Seeing to the Event Horizon: Probing accretion physics with X-ray reflection

Dan Wilkins *CITA National Fellow*
Saint Mary's University, Halifax, Nova Scotia

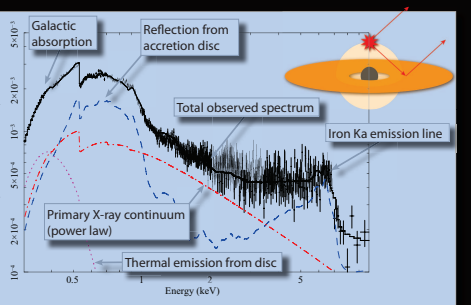
Accretion onto supermassive black holes in active galactic nuclei is known to power some of the most luminous objects we see in the Universe, which through their vast energy outputs must have played an important role in shaping the large scale structure of the Universe we see today. Much remains unknown, however, about the fine details of this process; exactly how energy is liberated from accretion flows onto black holes, how the corona that produces the intense X-ray continuum is formed and what governs this process over time.

The reflection of the X-ray continuum off the inner regions of the accretion flow provides a powerful probe of the extreme environment around the black hole. In particular, measurements of the evolution of the corona as the X-ray luminosity varies by factors of up to 10 give important insight into the process by which the corona is formed and powered by the accretion flow. With its large collecting area and high spectral resolution, Athena promises to reveal the most detailed, dynamic picture of how energy is liberated in the close environments of supermassive black holes.

X-ray Emission from Accreting Black Holes

The intense X-ray continuum is emitted from a corona of energetic particles surrounding the black hole and inner regions of the accretion flow. These particles are likely accelerated by the reconnection of magnetic fields anchored to the inner regions of the disc and Compton scatter thermal UV photons emitted from the disc up to X-ray energies. The X-ray continuum illuminates the accretion disc and is reflected. A number of absorption and emission features are imprinted on the spectrum, the most promenent of which is the Kα emission line of iron, at 6.4keV (as measured in the rest frame of the emitting material). Photons reflected from the inner regions of the disc are shifted in energy by the Doppler efefct as the material in the accretion disc orbits around the black hole, as well as by gravitational redshift. This causes the emission line to be greatly broadened with an extended redshifted wing to low energies that originates from the innermost parts of the disc, as close as $1.235r_g$ (the gravitational radius, $1r_g = GM/c^2$), to rapidly spinning black holes.

The X-ray emission from AGN is extremely variable and measurements of this variability has added a further dimension to the study of accreting black holes. Most notably, reverberation lags are detected, where variability in the X-rays reflected from the accretion disc lags behind that in the continuum emitted from the corona, owing to the additional light travel time between the X-ray source and reflector. These lag times correspond to the light travel time across just a few gravitational radii, so measurement of these lags probes the innermost regions of the accreting black hole right down to the innermost stable orbit and event horizon.

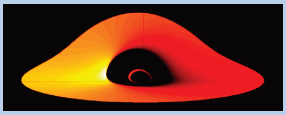


Resolving the Accretion Disc Using the Spectrum

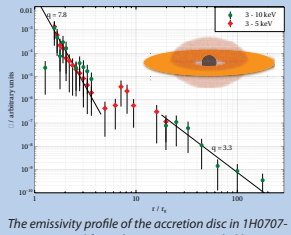
The illumination pattern of the accretion disc by the corona (the *emissivity profile*) can be measured, exploiting the variation in Doppler shift (due to the varying orbital velocity of material in the disc) and gravitational redshift as a function of radius from the black hole. The profile of the broad iron Kα emission line is modelled as the sum of the contributions from successive radii on the disc and the best-fitting contibution of each to the observed spectrum reveals the emissivity profile (Wilkins & Fabian 2011).

General relativistic ray tracing simulations (Wilkins & Fabian 2012) allow the observed emissivity profile of the accretion disc to interpreted and used as a measure of the geometry and extent of the corona. Observed emissivity profiles in a number of AGN, including that in the narrow line Seyfert 1 galaxies 1H0707-495, IRAS 13224-3809 (Fabian *et al.* 2012) and Markarian 335 (Wilkins & Gallo 2015) are reproduced by coronae extending radially over the inner regions of the disc to a few tens of gravitational radii while extending just a few gravitational radii vertically above the plane of the disc.

