The relativistic iron line produced by a viscously spreading ring near a massive black hole

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Outline

Introduction

- We consider a spectral line formed by an X-ray illumination of an accretion ring near a supermassive rotating black hole.
- The ring is assumed to be gradually dissolved by viscous processes.
- We consider a simple model spectrum consisting of a power-law primary continuum and K-alpha reflection line of iron, and we show how the observed spectral profile changes in time.
- Model parameters are view angle of the observer, spin of the black hole, the initial radius of the ring, and its viscosity parameter.

The density distribution

- The evolution of the surface density distribution Σ is given by a diffusion equation

$$\frac{\partial \Sigma}{\partial t} = \frac{3}{r}\frac{\partial}{\partial r}\left[r^{1/2}\frac{\partial}{\partial r}\left(\nu \Sigma r^{1/2}\right)\right].$$

- We suppose the α-prescription of the disk

$$\nu = \frac{2}{3}\frac{\alpha c_s^2}{\Omega_{\mathrm{K}}} = \frac{2}{3}\alpha \Omega_{\mathrm{K}} H^2,$$

where ν is the kinematic viscosity, α the viscosity parameter, c_{s} the sound speed, Ω_{K} Keplerian angular velocity and H the thickness of the disk.

The solution of $\frac{\partial \Sigma}{\partial t}$

- The diffusion equation can be solved analytically using Green's function (Lynden-Bell & Pringle 1974) if the kinematic viscosity is a power-law function of the radius

$$\nu(r) = \nu_0 \left(\frac{r}{r_0} \right)^n ,$$

where the parameter n characterizes the accretion disk, $1/2$ is a disk without cooling, $3/2$ is an isothermal disk, $3/5$ and $3/4$ are thin disks, (Shakura & Sunyaev 1973).

- The diffusion equation can be rewritten in the form of Bessel function if we set the dimensionless variables

$$\xi \equiv \left(\frac{r}{r_0} \right)^{1/2} ; \tau \equiv \frac{t}{t_0} ; \sigma(\xi, \tau) \equiv \frac{\Sigma(r)}{\Sigma_0} ,$$

r_0, Σ_0 are constants and t_0 corresponds to the diffusion timescale at r_0, $t_0 \equiv \frac{4r_0^2}{3\nu_0} = \frac{2r_0^2}{\alpha \Omega_{\rm K} H^2}$.

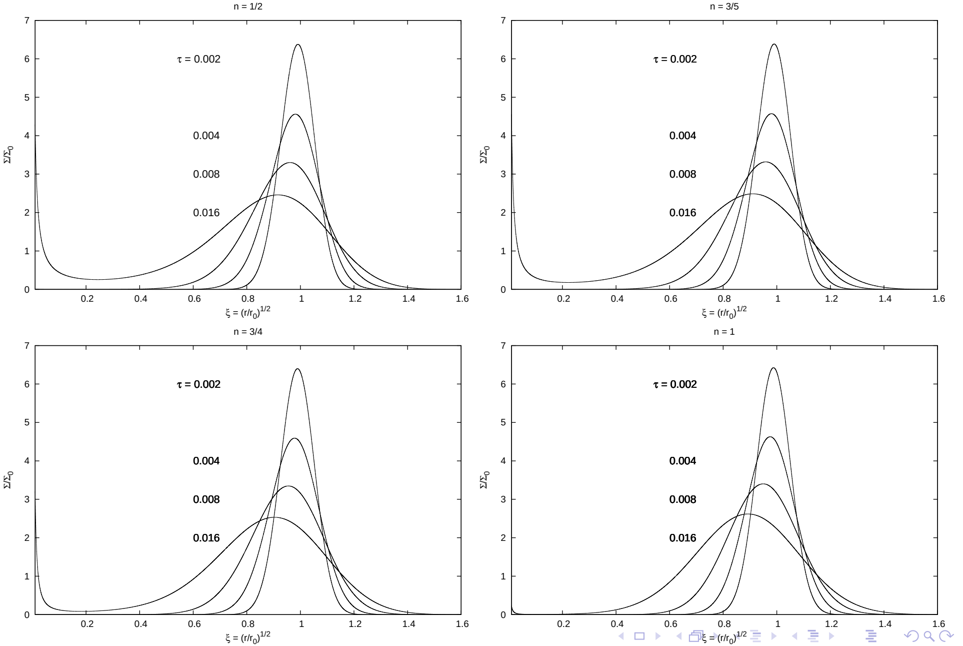
The solution of $\frac{\partial \Sigma}{\partial t}$

- For δ-function type initial condition, $\sigma(\xi, \tau = 0) = \delta(\xi - 1)$, the solution of the diffusion equation is

$$\sigma(\xi, \tau) = |\mu| \frac{\xi^{1/\mu - 9/2}}{\tau} \exp\left[-\frac{\mu^2(\xi^{1/\mu} + 1)}{\tau}\right] I_{|\mu|}\left[\frac{2\mu^2 \xi^{1/(2\mu)}}{\tau}\right],$$

  where $\mu = \frac{1}{4-2n}$ and $I_{|\mu|}$ is the modified Bessel function of first order.
- Now we can calculate the evolution of the inner and outer radius of an accretion ring, respectively a belt or a disk.

