Understanding X-ray Reflection in AGN

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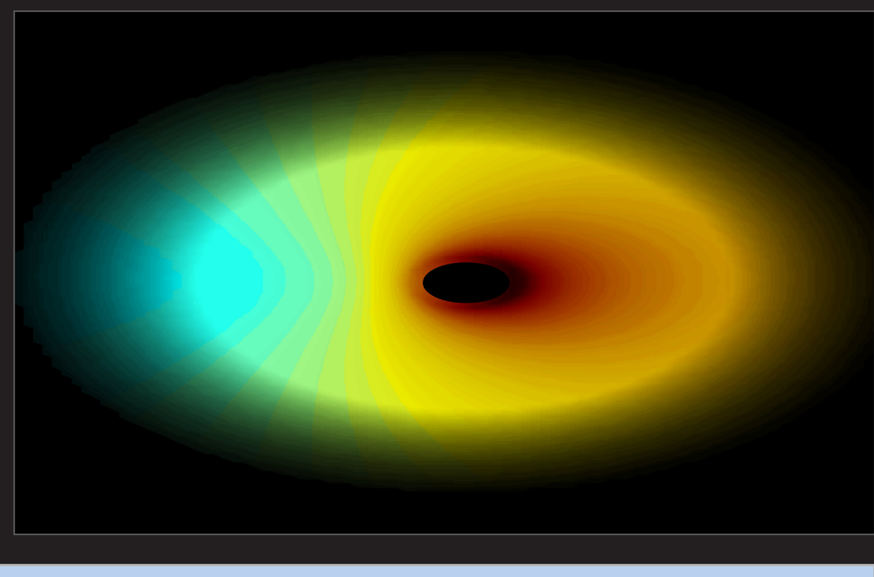
High quality X-ray observations of AGN reveal a number of spectral features resulting from the reflection of X-ray continuum emission from a source in a corona surrounding the central black hole off the accretion disc. These features include the prominent iron Kα emission line at 6.4keV, broadened by relativistic effects close to the black hole and can probe right down to the event horizon. Detailed analysis of the emission line profile reveals the illumination pattern of the accretion flow by the X-ray source (the emissivity profile), which depends on a number of factors including the location and geometry of the primary X-ray source.

Observed emissivity profiles are naturally explained by general relativistic effects on the rays and the accretion disc. Comparing observed emissivity profiles to systematic, high performance, GPU-based ray tracing simulations relates the emissivity profile to the properties of the X-ray source. When combined with measurements of reverberation time lags, constraints can be placed on the location and geometry of the coronal X-ray sources in AGN from observed emissivity profiles.

