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The Future of X-ray Reverberation from AGN

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XMM-Newton is capable of making a transformational advance in our understanding of how luminous accreting black holes work, by dedicating about 10% of future observing time to long observations, of order Megaseconds, to X-ray variable Active Galactic Nuclei (AGN) research. This would enable reverberation studies, already a commonplace feature of AGN, to proceed to the next level and follow the behaviour of the powerful dynamic corona. Such a dedicated legacy programme can only be carried out with XMM-Newton.

1 Introduction

The current picture of the inner regions of a luminous Active Galactic Nucleus (AGN) shows an accretion disc extending down to the Innermost Stable Circular Orbit (ISCO) around a supermassive black hole. Magnetic fields extending upward from the disc power a compact corona (Galeev et al. 1979; Haardt & Maraschi 1993). Energetic electrons in the corona Compton scatter soft thermal photons from the accretion disc to produce a power-law X-ray continuum. This emission in turn irradiates the disc to produce fluorescent and other lines with backscattered continuum X-rays, together known as the reflection spectrum (Fabian & Ross 2010; George & Fabian 1991). If the coronal power varies, we see changes in both the power-law continuum and in the reflection spectrum, but with a delay between them due to the longer light path taken by reflection: this is the process of reverberation (Uttley et al. 2014).

The observer sees the sum of the coronal power-law and the delayed reflection, which also has a continuum component. They can be separated since the reflection spectrum differs in shape from the coronal power-law, due to atomic emission and absorption processes as well as Compton recoil (for analysis techniques see Uttley et al. (2014)). It generally appears as a soft excess at low energies below 1 keV, a broad iron line from about 4–7 keV and a Compton hump above 10 keV. This means that lightcurves made in soft X-rays (0.3–1 keV)and the iron-K band lag behind those made in bands dominated by the coronal power-law emission. Using many different bands, a full reverberation energy spectrum has been made in many of the brightest X-ray variable AGN (Fig. 1), revealing the broad iron line characteristic of inner disc reflection which confirms the above picture. The lag timescales indicate that the separation of the corona from the disc is often small, about 10 gravitational radii ($10r_{\rm g} = 10GM/c^2$) or less (Cackett et al. 2014; Chainakun & Young 2015; De Marco et al. 2013; Emmanoulopoulos et al. 2014).

The combination of reflection and reverberation means that we have a powerful tool with which to explore luminous accretion onto black holes. They can help to solve outstanding questions about the origin, shape and activity of the corona. How is the corona powered, how does it change in size or location as the power increases or decreases? Is the corona related to jets and/or winds from AGN? How well can we determine the radius of the ISCO and thus the spin of the black hole? Does the disc truncate as its power or the mass accretion rate drops? Reverberation/reflection studies have the potential to transform our understanding of the inner regions of accreting black holes.

Rapid X-ray reverberation in AGN was discovered with XMM-Newton (Fabian et al. 2009) and most results have since been obtained with XMM-Newton, together with a handful of NUSTAR contributions which have revealed the reverberation of the Compton hump (Zoghbi et al. 2014). About 50 per cent of a sample of 43 variable AGN observed with XMM-Newton show high frequency, iron K reverberation which indicates that reflection is involved (Kara et al. 2016, Fig. 1). The key requirements for such studies are lots of photons (defining “variable counts” to be total counts

