Measuring Properties of Accreting Black Holes with X-Ray Reverberation
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Summary

Accreting black holes show characteristic components in the time-averaged energy spectrum and distinctive features in their time variability. When properly modelled, these diagnostics can constrain the geometry of the systems and the parameters of the black hole. Jointly accounting for both the energy and the time dependence of the X-ray radiation from accreting black holes exploits the complete information provided by the observations. This thesis focuses on studying the variability and energy dependence of the reflection component. This is the emission due to photons originally radiated from the corona (hot optically thin plasma close to the black hole) that illuminate the accretion disc, are re-processed in the disc atmosphere and are re-emitted before reaching the observer. There is evidence that this process occurs both in black hole X-ray binaries and active galactic nuclei (AGN). Interestingly, the energy and timing response of the accretion disc is different for every patch of the disc, because of the different strength of the relativistic effects that shift the energy of photons as they travel from source to observer, and the different light crossing times of the illuminating and reflected radiation. Therefore the reflection is a useful spectral component with which to exploit the possibilities afforded by combining the energy and timing aspects of the emission. One of the best ways to do this is to study the time lags of variations in the reflection component compared to those in the continuum component, which is emitted directly towards the observer and whose variations therefore arrive earlier. These reverberation lags are observed at relatively short timescales (Fourier frequencies $> 300M_{\odot}/M$ Hz). At longer timescales, the lag energy spectrum is instead dominated by another process, thought to be associated with mass accretion rate fluctuations propagating through the accretion flow. These propagating mass accretion rate fluctuations lead to stochastic variations in the electron temperature of the corona by varying both the release of gravitational energy and the Compton cooling rate in the corona, which results in small fluctuations in the slope of the coronal emission (‘pivoting’) that can show up as time lags.

In this thesis, I present a new model that jointly addresses these two types of lag. Chapter 2 presents the mathematical formalism that describes this pivoting of the coronal spectrum and the lags that it produces. The illuminating spectrum seen at each point on the disc is different. This affects the reflection spectrum re-emitted by each disc patch and therefore the shape, and not just the strength, of the
reverberation energy spectrum. The consequences of these non-linear effects for the lag energy spectra are calculated assuming a compact corona located on the black hole spin axis, so that the slope of the illuminating spectrum depends on disc radius but not azimuth. Although the formalism of Chapter 2 does not include a full General Relativistic calculation of the photon trajectories from the corona to the disc and from the disc to the observer, we present a proof-of-principle analysis of Rossi X-ray Timing Explorer data of Cygnus X-1 and achieve an acceptable fit, albeit with some residual structure around the iron Kα emission line.

Chapter 3 presents the new model RELTRANS, which improves upon the model explored in Chapter 2 by calculating the exact geodesic trajectories of the photons in the Kerr metric with a ‘ray tracing’ technique. The model accounts for both the energy and the timing response of the accretion disc, and so computes both the time-averaged spectrum, which can be compared with existing relativistic reflection models, and the time lag as a function of energy. The relativistic corrections to the reverberation mechanism are calculated using a transfer function formalism.

In Chapter 4 RELTRANS is extended by now also including the non-linear effects due to the hardness fluctuations first explored in Chapter 2. The proof-of-principle Cygnus X-1 fit presented in Chapter 2 suggested an inner radius of the disc and a position of the illuminating source both very close to the black hole. However, in these conditions the relativistic effects are important, and thus our new fully relativistic version of the model is required to accurately describe the data. Indeed, the new Cygnus X-1 analysis improves the fit to the data, and by jointly fitting the time-averaged energy spectrum and the complex cross-spectrum as a function of energy for multiple Fourier frequencies we are able to accomplish the first X-ray reverberation mass measurement of a stellar mass black hole. Moreover, we find that model configurations that account for a radial ionization profile in the disc are statistically preferred over configurations that make the less physical assumption of constant ionization. The different masses measured using different ionisation profiles are all compatible with the dynamical mass measurement of Cygnus X-1 within 3σ, with a more realistic ionisation profile producing a reverberation mass value closer to the dynamical value.

Finally we also considered the applicability of the model to a supermassive black hole, Markarian 335, first fitting only the reverberation lags (Chapter 3) and later the correlated variability amplitudes and the time lags at different timescales (Chapter 5). The results in Chapter 5 already show that the model produces a useful constraint on mass. However, they also make clear that fitting only a single frequency range leaves some degeneracy among parameters, such as source height and black hole mass. Therefore, Chapter 5 provides experiments towards a more sophisticated analysis of the time lags and the variability amplitude of Markarian 335 studying both the reverberation lags and the intrinsic lags due to the pivoting. The fit to the time lags seems to favour lower values of the black hole mass (a few million Solar masses) than the optical reverberation mapping measurements (∼ 10 - 20 million Solar masses).
However, when we fit our model also to the correlated variability amplitudes, the model is unable to describe some characteristic reverberation features present in the data, and can not provide useful constraints to the black hole mass, suggesting the presence of physical processes not addressed by the model. In fact the coherence between energy bands is not unity at all the timescales as assumed in the model.

The conclusion of the work is that energy-resolved Fourier timing analysis of accreting black holes is a powerful tool for inferring information from spectral variability data not otherwise accessible. In this thesis we modelled the spectral timing behaviour by creating and exploring a mathematical formalism that enables the reverberation lags to be self-consistently modelled for a large range of variability timescales in an analytic model suitable to fit to real-world data.