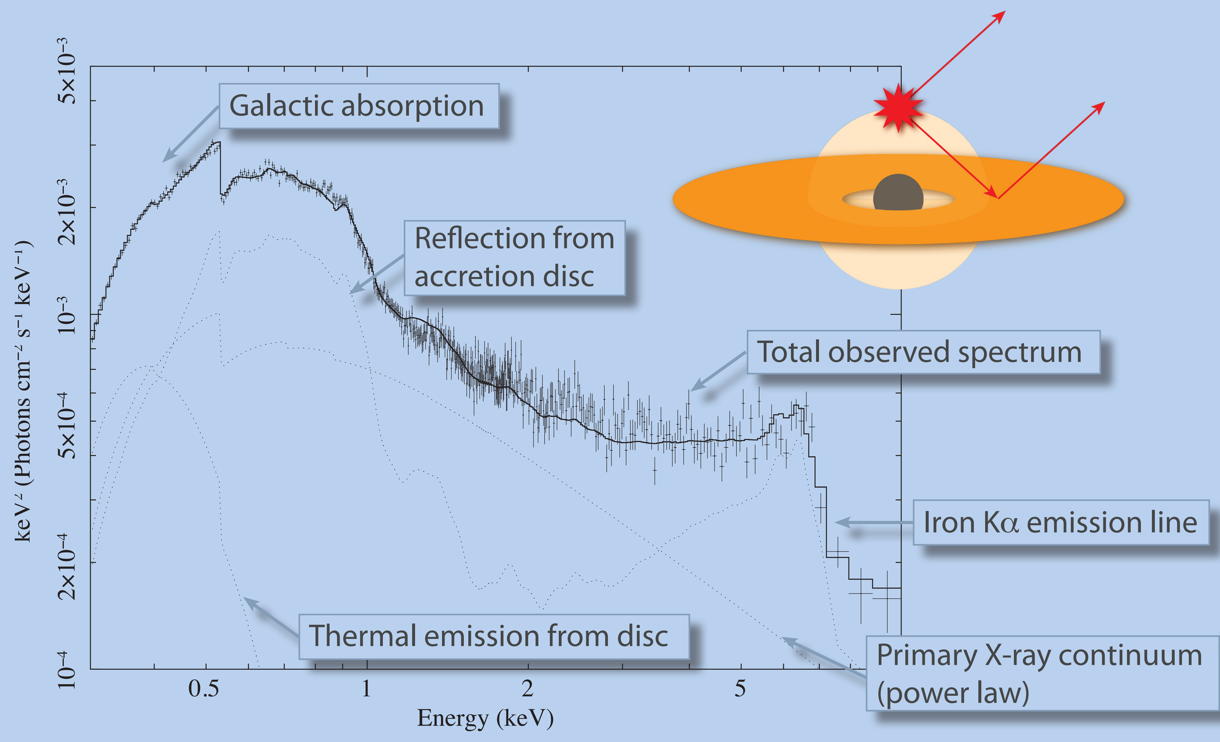


X-ray Reflection

When the X-ray continuum originating from a source in the corona surrounding the central black hole of an AGN is incident upon the accretion disc around that black hole, the incident X-rays are reflected. This imprints a number of absorption and emission features on the reflected X-ray spectrum from the accretion disc, the most promenent of which is the Kα emission line of iron at 6.4keV (measured in the rest frame of the emitting material). The reflection spectrum can be modelled by the REFLIONX code (Ross & Fabian 2005).

An emission line originating from an accretion disc around the black hole will be affected by relativistic effects. These arise from the Doppler shifting of the emission as material in the accretion disc orbits the black hole and gravitational redshift of the emission from material closer to the central black hole. This causes the emission line to be greatly broadened with an extended redshifted wing to lower energies originating from the innermost parts of the disc, as far in as $1.235r_g$ ($r_g = GM/c^2$), for rapidly spinning black holes.

The illumination pattern of the accretion disc (and thus the relative reflected fluxes from different parts of the disc) is characterised by the *emissivity profile*, defined as the reflected flux (per unit area) as measured in the local rest frame on the disc. The details of the emissivity profile will depend on the location, geometry and extent of the primary X-ray source that illuminates the accretion disc. If the emissivity profile can be determined, constraints may be placed on the properties of the coronal X-ray source in AGN.

