Time lags and reverberation in the lamp-post geometry of the compact corona illuminating a black-hole accretion disc

Michal Dovčiak

Astronomical Institute
Academy of Sciences of the Czech Republic, Prague

Astrophysics group seminar, Department of Physics, University of Crete, Heraklion, Greece

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**Institutes:** AsU, CNRS, UNIROMA3, UCAM, CSIC, UCO, CAMK

**Webpages:** [http://stronggravity.eu/](http://stronggravity.eu/)  
Active Galactic Nuclei – scheme

Unified Schemes for Radio-Loud Active Galactic Nuclei
PASP, 107, 803
Active Galactic Nuclei – X-ray spectrum

Fabian A.C. (2005)
X-ray Reflections on AGN,
Emmanoulopoulos et al. (2014)

*General relativistic modelling of the negative reverberation X-ray time delays in AGN*, MNRAS **439** 3931
Kara et al. (2014)
The curious time lags of PG 1244+026: Discovery of the iron K reverberation lag, MNRAS 439 L26
References


\[ L_0(v, t) = \int_{-\infty}^{\infty} dt' L_p(t') \psi(v, t - t') \]

» Stella (1990) Nature 344 747 → time dependent Fe Kα shape \((a = 0)\)

» Matt & Perola (1992) MNRAS 259 433
  → Fe Kα response and black hole mass estimate → \(t \sim GM/c^3\)
  → time dependent light curve, centroid energy and line equivalent width
  \((h = 6, 10; a = 0; \theta_0)\)

» Campana & Stella (1995) MNRAS 272 585
  → line reverberation for a compact and extended source \((a = 0)\)

  → fully relativistic line reverberation \((h = 10; a = 0, 1)\)
  → more detailed reprocessing, off-axis flares
  → ionized lines for Schwarzschild case, outward and inward echo,
    reappearance of the broad relativistic line
References

More recent references:

- **Chainakun & Young (2012) MNRAS 420 1145**
  - fully relativistic, lamp-post geometry, ionized accretion disc

- **Wilkins & Fabian (2013) MNRAS 430 247**
  - fully relativistic, extended corona, propagation effects

- **Cackett et al. (2014) MNRAS 438 2980**
  - Fe Kα reverberation in lamp-post model (spectral line)

- **Emmanoulopolous et al. (2014) MNRAS 439 3931**
  - Fe Kα reverberation in lamp-post model (soft excess)
Why to study toy model of lamp-post geometry?

- physical motivation: base of a jet
- many effects should be qualitatively similar with this simple geometry
- it can give us certain limits on the model (e.g. spin versus height)
- we can easily explore the dependence on many parameters (height of the corona, ionization of the disc, ...)
- if we want to study the dependence on geometry, we should know how other parameters influence the results
  (i.e. Is the idea of measuring geometry of the corona via reverberation feasible?)
Scheme of the lamp-post geometry

- central black hole – mass, spin
- compact corona with isotropic emission  
  → height, photon index
- accretion disc  
  → Keplerian, geometrically thin, optically thick  
  → ionisation due to illumination  
    \((L_p, h, M, a, n_H, q_n)\)
- local re-processing in the disc  
  → REFLIONX with different directional emissivity prescriptions
- relativistic effects:  
  → Doppler and gravitational energy shift  
  → light bending (lensing)  
  → aberration (beaming)  
  → light travel time
Total light travel time includes the lamp-to-disc and disc-to-observer part

first photons arrive from the region in front of the black hole which is further out for higher source

contours of the total time delay shows the ring of reflection that develops into two rings when the echo reaches the vicinity of the black hole
Light curve

- the flux for Schwarzschild BH is much smaller than for Kerr BH due to the hole below ISCO (no inner ring in Schwarzschild case)
- the shape of the light curve differs substantially for different spins
- the “duration” of the echo is quite similar
- the higher the inclination the sooner first photons will be observed
- magnification due to lensing effect at high inclinations
Dynamic spectrum – spectral line