The evolution of Σ for different n



The evolution of Σ for different n

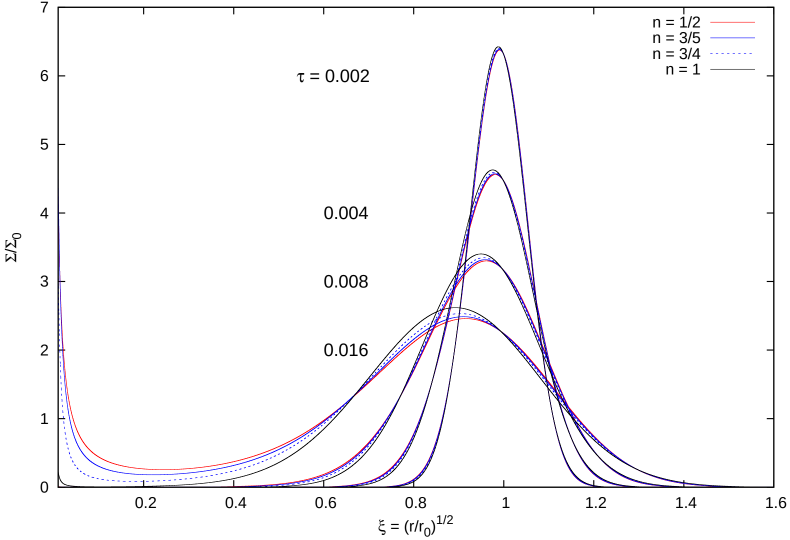


Fig. 2: The evolution of the surface density for different accretion disks.

The initial parameters

- We need know the initial parameters to calculate the spectral profile changes of iron line in time for a specific case.
- The initial parameters are the initial radius r_0, initial surface density Σ_0 and diffusion timescale t_0 at r_0.
- If we suppose the accretion ring is formed from the debris of a tidally disrupted star by a massive black hole then
  - the initial radius is the tidal radius $r_0 = R_{\mathrm{T}} = R_*(M_{\mathrm{BH}}/M_*)^{(1/3)}$
  - the initial surface density is $\Sigma_0 = \frac{M}{2\pi r_0^2}$, where $M = 0.5M_*$.
- The diffusion timescale is $t_0 = \frac{2r_0^2}{\alpha\Omega_{\mathrm{K}}H^2}$, where the thickness H can be estimated from the standard Shakura-Sunyaev model for the inner region,
  $H \geq 3.235\left(\frac{M_{\mathrm{BH}}}{M_\odot}\right)^{7/8}\alpha^{-1/8}\left(1-\sqrt{\frac{6r_g}{r}}\right)$ m.

The initial parameters

- If we set $\theta_o = 30$ deg, $M_{\rm BH} = 10^7\ M_\odot$, spin $a = 0.7$, $M_* = 1\ M_\odot$, $\alpha = 0.8$, $n = 3/4$ and $H \simeq 6{\rm x}10^6$ m then
- $M = 0.5\ M_\odot$
- $r_0 = 10.145\ R_g$
- $\Sigma_0 = 7.05{\rm x}10^6\ {\rm kg/m^2}$
- $t_0 = 83000$ years