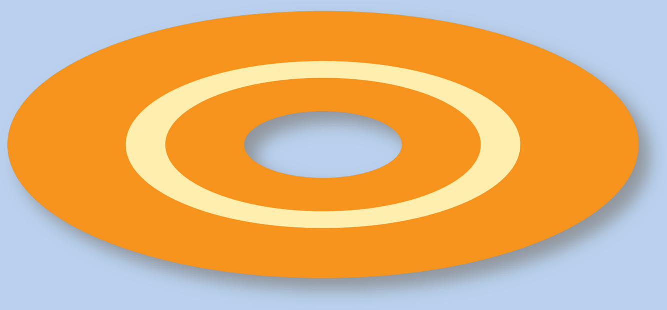


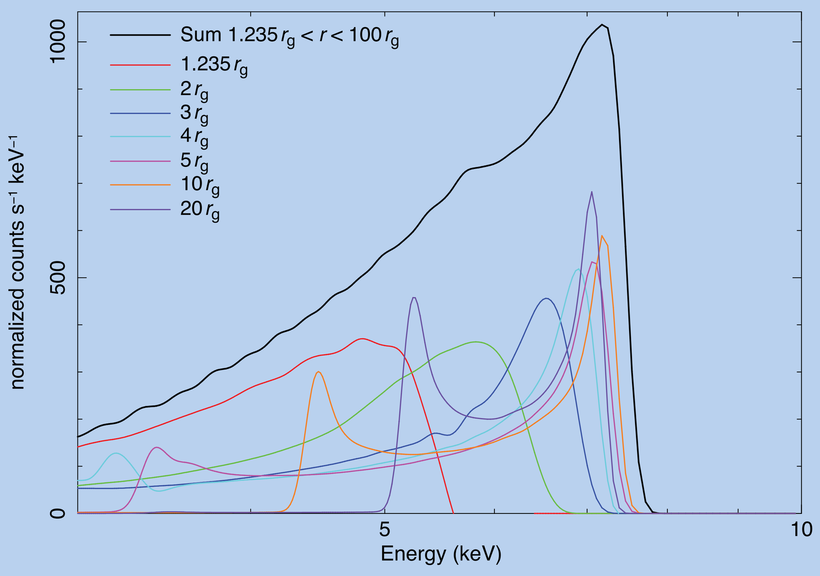
The X-ray spectrum of the narrow line Seyfert 1 galaxy 1H 0707-495 from XMM Newton arising from a primary X-ray continuum reflecting off the accretion disc

Finding the Emissivity Profile

The observed emission line from the accretion disc, broadened by relativisitic effects, can be considered as the sum of the contibutions from succesive annuli in the disc. Since the orbital velocity and the graviatational redshift vary with position in the disc, the line profile originating from each annulus will be different.

To determine the emissivity profile of the accretion disc, the photon counts from the contributions to the iron Kα emission line from successive annuli are fit, using the X-ray spectral analysis package XSPEC, to the observed line in the X-ray spectrum of the AGN. Dividing these photon counts by the areas of the annuli (measured in the rest frame of the reflecting material, taking into account relativistic effects) gives the emissivity profile of the accretion disc due to X-ray reflection.





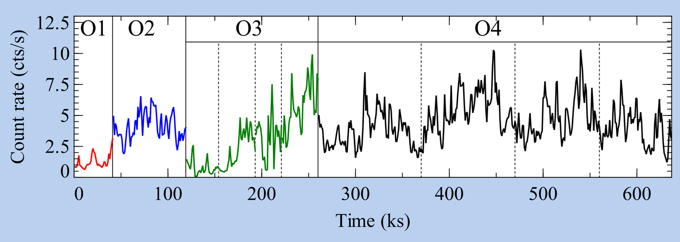
Relativistically broadened emission line profiles from successive annuli in the accretion disc (coloured lines) which contribute to the overall line profile observed (black line)

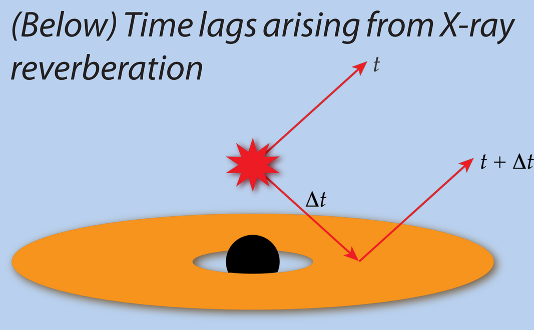
Reverberation Time Lags

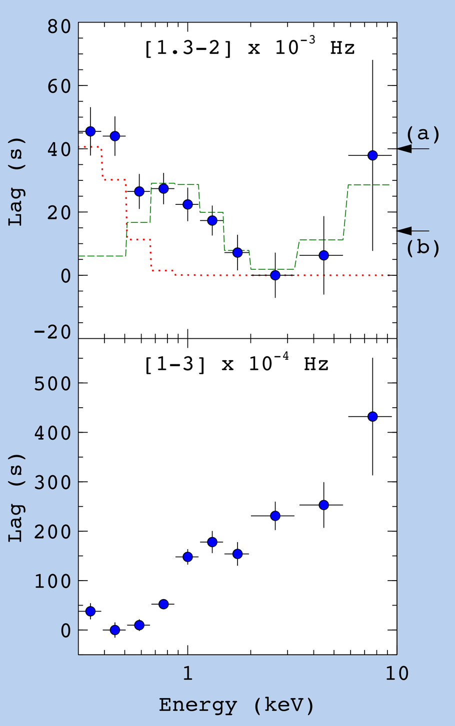
Where the primary X-ray emission is reflected off the accretion disc, variability in the primary source flux will be reproduced in the reflected emission after a time lag due to the light travel time between the source and the reflector, observed in 1H 0707-495 by Zoghbi et al (2010).

