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

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**Webpages:** 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,
References

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

- Stella (1990) Nature 344 747 → time dependent Fe K\& shape \((a = 0)\)

  → Fe K\& 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

- 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
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

- signature of outer and inner echo in dynamic spectra
- large amplification when the two echoes separate
- intrinsically narrow Kα line can acquire weird shapes
Transfer function for reverberation

Stationary emission from the accretion disc:

\[ F(E) = \int r \, dr \, d\varphi \, G(r, \varphi) \, F_l(r, \varphi, E/g) \]

Response to the on-axis primary emission:

\[ F(E, t) = \int dt' \int r \, dr \, d\varphi \, G(r, \varphi) \times
\]
\[ N_p(t') \, N_{\text{inc}}(r) \, M(r, \varphi, E/g, t' + t_{pd}) \, \delta([t - t_{do}] - [t' + t_{pd}]) \]

Line reverberation:

\[ F(E, t) = \int dt' \, N_p(t') \int r \, dr \, d\varphi \, \psi_0(r, \varphi) \, \delta(E - gE_{\text{rest}}) \, \delta([t - t'] - [t_{pd} + t_{do}]) \]

Transfer function → response to a flare \([N_p(t') = \delta(t')]\):

\[ \psi(E, t) = \sum_{g = E/E_{\text{rest}}} r \, \psi_0 \frac{r}{E_{\text{rest}}} \left| \frac{\partial(g, \Delta t)}{\partial(r, \varphi)} \right|^{-1} \]
\[ F(E, t) = \int dt' \, N_p(t') \, \psi(E, t - t') \]

\[ \nabla g \parallel \nabla(\Delta t) \]
Caustics – Schwarzschild case

- the black curves show the points where the energy shift contours are tangent to the time delay ones
- contour of ISCO in energy-time plane is shown by the blue curve
- the correspondent points A, B, C, D and E are shown in each plot for better understanding
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Caustics

- plots of infinite magnification in the x-y (top) and g-t (bottom) planes
- the plots for Schwarzschild case (red) above ISCO are very similar to the extreme Kerr case (blue)
- the shape of these regions change with inclination
Dynamic spectrum – narrow spectral line
Dynamic spectrum – neutral disc
Dynamic spectrum – ionised disc

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

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

\[ M = 10^8 M_\odot \]
\[ a = 1 (0) \]
\[ \theta_0 = 30^\circ (60^\circ) \]
\[ h = 3 (1.5, 6, 15, 30) \]
\[ L_p = 0.001 L_{Edd} \]
\[ \Gamma = 2 (1.5, 3) \]
\[ n_H = 0.1 (0.01, 50, 5, 0.2) \times 10^{15} \text{cm}^{-3} \]
\[ q_n = -2 (0, -5, -3) \]

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
Phase lag dependence on geometry

- 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 $K\alpha$ 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 Kα 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
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

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

\[ \frac{1}{1 + [A_r(E, f) + A_r(E_0, f)] \cos \phi_r(f) + A_r(E, f)A_r(E_0, f)} \]

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

\[ \Delta \tau(E, f) \approx \frac{1}{2\pi f} \left[ A_r(E, f) - A_r(E_0, f) \right] \]
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.
two aspects of reverberation – in the timing and frequency domains
the response of the disc peaks in the vicinity of the black hole
the phase lag is used to get information on the system properties
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, ...)
extended corona
→ brings several new parameters (size, propagation speed, “ignition” position, inhomogeneities)
→ broadens the response of the disc