TRANSFER OF LINE EMISSION FROM ACCRETING BLACK HOLES

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Observations of emission lines provide the opportunity to probe the extreme environment around black holes. We calculate line profiles from accretion disks including the effects of resonant absorption by relativistic media, as the photons propagate through the curved space-time.

1. Relativistic Radiative Transfer

The radiative transfer equation in curved space-time reads

$$\frac{d\mathcal{I}}{d\lambda} = -p_\alpha u^\alpha|_\lambda \left[-\chi_0(x^\beta,\nu)\mathcal{I} + \eta_0(x^\beta,\nu) \right]. \qquad (1)$$

$\mathcal{I} = I/\nu^3$	Lorentz invariant intensity
$\chi_0(x^\beta,\nu)$	absorption coefficient
$\eta_0(x^\beta,\nu)$	emissivity
λ	affine parameter

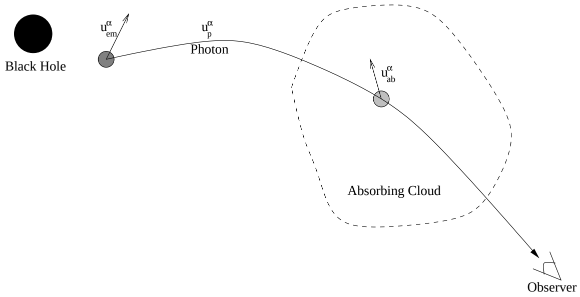

Figure 1. The emitters and absorbers are in motion, causing Doppler shifts of the line. The absorption is also altered due to Lorentz contraction and time dilation.

2. Motion of the Emitters and Absorbers

Rotating black holes drag space-time around. The angular velocity of the orbit of an emitter in the accretion disk is [1]

$$\omega_k = \frac{1}{r^{3/2}+a}, \qquad (2)$$

and its four-velocity is [2]

$$\begin{aligned} u^\alpha_{\rm disk} &= \begin{bmatrix} \dot t \\ \dot r \\ \dot\theta \\ \dot\phi \end{bmatrix}, \\ &= \frac{1}{\sqrt{r}\sqrt{r^2-3r+2a\sqrt{r}}} \begin{bmatrix} r^{3/2}+a \\ 0 \\ 0 \\ 1 \end{bmatrix} \end{aligned} \qquad (3)$$

where a is the specific angular momentum of the black hole.

We assume that the velocities of the absorbers match those of the disk material at $\theta = \pi/2$, and the absorbers are pressure supported such that they are suspended out of the equatorial plane. The absorbers four-velocity is

$$\begin{aligned} u^\alpha_{\rm abs} &= 1 \Big/ \sqrt{\Sigma\left(\Sigma(r+1) - 4r^2 + 2a\sin\theta\sqrt{r(2r^2-\Sigma)}\right)} \\ &\quad \times \begin{bmatrix} \Sigma\sqrt{r} + a\sin\theta\sqrt{2r^2-\Sigma} \\ 0 \\ 0 \\ 1/\sin\theta \end{bmatrix}. \end{aligned} \qquad (4)$$

3. Line Profiles

We obtain the energy shift of the emission from the invariance $p_\alpha u^\alpha$. The trajectories are calculated using and Euler-Lagrange formulation. We trace the ray backwards in time from the observer to the emitter [3]. The optical depth is integrated along the path (affine parameter) for each photon.

We consider two absorber models: The grey model, and the narrow line model. By summing the emission over the four lowest order images, we obtain line profiles.

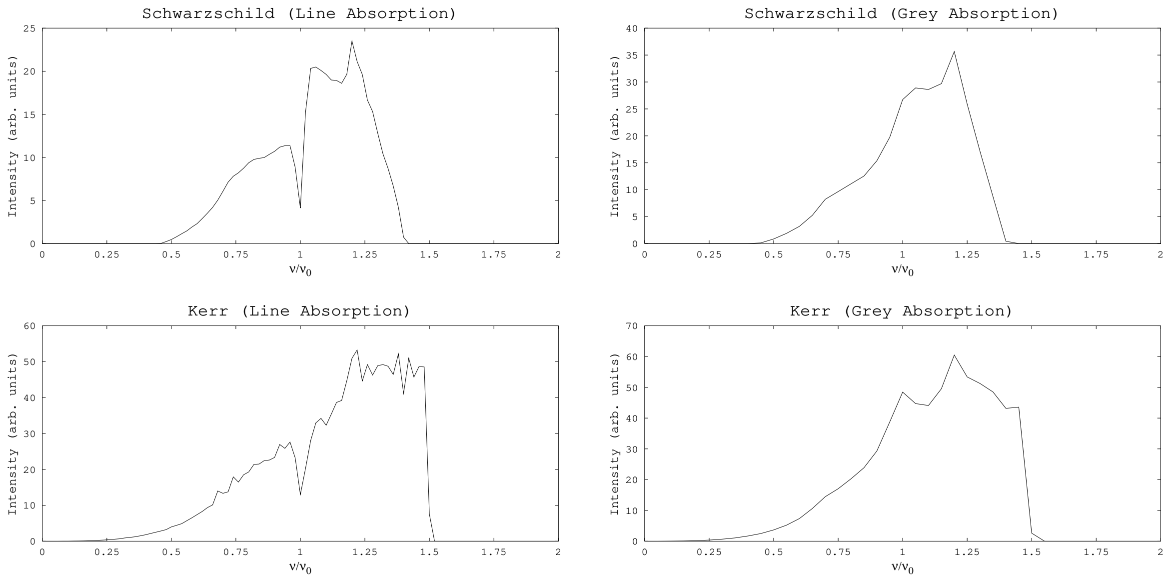

Figure 2. The above four panels show line profiles resulting from emission from an accretion disk with a norm inclined at 85°, for two absorption models. The absorbers are assumed to have a Gaussian absorption frequency profile in the rest frame. There are two differing profile widths, with the narrow resonant line model having a line width of 0.01 of the rest frequency, and the grey absorber corresponding to a width of four times the rest frequency.