(Right) Variability in the X-ray emission from 1H 0707-495

(Below) Time lags arising from X-ray reverberation



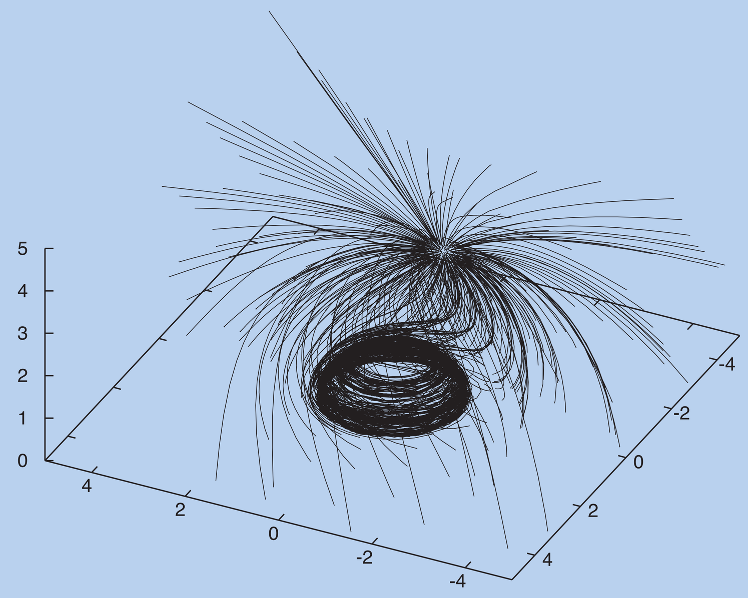




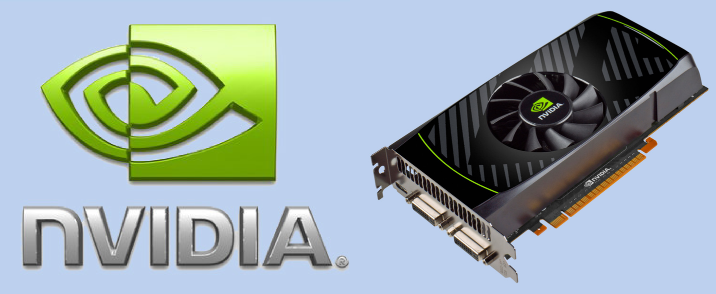
(Right) The time lag between the reflected iron Kα and L emission lines at 6.4 and around 0.9 keV respectively and the X-ray continuum seen here at 3 keV (Zoghbi et al, 2010)

Theoretical Predictions

To understand how the properties of the primary X-ray source affect the accretion disc emissivity profile, ray tracing simulations from an isotropic point source (emitting equal power into equal solid angle in its own instantaneous rest frame) or extended source in the corona, around the black hole, to the accretion disc are undertaken for various source parameters.

