Large X-ray time lags from compact black hole coronae

Phil Uttley[1*] and Julien Malzac[2]

1. Anton Pannekoek Institute, University of Amsterdam, Science Park 904, 1098 XH Amsterdam, The Netherlands, *email: p.uttley@uva.nl
2. IRAP, Université de Toulouse, CNRS, UPS, CNES, Toulouse, France

Introduction

The positive ('hard') and negative ('soft') X-ray time lags in black hole X-ray binary ***hard states*** can shed light on the innermost geometry of their emitting regions.

The observed lags can be surprisingly large[1,2]. Explanations for the lags which include light-travel delays (e.g. scattering in the jet[3], or thermal reverberation of coronal emission by the disk[4]) or propagation through a 'hot flow' corona with radial temperature dependence[5], are difficult to reconcile with the small disk radii inferred from observed disk variability time-scales[6] and broad Fe K profiles[7]. Here we show that these lags can be produced by compact single-temperature coronae, by accounting for the natural delay expected between seed photon variations and coronal heating, as accretion fluctuations propagate through the disk to the corona.

Impulse response functions

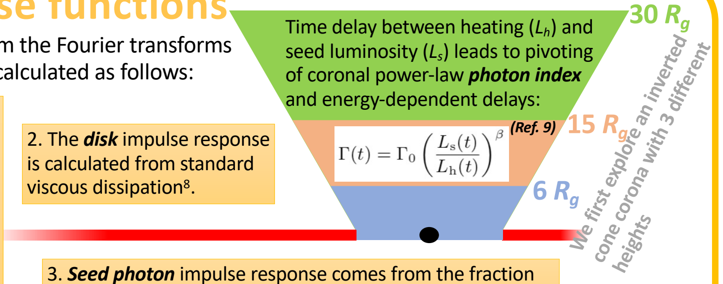
Lag vs. frequency is obtained from the Fourier transforms of impulse response functions[4], calculated as follows:

1. Fluctuations generated at all disk radii (frequency $\nu = kr^{-3/2}$) propagate through the disk with radial drift velocity $v_r = kr^{-1/2}$ to give the ***delay*** time. To explain the observed lags, $k = \alpha(h/r)^2 = 0.01$ in the disk and >10 times larger In the corona.

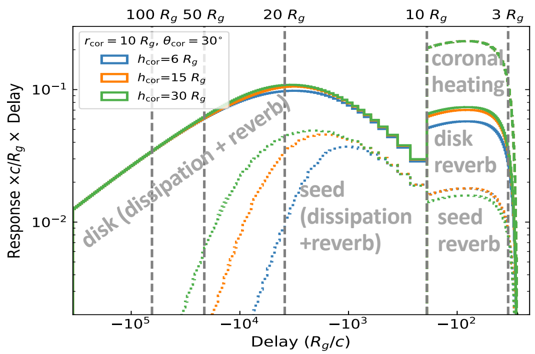
2. The ***disk*** impulse response is calculated from standard viscous dissipation[8].

Time delay between heating (L_h) and seed luminosity (L_s) leads to pivoting of coronal power-law ***photon index*** and energy-dependent delays:

$$\Gamma(t) = \Gamma_0 \left(\frac{L_s(t)}{L_h(t)}\right)^{\beta}$$ (Ref. 9)



3. ***Seed photon*** impulse response comes from the fraction of photons from each disk radius intercepted by the corona.



4. ***Coronal heating*** is given by viscous dissipation inside r_{cor} (10 R_g here).

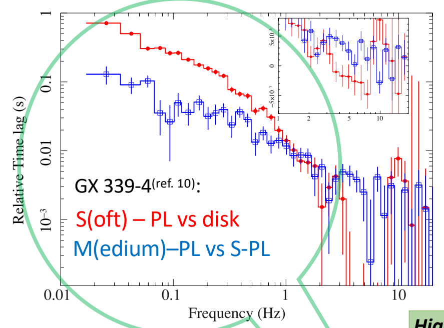
5. ***Reverberation*** contributions are calculated from fraction of coronal luminosity intercepting the disk. ***Light-travel delays are set to zero!***

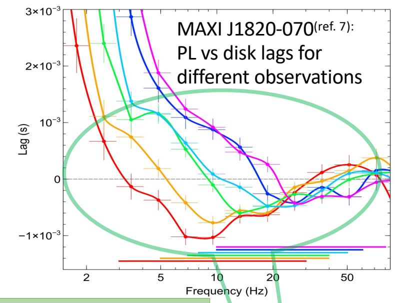
6. Finally the ***energy dependent power-law flux*** impulse responses are calculated from seed and coronal heating by linearising the equation:

$$N(E,t) = \frac{L_s(t)(\Gamma(t)-1)}{E_s^2}\left(\frac{E}{E_s}\right)^{-\Gamma(t)}$$

(assuming[9] $\Gamma_0 = 2.33, \beta = 1/6$)

Lags vs frequency compared with observations





Low-frequency hard lags occur between power-law (PL) bands with log-linear energy dependence. The PL vs. disk lags are substantially larger, as observed.
Observed PL lags often show distinct 'steps', suggesting a more complex coronal geometry or accretion-related effects than are included in our model.

