top), and an additional line emitted from a disk with the inclination of 45° (bottom).

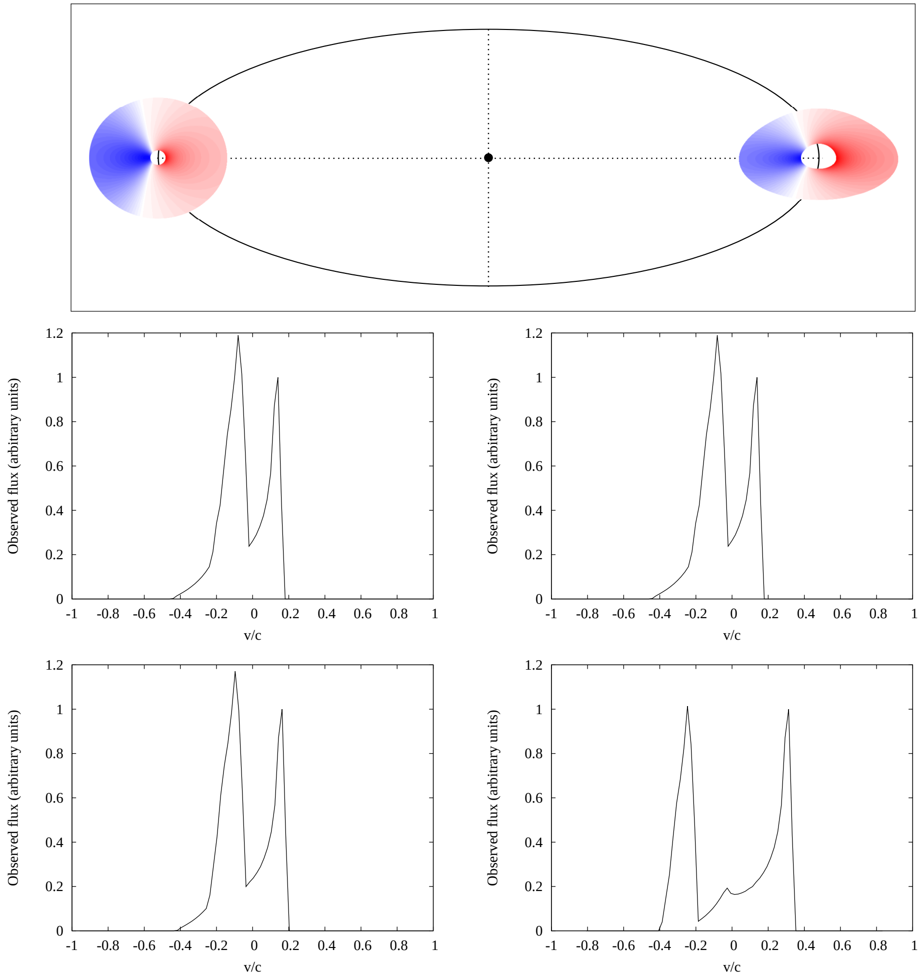

FIG. 3.1: *Top panel:* An illustration of a binary system of SMBHs, surrounded with their relativistic accretion disks and orbiting around their center of the mass. *The last two panels:* The simulated total line profiles emitted from an SMB system with different distances, i.e., maximal radial velocities of 0, 500, 5000 and 50000 km s^{-1} (from top-left to bottom-right, respectively).

Both disks have the same outer radii of 50 R_g (where $R_g = GM_{BH}/c^2$ is the gravitational radius of the central SMBH), and their emission is coming from the innermost stable orbit around a rotating SMBH with spin $a = 0.5$. We assumed that both SMBHs have the same masses of $M_{BH} = 10^8\ M_\odot$ and performed simulations for different distances between them, and consequently, for their different orbital velocities. An illustration of such a binary system of SMBHs, surrounded with their relativistic accretion disks, is given in the top panel of Fig. 3.1. The corresponding emitted line profiles in the rest frame are presented in the last two panels of Fig. 3.1.

As it can be seen from Fig. 3.1, these simulations resulted with a complex Fe Kα line profile with several peaks, in which the constituent profiles from both disks can be almost completely resolved. The separations between their peaks vary depending on the orbital velocities of two SMBH components in the binary system. The maximum separation between the peaks is obtained for the highest value of orbital velocity in the SMB. 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 SMB [20]. One could then fit Keplerian orbits to these velocity curves in order to determine the orbital elements and masses of the components (for more details see e.g. [20, 1]).

However, in order to study some more realistic cases, we recently performed similar simulations, but for two disks with different emissivities, radii, inclinations and mass ratios [20]. The obtained results showed that these parameters, especially mass ratios of the SMBH components and emissivity of their accretion disks, had significant impact on detected composite Fe Kα line profiles, which were found to be complex with several peaks. Also, variability of such profiles was in the form of ripple effects which oscillated with orbital period of the SMBH binary system [20].

All these results are in good agreement with some recent studies of the shape of the Fe Kα line emitted from SMBs. For example, [21] discussed possibility to use the shape of the Fe Kα line to explore the existence of the binary black holes, and found that the line profiles may be very complex, with several peaks. They concluded that such galaxies with unusual Fe Kα line profiles may be a good candidate for SMB hosts [21]. The spin axes of the two SMBHs are very likely to be misaligned [22, 21], and therefore the accretion disks in this system associated with the SMBs can also have different inclinations to the line of sight, as well as different parameters. Taking all this into account, it is expected that SMBs emit a very complex Fe Kα emission.

4. Conslusion

We used a model of a relativistic accretion disk around a SMBH, based on ray-tracing method in the Kerr metric, to simulate the profiles of the Fe Kα spectral line emitted from a binary system of SMBHs. We can outline the following most important results of these simulations:

1. The broad Fe Kα line emitted from a binary system of SMBHs could provide an evidence about the presence of such a system, and represents a powerful

tool for studying its properties, such as the orbital elements and masses of its components;

2. The most favorable candidates for observational studies are the SMBs which relativistic accretion disks emit the complex Fe Kα line profiles with clearly separable peaks of the constituent profiles;

3. Such a case may occur during the phase of galactic merger when the orbital velocities of two SMBH components are very large and exceed several thousand km s^{-1}.

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