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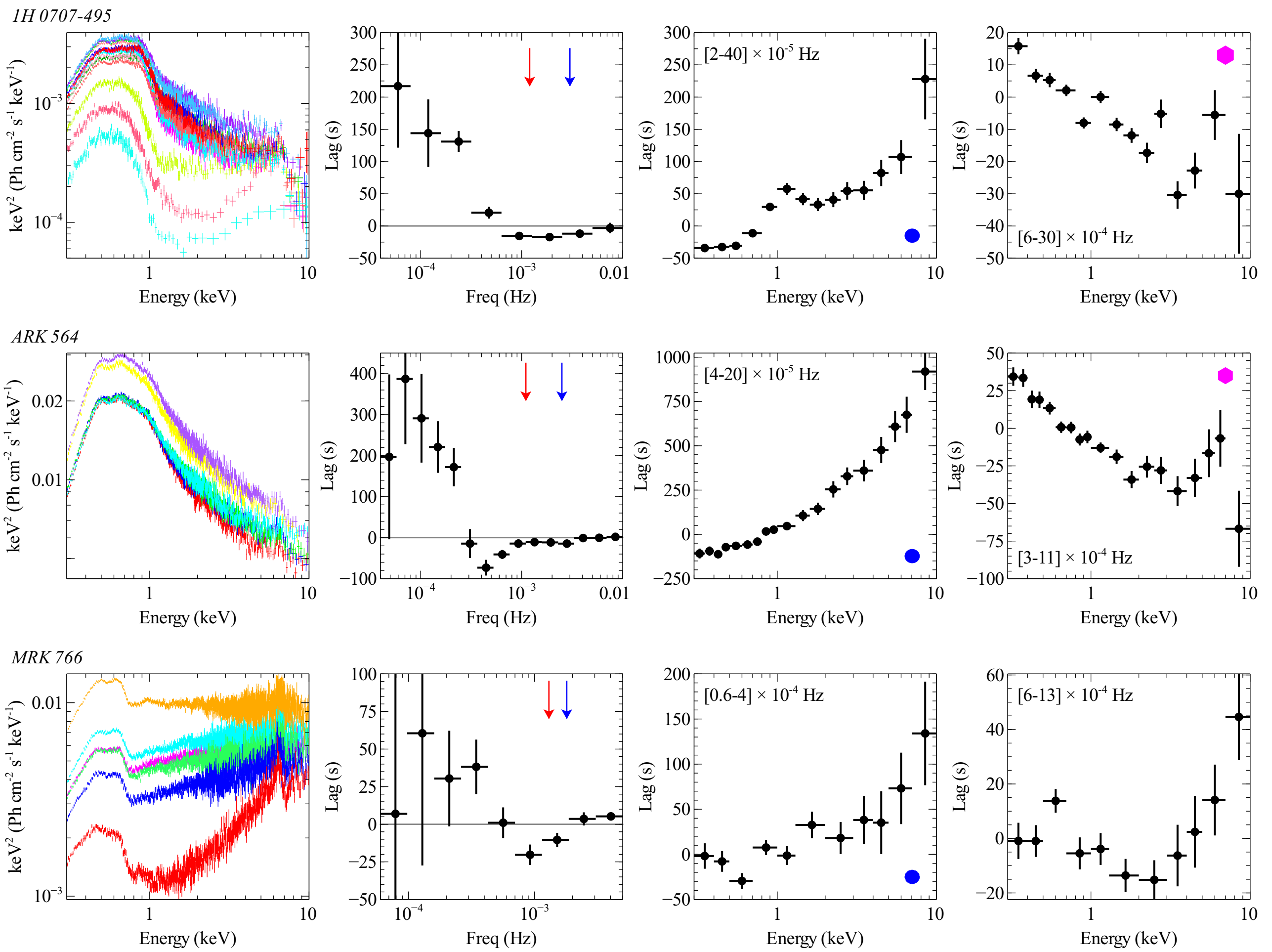

Fig. 1 From left to right: Energy spectrum, lag-frequency spectrum, low frequency lag-energy spectrum, high frequency lag-energy spectrum for (top to bottom) 1H0707-495, Ark 564, MRK766; Kara et al. (2016). Note in Ark564 that the low frequency lag energy spectrum is featureless, whereas the high frequency one reveals an iron line, showing that it is due to reflection. Mrk766 has no obvious iron line in its high frequency lag energy spectrum. Its behaviour resembles that of MCG–6-60-15.

times fractional variability, $> 7,000$ are needed, Fig. 2) and long observing times (> 40 ks Kara et al. (2016)).