- Signature of outer and inner echo in dynamic spectra
- Large amplification when the two echos separate
- Intrinsically narrow Kα line can acquire weird shapes
Dynamic spectrum – ionised disc

\[ E^2 \times F(E) \]

\[ a = 0, \theta_0 = 30^\circ, h = 3.0, \Delta t = 1 \]

\[ a = 1, \theta_0 = 30^\circ, h = 3.0, \Delta t = 1 \]
Definition of the phase lag

\[ F_{\text{refl}}(E, t) = N_p(t) \ast \psi(E, t) \quad \Rightarrow \quad \hat{F}_{\text{refl}}(E, f) = \hat{N}_p(f) \cdot \hat{\psi}(E, f) \]

where

\[ \hat{\psi}(E, f) = A(E, f)e^{i\phi(E, f)} \]

if

\[ N_p(t) = \cos(2\pi ft) \quad \text{and} \quad \hat{\psi}(E) = A(E)e^{i\phi(E)} \]

then

\[ F_{\text{refl}}(E, t) = A(E) \cos\{2\pi f[t + \tau(E)]\} \quad \text{where} \quad \tau(E) = \frac{\phi(E)}{2\pi f} \]

\[ F(E, t) \sim N_p(t) \ast (\psi_r(E, t) + \delta(t)) \quad \Rightarrow \quad \hat{F}(E, f) \sim \hat{N}_p(f).(\hat{\psi}_r(E, f) + 1) \]

and

\[ \tan \phi_{\text{tot}}(E, f) = \frac{\hat{A}_r(E, f) \sin \phi_r(E, f)}{1 + \hat{A}_r(E, f) \cos \phi_r(E, f)} \]
Parameter values and integrated spectrum

\[ E^2 \times F(E) \]

\( a = 1, \ h = 3, \ \theta_o = 30^\circ \)

\[
\begin{align*}
M &= 10^8 M_\odot \\
a &= 1 (0) \\
\theta_o &= 30^\circ \ (60^\circ) \\
h &= 3 \ (1.5, 6, 15, 30) \\
L_p &= 0.001 L_{\text{Edd}} \\
\Gamma &= 2 \ (1.5, 3) \\
n_H &= 0.1 \ (0.01, 50, 5, 0.2) \times 10^{15} \text{cm}^{-3} \\
q_n &= -2 \ (0, -5, -3)
\end{align*}
\]

Energy bands:
- Soft excess: 0.3 – 0.8 keV
- Primary: 1 – 3 keV
- Iron line: 3 – 9 keV
- Compton hump: 15 – 40 keV
Phase lag dependence on geometry

- reflected photon flux decreases with height
- primary flux increases with height
- the delay of response is increasing with height
- the “duration” of the response is longer
- the phase lag increases with height, it depends mainly on the “average” response time and magnitude of relative photon flux
- the phase lag null points are shifted to lower frequencies for higher heights due to longer timescales of response
- relative photon flux and the phase lag increase with inclination for low heights
- the delay and duration of response do not change much with the inclination and thus the phase lag null points frequencies change only slightly
Phase lag dependence on spin and energy band

- the relative flux in the energy band where primary dominates may in some cases be larger than that in Kα and Compton hump energy bands

- the magnitude of the phase lag in different energy bands differs (in extreme Kerr case the larger lag in SE is due to larger ionisation near BH)

- the magnitude of the phase lag is smaller in Schwarzschild case due to the hole in the disc under the ISCO

- the null points of the phase lag change only slightly with energy and spin
the phase lag in $K\alpha$ band is shown

the reflection component of the spectra are steeper for higher ionisation

the magnitude of the phase lag depend on ionisation

the null points of the phase lag does not change with the ionisation
Directionality and photon index

The phase lag in SE band is shown.
The magnitude of the phase lag changes in all three cases.
The null points of the phase lag does not change with different directionility dependences or power-law photon index.
Phase lag energy dependence

for low $f$:

$$A_r(E, f) \approx A_E(E) A_f(f)$$

$$\phi_r(E, f) \approx \phi_r(f)$$

and

$$\Delta \tau(E, f) \approx \frac{1}{2\pi f} \text{atan} \left( \frac{[A_r(E, f) - A_r(E_0, f)] \sin \phi_r(f)}{1 + [A_r(E, f) + A_r(E_0, f)] \cos \phi_r(f) + A_r(E, f) A_r(E_0, f)} \right)$$

and for $f$ such that $\phi_r(f) = \pm \frac{\pi}{2}$:

$$\Delta \tau(E, f) \approx \frac{1}{2\pi f} [A_r(E, f) - A_r(E_0, f)]$$
Phase lag energy dependence

- The energy dependence of the phase lag follows the spectral shape perfectly at particular frequencies.
Phase lag energy dependence

- if the second phase lag maximum is too small the phase lag energy dependence does not follow the spectral shape that well
the frequency dependence of the phase lag is mainly due to geometry (height of the corona)

the magnitude of the phase lag depends on many details of the model (height, spin, ionisation, unisotropy, energy, ...)

lag versus energy follows the spectral shape at the right frequencies

extended corona
  → brings several new parameters (size, propagation speed, “ignition” position, inhomogeneity)
  → broadens the response of the disc