The evolution of the surface density

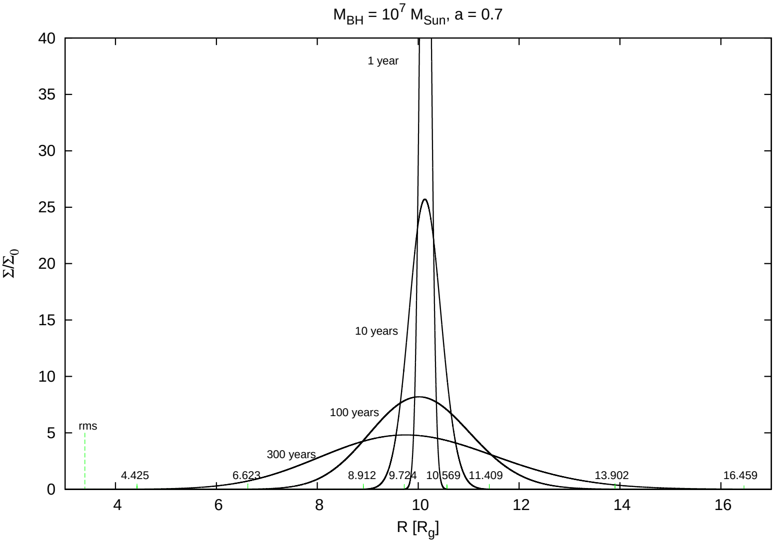
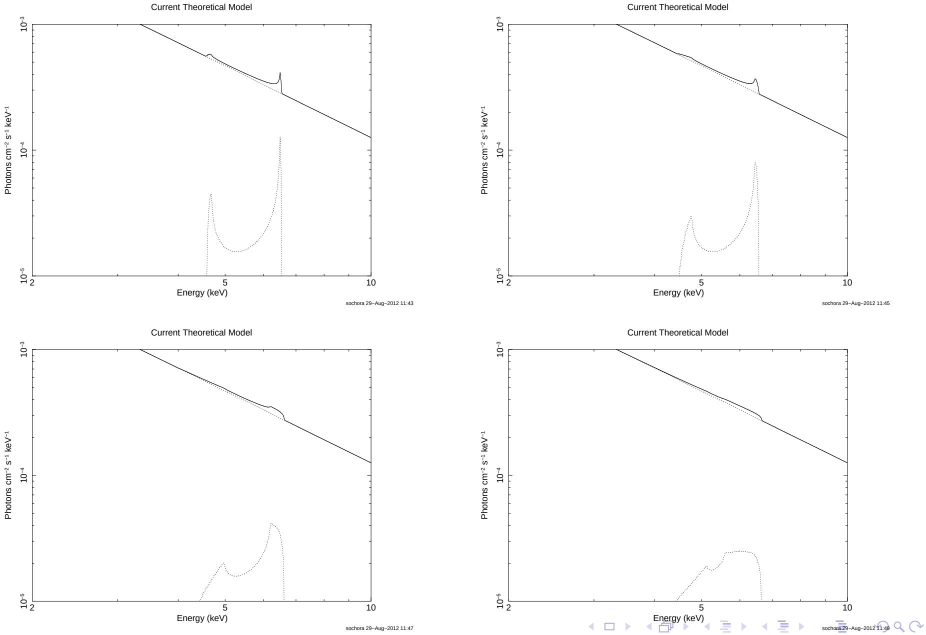


Fig. 3: The evolution of the surface density.

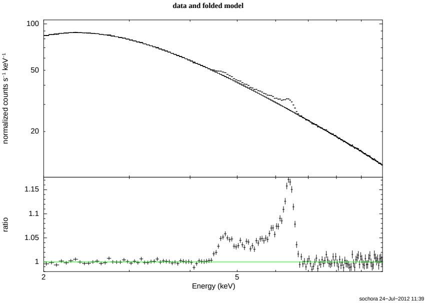
The influence of the initial parameters

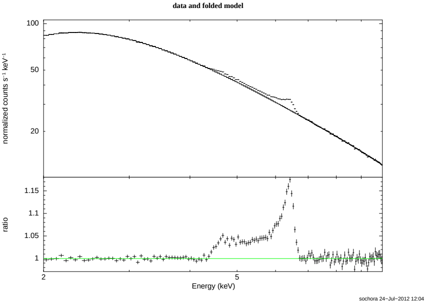
- The mass of a black hole M_{BH} changes the initial radius r_0. For $M_{\mathrm{BH}} > 10^8\ M_{\odot}$ the initial radius can be below marginally stable orbit.
- The initial parametrs α, Ω_{K} and H influence the timescale t_0, how quick is the spreading of the ring.
- The parameter n influences the profile of the evolution of the surface density Σ and has an effect on the inner and outer radius of the ring.

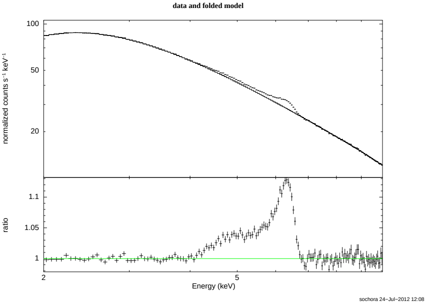
The theoretical spectral profile

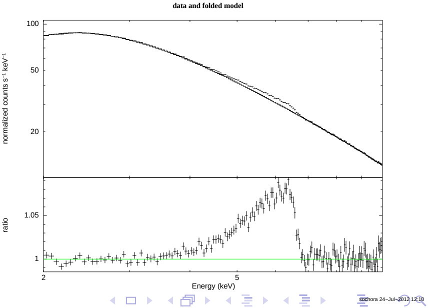


The simulated data with LOFT









Thank you for your attention.