Even with a few 100ks of exposure (ie 2–3 XMM-Newton orbits), the typical current reverberation data quality allows identification of only a characteristic reverberation time which translates roughly to the height of the corona from the disc. This typically is about $3-10r_{\rm g}$. The archival data have now been thoroughly explored (De Marco et al. 2013; Kara et al. 2016). As shown in Fig. 3, the reverberation signal is richer than this and it should be noted that the corona is also likely to be a dynamic not static phenomenon. Pushing the subject forward so that we can explore and map the inner regions of the X-ray emission region around luminous variable accreting black holes requires a leap of 3 to 10 in observing time for a significant sample of AGN (Fig. 4). This means exposures of 300 ks to 1Ms.

Studying a sample drawn from the 33 objects with more than 5,000 variable counts in Fig. 2 would be an excellent start. As well as examining in more detail the known lag sources we need to explore why some sources do not yet show lags despite reasonable exposures.

At its current observing efficiency, XMM-Newton obtains data for about 18 Ms per year, so over the next 5 years, the total integrated exposure should be 90 Ms. If 10 per cent of this observing time is dedicated to long (Ms) AGN exposures then a sample of about 10–20 objects can be studied in depth. What this represents is a committed reverberation/reflection study to understand how the central engine in the most luminous persistent objects in the Universe operates, namely the accreting supermassive black holes. It is a legacy study that cannot be carried out at any other wavelength.

2 Some Details

A pulse of emission from a point-like corona reverberates off the disk in the manner shown in Fig. 3. The result

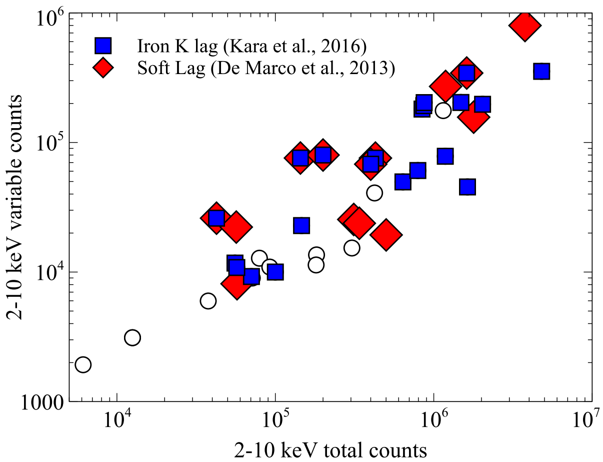

Fig. 2 Variable counts in the 2-10 keV band plotted against total counts for 43 variable AGN (adapted from Kara et al. (2016)). Open circles represent non-detections. 80% of AGN with more than 7,000 variable counts (total counts times fractional variability) show reverberation lags. Sources with soft lags (De Marco et al. 2013) are marked by a red diamond.

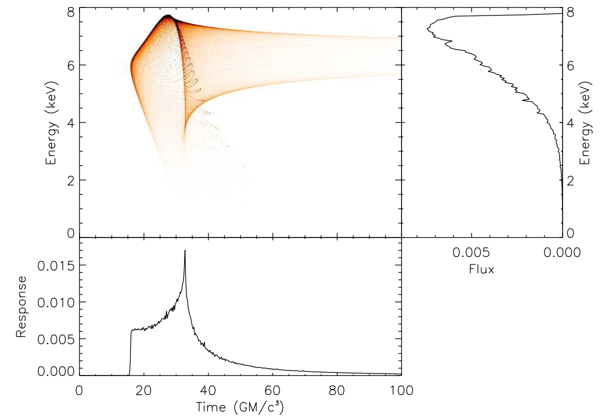

Fig. 3 Theoretical energy – time-lag diagram from single irradiation flash from a point-like corona at a height 10 r_g above the centre of an accretion disc above a rapidly spinning black hole. The disc is inclined at 60 degrees. What is seen is the development of the reverberation of a 6.4 keV iron fluorescent line. The largest energy spread comes from the smallest radii. The projection onto the energy axis shows the broad iron line (to the right) and onto the time axis the impulse response function (for all energies). See (Cackett et al. 2014; Campana & Stella 1995; Reynolds et al. 1999).

changes with inclination. The reverberation signal in both temporal frequency and energy contains valuable information on the size and geometry of the inner accretion flow and the corona. Most current work has only captured the gross aspects of the the reverberation process, yielding a characteristic time associated with the bulk of the return signal.