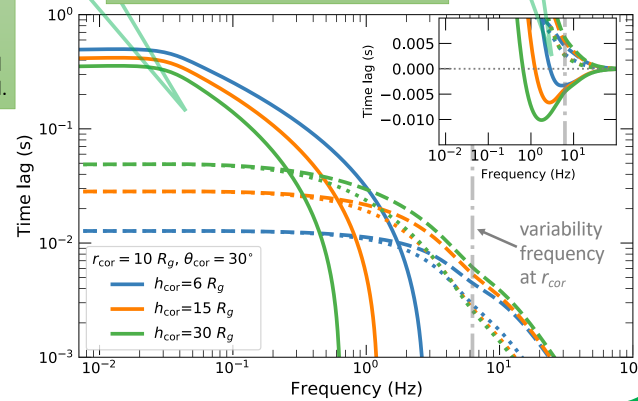
High-frequency soft lags: seed photons have a smaller reverberation contribution than disk, causing the disk to lag PL on short time-scales. These lags are due to ***accretion propagation + dilution by reverberation, not light-travel times.***

Changes in lag amplitude/frequency can be explained by changes in ***coronal height.***

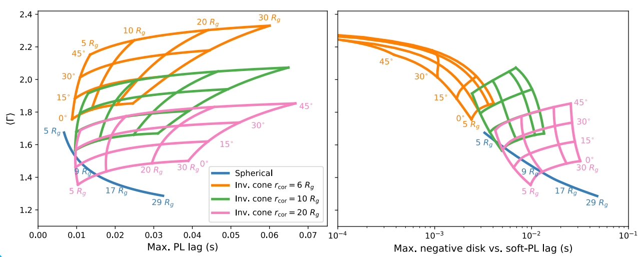
Right: Model predictions for 10 M$_\odot$ BH disk and PL (S/M/H: 3/9/27 times seed energy)

Solid lines: S-PL vs disk lags

Dashed/dotted lines: H-PL vs M-PL/M-PL vs S-PL



Effects of coronal geometry



The maximum ***hard (left)*** and ***soft (right) lag amplitudes***, as well as ***power-law photon index*** are highly sensitive to the coronal geometry, including varying coronal ***radius*** (colours), ***height*** and cone ***opening angle*** (see labelled grid points). In combination, and with more realistic geometries (also including relativistic effects and coronal opacity) the different lags and spectral shape provide a powerful probe of the inner regions. Impulse responses can be combined with those from other processes (e.g. light-travel delays), for more complete models.

Conclusions

1. Propagation of accretion fluctuations through the disk to the corona can explain most observed properties of the lags, once the effect of seed photon variations is accounted for.
2. Where are the light-travel lags? We must look to frequencies ≳ 100 Hz (*eXTP, STROBE-X*).
3. The implied coronae are compact (or predicted lags are too large). The lags can be further reduced by putting more seed photons close to/inside the corona (internal synchrotron, light-bending effects?).
4. $\alpha(h/r)^2 \approx 0.01$ is large for an optically thick disk in the hard state, but hard to escape from. Is this a sign of non-'standard' viscous propagation due to MHD effects?

For more details, look out for our forthcoming paper on arXiv, to appear soon.

References: 1. Miyamoto S., e al., 1988, Nature, 336, 450; 2. De Marco, B., Ponti, G., 2016, ApJ 826, 70; 3. Reig P., Kylafis N. D., Giannios D., 2003, A&A , 403, L15; 4. Uttley P. et al, 2014, A&ARv, 22, 725; 5. Arévalo P., Uttley P., 2006, MNRAS , 367, 801; 6. Wilkinson T., Uttley P., 2009, MNRAS, 397, 666; 7. Kara E., et al. 2019, Nature, 565, 7738, p198; 8. Frank J., King A., Raine D. J., 2002, Accretion Power in Astrophysics. CUP, 9. Beloborodov, A., 1999, ASP Conf. Ser., 161, 295; 10. Uttley P., et al. 2011, MNRAS , 414, L60