Guided by theoretical results from ray tracing simulations, high resolution measurement of the accretion disc emissivity profile will all the geometry of both the corona and the inner regions of the accretion flow to be measured in detail.



Variation in the Doppler shift and gravitational redshift across the disc can be exploited to measure the pattern of illumination of the accretion flow by the coronal X-ray continuum. This enables detailed measurements of the inner regions of the accretion flow.

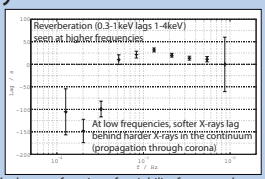


The emissivity profile of the accretion disc in 1H0707-495, measured from the spectrum recorded by XMM-Newton (500ks). The emissivity profile suggests the corona is extended to around $30r_g$ over the disc.

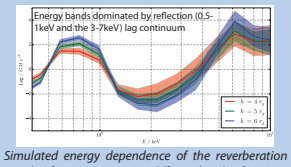
Probing the Corona through X-ray Reverberation

The measured time lags between variability in energy bands dominated by the continuum and those dominated by reflection from the accretion disc are sensitive to the vertical distance between the coronal X-ray source and the disc so allow the vertical extent of the corona to be constrained, complimentary to the radial constraint obtained from the accretion disc emissivity profile. Reverberation lags in 1H0707-495 suggest that although extending radially out to around $30r_g$ the corona extends vertically just $2r_g$ from the disc (Wilkins & Fabian 2013, Cackett *et al.* 2014, Uttley *et al.* 2014).

The X-ray reverberation lag is seen in the high frequency components of the variability, at low frequencies, harder energy bands systematically lag behind softer bands (Kara *et al.* 2013), thought to correspond to the propagation of luminosity fluctuations through the corona with energy initially injected in the less energetic outer parts as fluctuations accrete inward through the disc (e.g. Arévalo & Uttey 2006). Detailed modelling traces the propagation of fluctuations in luminosity through the corona, revealing how and where energy is injected into the powerful X-ray source from the accretion flow.



The lag as a function of variability frequency between the 1-4keV continuum-dominated band and 0.3-1keV reflection-dominated band in 1H0707-495, measured with XMM-Newton in 1Ms (Kara et al. 2013).



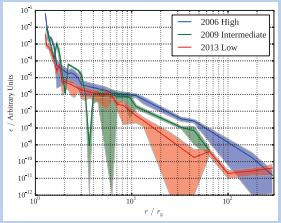
Simulated energy dependence of the reverberation time lag for point sources at different heights for a 1Ms observation with XMM-Newton.

Where reverberation is detected from the accretion disc, the measured energy shift of photons in broadened emission lines depends on the location of reflection on the disc while the measured lag reveals the distance to the illuminating corona, allowing a 3D image to be built up of the immediate vicinity of the black hole.

Variability in the Corona: The driving force behind the luminous X-ray emission

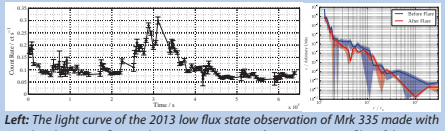
The X-ray emission from AGN is seen to be highly variable with the count rate from many Seyfert galaxies (in particular the narrow line Seyfert 1 galaxies) seen to vary by factors of 2~3 on timescales of just hours. Markarian 335 is a particularly variable NLS1 galaxy which has been observed in high, intermediate and low flux states, with XMM-Newton in 2006 and 2009 and Suzaku in 2013, respectively. The X-ray flux varied by more than an order of magnitude between the high and low flux states.

Measuring the emissivity profile of the accretion disc during each of these epochs reveals that the higher flux states corresponds to the corona expanding to cover a larger part of the inner accretion disc, while in the low flux states, the corona had collapsed down to a compact region close to the black hole (Wilkins & Gallo 2015). Similar behaviour has been observed in 1H0707-495 (Wilkins *et al.* 2014).