This constitutes the simple lamp-post model in which the corona is a point source on the rotation axis of the accretion disc. It makes the situation computable and minimises the number of free parameters. Note that the computations need to be carried out in the Kerr metric, with strong light bending and energy shifts. In practice of course the corona is extended, either radially and/or vertically as discussed by Wilkins et al. (2016). It probably changes size. If for example it is extended vertically (Fig. 5) and its length h varies, then strong light bending means that the upper end may dominate the observed continuum while the lower end dominates the reflection. This could be the situation in MCG–6-30-15 and Mrk766 which both show soft lags (0.3–1 vs 1–4 keV), but the continuum and iron line are not well correlated and no Fe-K reverberation is seen as yet.

The coronal matter may be outflowing through the corona leading to the continuum being beamed away from the disc at mildly relativistic velocity. This situation has been modelled by (Beloborodov 1999) and can plausibly explain the low reflection fraction seen in some objects. The corona may evolve from being static to outflowing in an object, leading to an apparent continuum outburst as seen in Mkn 335 (Wilkins et al. 2016; Wilkins & Gallo 2015, Fig. 4). It is also plausible that the corona is corotating with the disc beneath it and beaming coronal radiation along the disc. In other words, the corona is likely to be dynamic, rather

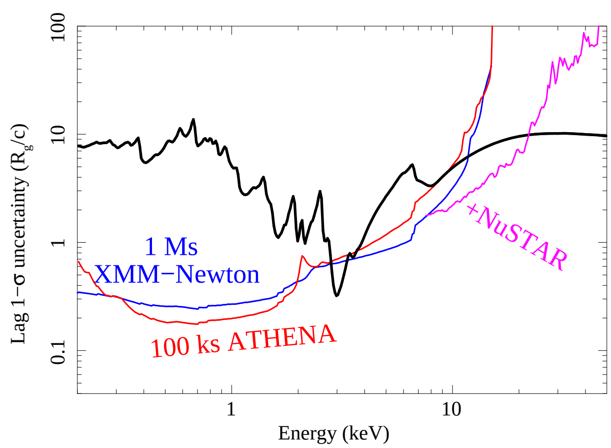

Fig. 4 Simulation showing achievable sensitivity in units of r_g/c, adapted from (Uttley et al. 2014). The black line is a 'sample' lag-energy spectrum (for a 10^6 $M_\odot$ AGN). The assumed 2–10 keV flux is 4×10^{-11} cgs (for AGN everything scales with $\sqrt{\text{flux}}$ so it is easy to see what is needed for other flux levels). The lag errors just scale with $1/\sqrt{\text{exposure time}}$. Note that whilst a 100 ks ATHENA exposure can statistically match a 1 Ms XMM-Newton exposure on high frequency lags (modelled here) it cannot reach the lowest frequency propagation lags ($\ll 10^{-4}$). Similarly, the long XMM-Newton exposures yield an average result whereas a shorter ATHENA exposure can follow the changes in a corona on 100 ks timescales.