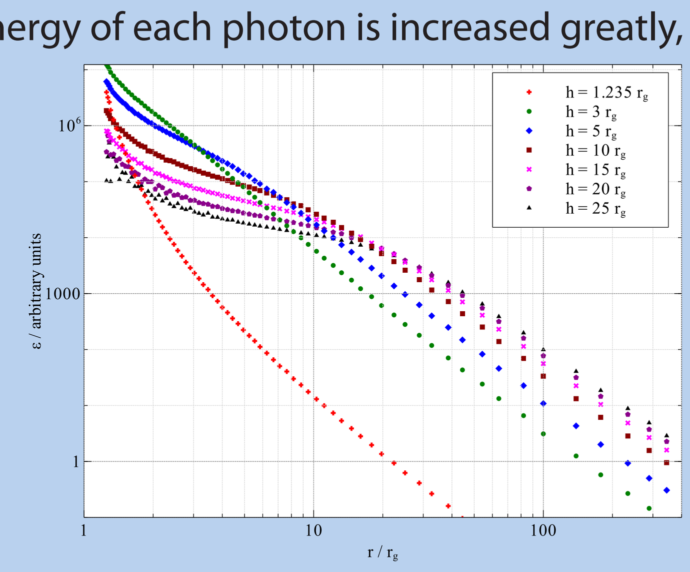


To compute the emissivity profile of the accretion disc, rays are propagated until they reach the equatorial plane (the disc) which is divided into radial bins. The emissivity profile is calculated by dividing the number of rays landing in each bin by the area of the bin (including relativistic effects) and also accounting for the energy and arrival rate of photons along each ray. This is measured in the frame of the reflecting material in the disc since the emissivity is defined as the reflected flux as a function of location on the disc, measured in the frame of the disc material.

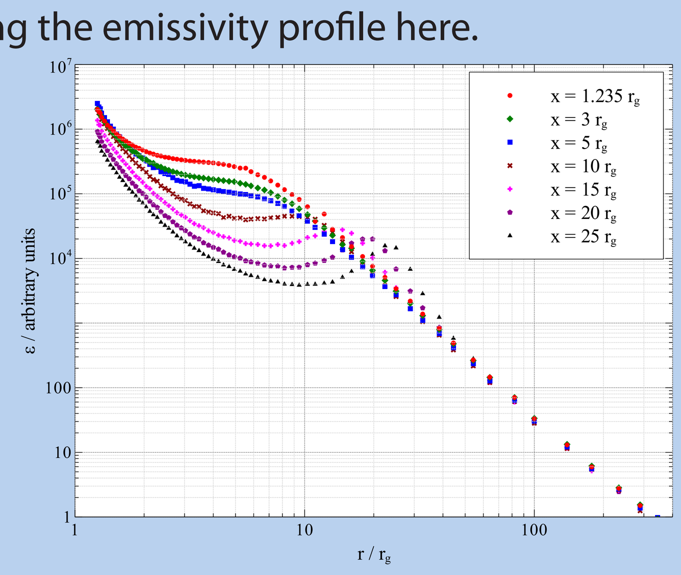


Simulations are performed on graphics processing units (GPUs) using the NVIDIA CUDA programming framework, allowing efficient computation of many rays in parallel

As rays propagate towards the accretion disc, they are focussed towards the inner regions of the disc by gravitational light bending towards the black hole. The emissivity profile is also enhanced on the inner regions as time elapses more slowly closer to the black hole so the photon arrival rate and energy of each photon is increased greatly, steepening the emissivity profile here.



Theoretical emissivity profiles arising from stationary point sources on the rotation axis at varying heights above the black hole



Theoretical emissivity profiles due to point sources at varying radius at a height $5r_g$ co-rotating with the disc

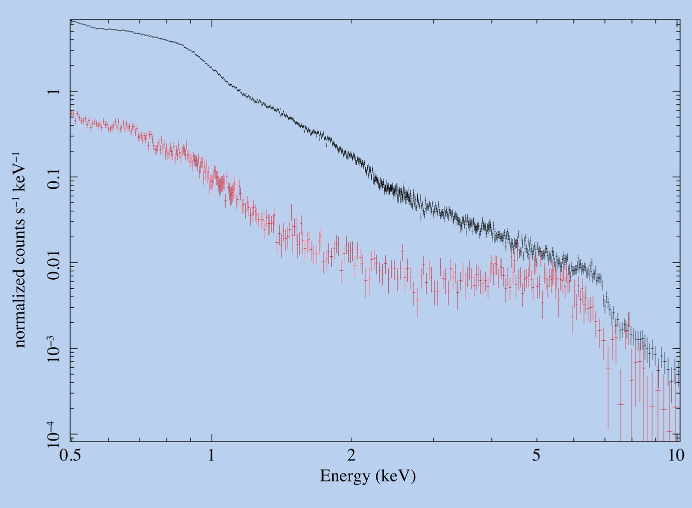
1H 0707-495 – Locating the X-ray Source

The X-ray spectrum of the narrow line Seyfert 1 galaxy 1H 0707-495 was obtained in January 2008 using XMM Newton. The emissivity profile of the accretion disc due to X-ray reflection was determined and was found to take the form of a twice-broken power law, falling off steeply with an index of around 7 out to a radius of $5r_g$, then flattening before tending to a constant power law of index slightly steeper than 3 from a radius of $35r_g$ outwards.