Variation in the emissivity profile of the accretion disc in Mrk 335 between high, intermediate and low flux epochs reveals variation in the extent of the corona from the location of the outer break radius. Shaded regions show 1σ errors.

On short timescales, analysis of the accretion disc emissivity profile as well as the spectrum of X-rays reflected from the accretion disc revealed that flares seen during the low flux state of Mrk 335 in 2013 and 2014 marked a reconfiguration of the corona. During the flare, the corona became collimated vertically and was ejected, before the collapsing down to a confined region around the black hole, reminiscent of an aborted jet-launching event (Wilkins *et al.* 2015a,b). Such events give clues to the processes by which the corona is formed and powered and to how jets may be launched.



Left: *The light curve of the 2013 low flux state observation of Mrk 335 made with Suzaku, showing a flare in the X-ray emission.* ***Right:*** *Emissivity profiles of the accretion disc before and after the flare, showing that the flare correspoded to a reconfiguration of the corona from a slightly extended to compact structure.*

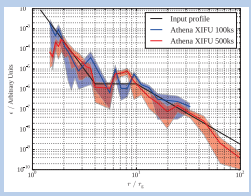
Analysis of the X-rays reflected from the disc, including the accretion disc emissivity profile, suggests that during the flare, the corona became collimated vertically and material was ejected before collapsing down to a confined region.

Prospects with Athena

In order to assess the prospects of the Athena X-ray observatory to make detailed measurements of the X-ray emitting corona, an observation of an object with similar characteristics to the narrow line Seyfert 1 galaxy 1H0707-495 was simulated. Some of the most detailed measurements of the corona have been made from the accretion disc emissivity profile and reverberation time lags in this object.

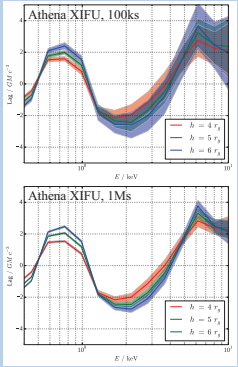
The X-ray spectrum was simulated based on the best-fitting model to 1H0707-495 consisting of directly observed continuum emission from the corona and relativistically blurred reflection from the accretion disc with a twice-broken power law emissivity profile, corresponding to a radially extended corona (as above). An observation was simulated using the Athena XIFU response matrix and the emissivity profile of the disc was measured from the simulated spectrum.

During long observations (500ks or greater), Athena will be able to produce detailed measurements of the accretion disc emissivity profile enabling high fidelity measurements of the corona and opening the possibility of measuring the disc geometry in bright sources. Comparable errors to 500ks observations with XMM-Newton over the inner regions of the disc can be achieved in just 100ks, meaning the chaning emissivity profile (and hence the changing corona) can be followed, in detail, during X-ray flares and other transient events.



Right: *Simulated measurements of lag-energy spectra for an object similar to 1H0707-495 but with a point source illuminating the disc to test the ability of the observations to measure the coronal height.*

Left: *The measured emissivity profiles from simulated spectra of an object similar to 1H0707-495 obsered using the Athena XIFU. 1σ errors are shown.*



X-ray reverberation was simulated from general relativistic ray tracing simulations of X-rays emitted from point sources at varying heights above the black hole. Light curves were simulated to reproduce the count rate and variability that would be expected using the Athena XIFU. Poisson noise was added and lag spectra were computed from the simulated light curves as for real observations.

The large collecting area of Athena would allow precise measurements of reverberation lag in the 0.3-1keV band. The height of the corona could be measured to $1r_g$ precision (at the 1σ level) with just a 100ks observation. Accurate measurement of reverberation of the iron Kα line, where line emission can be resolved into distinct regions of the disc based on the energy shift is more challenging, however in a 1Ms observation, the coronal height can be measured to $2r_g$ accuracy (at the 1σ level). The variation in time lag between energies in the redshifted wing of the line can be easily distinguished, allowing the disc to be resolved in radius.

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E-mail: drw@ap.smu.ca
Web: http://www.ap.smu.ca/~drw

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