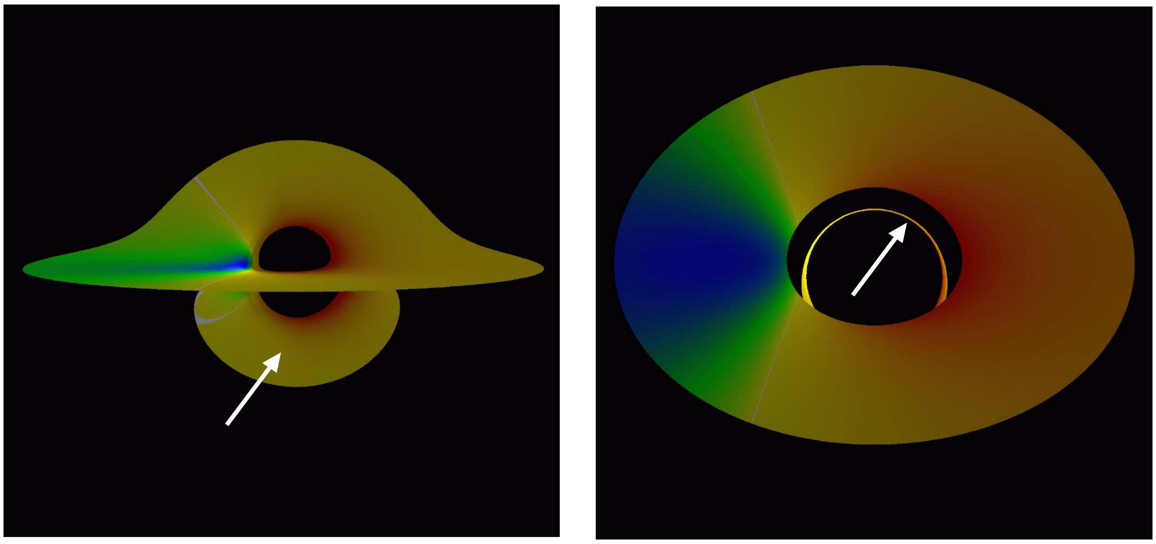

Figure 3. Accretion disk images around a Schwarzschild black hole with an inclination angle of 60° (left), and a Kerr black hole with an inclination of 85° (right). The false-colour shows the degree of red or blue shift of the emission. The first of the infinite series of non-direct images are indicated by an arrow.

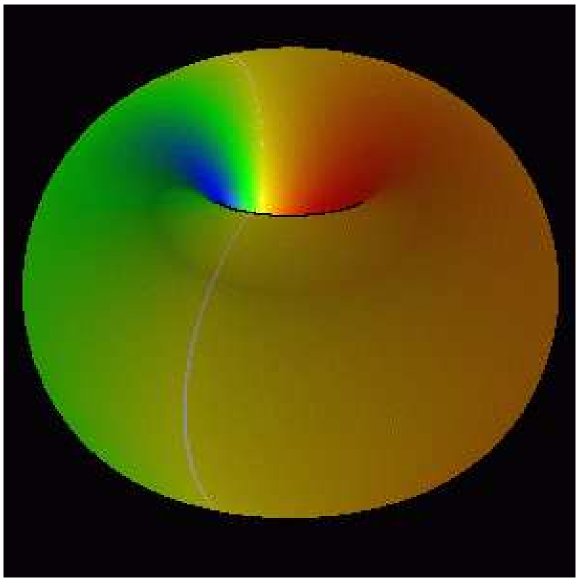

Figure 4. The frequency-shift colour image of a torus around a Kerr black hole, with an outer radius of $20R_{\rm G}$, and an inner radius of $1.23R_{\rm G}$.

4. Results

For grey absorbers, all frequencies are attenuated approximately equally. The wings of the double-peaked line come from the fastest-moving emitters in the inner region of the accretion disk. The wings experience larger absorption than the line center, because we assume a power-law radial profile for the absorption.

For the narrow-line profile absorption model, the resonance between the absorption and the emission is important. Since the absorbers orbit outside the equatorial plane and have lower velocities than the emitters on the accretion disk surface, they absorb the emission at frequencies close to the rest-frame emission frequencies. As a result, it deepens the trough between the line emission peaks [4].

The optical depth along the path linearly depends on the $p_\alpha u^\alpha$ term. The red wing can be much less absorbed than the blue wing because of Lorentz contraction in the absorbing medium. This effect is more obvious for Kerr black holes than for Schwarzschild black holes (cf. the line profiles in the second and fourth panels).

Our calculations are applicable to thick accretion disks or tori around rotating black holes, when the velocity law and the emission surface are specified.

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