A lag of 30 seconds between variability in the primary X-ray continuum and the reflected emission is observed, indicating that the primary X-ray source is located a distance of $2r_g$ from the reflector.

The observed emissivity profile, when compared to theoretical results along with constraints from the reverberation time lag, imply that the primary X-ray source region extends out to a radius $35r_g$ a height of $2r_g$ above the plane of the accretion disc.

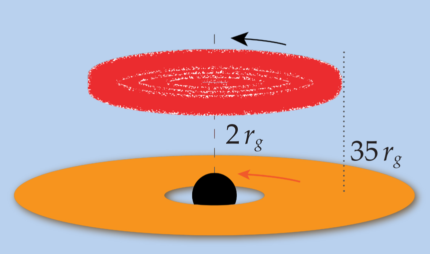
In January 2011, 1H 0707-495 was observed to drop into a low flux state dominated by the reflection spectrum with little or no power law continuum observed. The emissivity profile obtained in this case implies the source had collapsed down to a localised point 1.5-$2r_g$ above the disc plane.

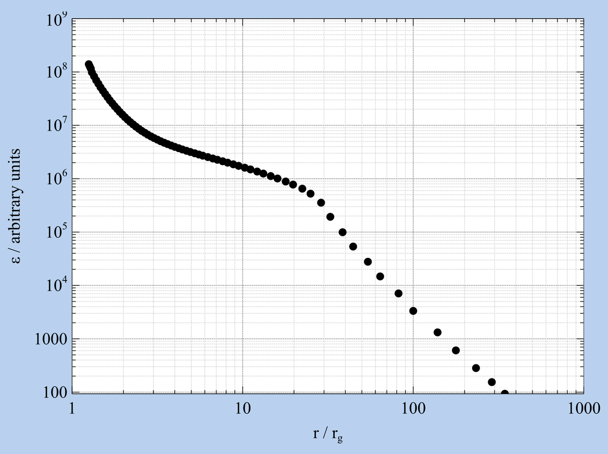


(Above) X-ray spectra for 1H0707-495 in January 2008 (black) and January 2011 (red) obtained using the EPIC pn instrument on board XMM Newton

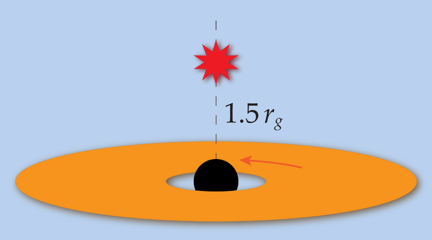
(Right) The observed accretion disc emissivity profiles for the 2008 and 2011 observations of 1H0707-495 reproduced by ray tracing simulations for the shown source geometries

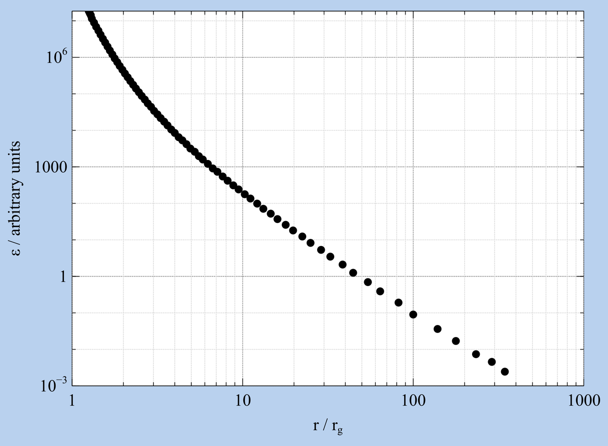
January 2008





January 2011





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