Probing the Evolving X-ray Sources of Accreting Black Holes

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Detailed analysis of observed reflection features in the X-ray spectrum and of the variability of the emission showing reverberation time lags between the directly observed continuum and reflection from the disc has made it possible to probe the innermost regions of accreting black holes, down to the innermost stable orbit and the event horizon. Comparing detailed analysis of energy and lag spectra to theoretical predictions constrains the locations of the X-ray sources in a number of AGN including 1H 0707-495, IRAS 13224-3809 and MCG-6-30-15.

With high quality data from long X-ray observations of these sources, it has, for the first time, been possible to follow the evolution of the coronal X-ray source as the luminosity of the source goes up and down. We are able to find evidence that the size and other properties of the X-ray source change on the timescale of a few hours, giving rise to the extreme variability seen in these sources, with the general trend being that as the source size and the luminosity increases, so does the variability. This detailed analysis of observed reflection features and of the variability of the emission showing reverberation time lags between the directly observed continuum and reflection from the disc has made it possible to probe the innermost regions of accreting black holes, down to the innermost stable orbit and the event horizon. Comparing detailed analysis of energy and lag spectra to theoretical predictions constrains the locations of the X-ray sources in a number of AGN including 1H 0707-495, IRAS 13224-3809 and MCG-6-30-15.

X-ray Emission from Accreting Black Holes

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 will be reflected. This causes a number of absorption and emission features to be imprinted on the spectrum of the X-rays reflected from the accretion disc, the most prominent of which is the Kα emission line of iron, at 6.4keV (as measured in the rest frame of the emitting material).

An emission line originating from an accretion disc around a black hole will be affected by relativistic effects due to the Doppler shifting of the emission as the material in the accretion disc orbits around the black hole as well as 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 close as 1.235GM/c^2, to rapidly spinning black holes.

The X-ray emission from AGN is extremely variable and measurements of this variability have 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. The time lags are a probing the innermost regions, right down to the innermost stable orbit and event horizon.

Observational Probes of Black Hole Structure

Detailed analysis of the X-rays detected from accreting black holes allows their structure to be probed down to just a few gravitational radii from the event horizon and the innermost stable orbit. This is achieved through analysis of both time-averaged X-ray spectra and the variability of the X-ray emission.

Resolving the Accretion Disc through Spectral Observations

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 profile of a relativistically broadened emission line is different from successive radii in the disc, due to the change in the orbital velocity and gravitational redshift moving further from the black hole. It is therefore possible to determine the emissivity profile of the accretion disc by fitting the relative contributions to the profile of the relativistically broadened iron Kα emission line of the blurred reflection spectrum from each radius (Wilkins & Fabian 2011).

Measurement of Reverberation Time Lags

The innermost structure of the accreting black hole can be probed by measuring the time lags between variability in an energy band dominated by direct continuum emission from the corona and one dominated by reflection from the disc. These time lags correspond to the additional light travel time between the source and reflector.

The time lags are found by taking the Fourier transform of the light curves and the time lag is calculated for each frequency component to produce a lag spectrum (Zoghbi et al 2010, Kara et al 2012).

Understanding Emissivity Profiles and Lag Spectra

Theoretical emissivity profiles are computed by tracing rays from their source in the corona until they hit the accretion disc where their location is recorded. When extended X-ray sources are considered, the outer break point of the emissivity profile, where the flat middle region becomes an inverse-cube fall-off over the outer part of the disc, is identified with the outermost radial extent of the X-ray source (Wilkins & Fabian 2012).

Observeable lag spectra may be simulated by computing the reverberation response from the accretion disc to an instantaneous flash in the corona. Counting the number of rays arriving as a function of time gives the transfer function. Convolving this with the intrinsic variability of the X-ray source (or the light curve observed in the continuum-dominated band) gives the light curve of the reflected band, and theoretical lag spectra between these bands can be calculated. It is necessary to know the arrival time of direct rays from the source and the fractions of continuum and reflected emission seen in each energy band as input to the simulation process.

Locating the Corona

From both the accretion disc emissivity profile and lag spectrum, the X-ray emitting coronae in AGN are found to extend out to cover the inner parts of the accretion disc and extend vertically to around 2r_g, in 1H 0707-495 and around 10r_g, in IRAS 13224-3809 and MCG-6-30-15, with the lower limit for the length of the coronal region becoming inversely proportional to 1/ r_g.

Conclusions

• Through detailed X-ray observations (spectral and timing) it is possible to probe the innermost regions of accreting black holes.

• It has been possible to locate the X-ray emitting coronae in 1H 0707-495, IRAS 13224-3809 and MCG-6-30-15.

• Studying the X-ray spectrum in changing flux states reveals that increases in X-ray count rate are associated with an expansion of the corona and a softening continuum spectrum.

• Observables products over a range of X-ray time scales, which would be used to test our understanding of the black hole.

References


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