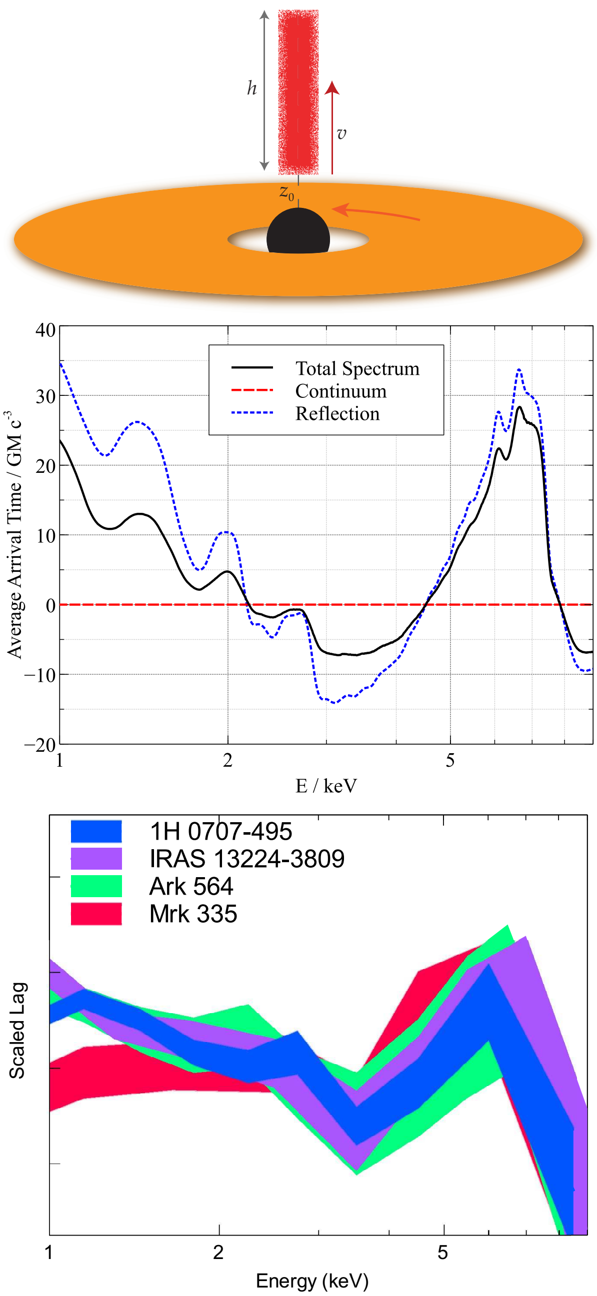

Fig. 5 Top: Schematic model of vertically extended corona in which the matter flows upward at velocity v (Wilkins et al. 2016). Centre: Lag energy spectrum resulting from this model when v increases upward with height h. Lower: Lag energy spectrum for 4 objects in which the dip at 3–4 keV matches that seen in the centre panel.

than a fixed object. To understand it we must be prepared to follow its changing nature.

All of the effects discussed above occur at high temporal frequency so we are dealing with variations on the light-crossing time of the inner region (frequency $f < c/50r_{\rm g}$ which is typically above 2×10^{-4}Hz for black holes of mass $10^6 - 10^7\,{\rm M}_\odot$). Below that frequency ($f < 2 \times 10^{-4}$Hz) it is common to see *hard* lags in which the 1–4 keV band lags the soft X-ray band of 0.3–1 keV. These are not due to reverberation but appear to be intrinsic to the process powering the corona. Such low frequency hard lags are common in accreting black hole systems and have been seen for a long time, being first seen in the Black Hole Binary Cyg X-1 (Miyamoto & Kitamoto 1989). Perhaps the best description of them is as fluctuations created and propagating through the accretion flow (Kotov et al. 2001).

Low-frequency, hard lags typically have a log-linear energy spectrum which does not show reflection features, unlike the high-frequency soft lags. They may however have a high frequency contribution which interferes with the detection of the true reverberation signal in some objects. They may be modelled and corrected for if we understood their origin better.

Finally, there can be variable absorption along the line of sight. This can be modelled and corrected as in NGC1365 (Walton et al. 2014), revealing the reflection spectrum underneath. It represents a source of additive noise to the variability process. Low frequency time lags can be affected by distant absorption (e.g. NGC1365; (Kara et al. 2015)), therefore time lag studies can place independent constraints on complex absorption (Silva et al. 2016).

3 Summary

A dedicated 5 year, 9 Ms, XMM-Newton legacy AGN reverberation programme is expected to transform our understanding of the innermost energy-generation region (the central engine) of luminous accretion onto black holes. It will enable us to go beyond the simple detection of a characteristic timescale and reveal the corona in dynamic detail, its interaction with the accretion flow and the inner accretion disc immediately around the black hole.

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