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A model for relativistic disk emission, flow and variability

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Abstract. Orbiting features near a black hole can cause variability in optical/UV and X-ray bands with quasi-periodic signatures. The variable flux is derived in Kerr geometry including the following relativistic effects: light bending, time delay, Doppler and gravitational shifts and aberration. The model can be used as a distinguishing timing signature to identify types of accretion disks in active galactic nuclei and X-ray binaries and to constrain the black hole mass and spin.

Keywords : accretion, accretion disks – black hole physics – gravitation – relativity – galaxies: active – X-rays: binaries

Accretion disk variability from active galactic nuclei (AGN) and X-ray binaries span optical/UV and X-rays (e.g. Mohan and Mangalam 2014). Early models included relativistic effects of time delay, gravitational and Doppler shift on emission from orbital features to simulate time variability (Zhang and Bao 1991; Mangalam and Wiita 1993). We calculate the variable flux from orbital features accounting for all relativistic effects (including light bending and aberration) in Kerr geometry. By orbital features, we refer to local regions of enhanced density (higher flux when compared to the quiescent level of flux from the background plasma inflow) on the disk produced by instabilities. Their azimuthal motion contributes to the flux variability. The line element (Boyer-Lindquist coordinates) is $ds^2 = e^{2\nu}dt^2 + e^{2\psi}(d\phi - \omega dt)^2 + e^{2\mu_1}dr^2 + e^{2\mu_2}d\theta^2$. For $\theta = \pi/2$, $e^{2\nu} = r^2\Delta/A$, $e^{2\psi} = A/r^2$, $e^{2\mu_1} = r^2/\Delta$ with $\Delta = (r^2 + a^2 - 2Mr)$, $A = (r^2 + a^2)^2 - \Delta a^2$. The proper time interval $d\tau^2 = -ds^2 = e^{2\nu}dt^2/\gamma^2$ where $\gamma^2 = (1 - \beta^2)^{-1}$, $\beta^2 = (\beta_r^2 + \beta_\phi^2)$ with $\beta_r = e^{\mu_1 - \nu}(dr/dt)$; $\beta_\phi = e^{\psi - \nu}(\Omega - \omega)$. The flow four-velocity and the photon four-momentum are $u^\alpha = \gamma e^{-\nu}(1, \beta_r e^{\nu - \mu_1}, 0, \Omega)$; $p_\alpha = \epsilon(-1, R^{1/2}/\Delta, \Theta^{1/2}, \lambda)$, with conserved photon energy ϵ, photon impact parameter λ, Carter constant q, $R = (r^2 + a^2 - \lambda a)^2 - \Delta((\lambda - a)^2 + q^2)$, $\Theta = q^2 + \cos^2\theta(a^2 - \lambda^2/\sin^2\theta)$. The effective redshift,

$$g = \frac{E_\infty}{E_{emm.}} = \frac{p_\alpha u^\alpha|_\infty}{p_\alpha u^\alpha} = \gamma^{-1}\sqrt{\frac{r^2\Delta}{A}}\left(1 - \beta_r\sqrt{\frac{R}{A}} - \lambda\Omega\right)^{-1}, \tag{1}$$

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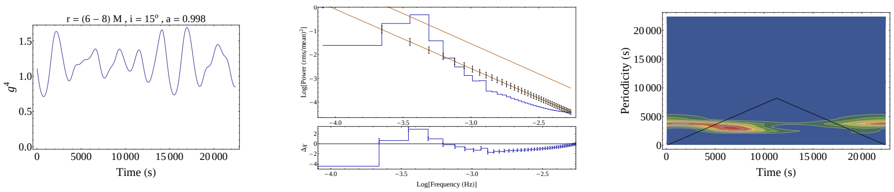

Figure 1. Left plot: mean light curve for $r = (6-8)\,M$; middle plot: PSD of the light curve fit with a power law (slope -2.3). The lower power law is the fit model and the upper is the 99% significance contour. A QPO is peaked at 2816 s; right plot: wavelet analysis of the light curve indicating a QPO of 3726 s.

where β_r can be evaluated for the thin and thick disks, advective flows, etc.; $\Omega = (r^{3/2}+a)^{-1}$; using $\int_r^\infty R^{-1/2} = \int_{\pi/2}^{i} \Theta^{-1/2} d\theta$ where i is the disk inclination angle, $\lambda = \lambda(q,i)$; the azimuthal position of the orbiting feature $\phi = \Omega\,(t+\tilde{t})$. The effective time delay $\tilde{t}$ is due to two effects: a signal from (r,ϕ,i) lags a signal from the centre of a face-on disk ($i=0, \lambda=0$); light bending (due to curved space-time),

$$\tilde{t} = \int_{\pi/2}^{i} (1+\Omega a \sin^2\theta)\left(\frac{\lambda - a\sin^2\theta}{\Theta^{1/2}\sin^2\theta} + \frac{a}{(q^2+a^2\cos^2\theta)^{1/2}}\right) d\theta \qquad (2)$$
$$+ \int_r^\infty \frac{\Omega(r^2+a^2)+a}{\Delta}\left(\frac{r^2+a^2-\lambda a}{R^{1/2}} - \frac{r^2+a^2}{(A-\Delta q^2)^{1/2}}\right) dr.$$

The observer time $\tau = \int e^\nu dt/\gamma$ and variable flux $F(\tau) = g^4(\tau)$ (e.g. Mangalam and Wiita 1993) We simulate a mean light curve using $\beta_r = 0$, $a = 0.998$, rings at radii $r = (6-8)\,M$ (using $M_\bullet$ to represent black hole mass, $M = GM_\bullet/c^2$ is the gravitational radius) and an observer inclination angle $i = 15^\circ$, to illustrate the quasi periodic oscillation (QPO) ranging between 2816 s - 3726 s for a supermassive black hole of mass $5\times10^6 M_\odot$, power law PSD (slope -2.3) using the periodogram (e.g. Mohan and Mangalam 2014) and wavelet analysis (e.g. Mohan et al. 2011; Gupta et al. 2012) of the light curve in Fig. 1. The variable flux from disk based orbital features includes the relativistic effects of light bending, aberration, time delay, gravitational and Doppler shifts.This is proposed as a method to distinguish variability from different accretion disks and constrain mass and spin of the black hole in AGN and X-ray binaries.

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