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X-ray reverberation in NLS1

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Reverberation from scattering material around the black hole in active galactic nuclei is expected to produce a characteristic signature in a Fourier analysis of the time delays between directly-viewed continuum emission and the scattered light. Narrow-line Seyfert 1 galaxies (NLS1) are highly variable at X-ray energies, and are ideal candidates for the detection of X-ray reverberation. We show new analysis of a small sample of NLS1 that clearly shows the expected time-delay signature, providing strong evidence for the existence of a high covering fraction of scattering and absorbing material a few tens to hundreds of gravitational radii from the black hole. We also show that an alternative interpretation of time delays in the NLS1 1H 0707–495, as arising about one gravitational radius from the black hole, is strongly disfavoured in an analysis of the energy-dependence of the time delays.

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1. Introduction

The measurement of reverberation at optical wavelengths has become a powerful technique for estimating the size of the broad-line region in active galactic nuclei (AGN), and combining with line velocity widths allows estimates of black hole mass in AGN to be made (e.g. [1]). Here we describe the characteristic signature we expect from reverberation and show evidence that this signature has been detected at X-ray energies, implying the existence of large global covering factors of material a few light hours from the black hole, corresponding to a few tens to hundreds of gravitational radii ($\mathrm{r}_g \equiv GM/c^2$).

2. Reverberation signatures in Fourier space

2.1 The analysis of data

Reverberation signatures are measured by cross-correlating two time series and searching for time delays between them. In AGN at optical wavelengths, one of the time series is the flux measured in a continuum bandpass, the other the flux measured in an emission line. A measured time delay between these two gives us the light travel time between the continuum source and the line-emission region, averaged over the distribution of circumnuclear material.

A natural approach to measuring cross-correlation time delays is to work in Fourier space, and we shall see below that reverberation creates a characteristic signature in the Fourier phases as a function of the frequency of variation of the source. However, we cannot simply take the Fourier transforms of the two light curves to make such an analysis, for several reasons:

1. Observed time series are discretely sampled, with non-uniform coverage and large gaps between multiple observations. If Fourier transformed, the window function of the observations would completely dominate the signal.
2. Observed time series have measurement noise, which adds a floor to the powerspectrum and which may bias the measured time delay if uncorrected.
3. Any one set of data is just a particular realisation of the source's variations: it is a snapshot in time. In order to correctly estimate the uncertainties in our measurements, we must allow for the expected statistical variations in the source.

To tackle these issues, we have developed a maximum-likelihood approach, which finds the powerspectra and cross-powerspectra that best fit the time-domain data, taking full account of the sampling and noise, and with estimated measurement uncertainties that fully account for the "cosmic variance" of item (3) above. The method is based on the "direct likelihood" approach used for analysis of small cosmic microwave background datasets [2]. More details are given by Miller et al. [3, 4].

2.2 The reverberation signature

In the following work, we shall consider the "lag spectrum": the time lags between two time series as a function of the frequency of the source variation. These time lags τ are obtained from the phases ϕ of the Fourier transform of the cross-correlation function, $\tau = \phi/\omega$, where ω is the angular frequency.

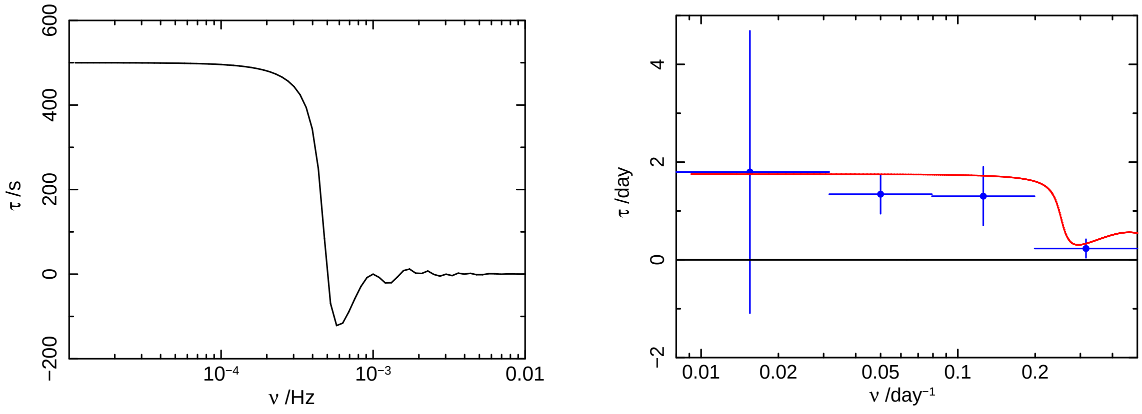

Figure 1: *Left panel:* The lag spectrum expected from a simple partial-covering thin shell of diameter 2000 light-seconds, showing the rapid transition in time delay at $\nu \simeq 5\times10^{-4}$ Hz, when the time period of the Fourier mode equals the light travel time across the shell (the low-frequency time delay of 500 s has been diluted in this realisation by adding direct light into the scattered-light time series). *Right panel:* The lag spectrum for the Hβ and optical continuum variations in NGC 4051 observed by [5], measured here using the maximum-likelihood method. The data (blue points with error bars) show a rapid transition at $\nu \simeq 0.2\,\mathrm{day}^{-1}$, indicating the distance across the emission-line region to be about 5 light days, with a mean lag of about 1.8 days. The red curve shows an illustrative model (not a best-fit) of an inclined scattering annulus.

Consider a simplified case of a thin spherical shell of material surrounding an AGN, where directly-seen light is emitted from a point-like source at the centre and measured in one time series, and light scattered from the shell is observed in a second time series. We get some interesting effects if we make the shell “partial-covering” by removing the parts of the shell that are both closest to us and furthest away, so that the shell resembles a ring seen end-on. Fig. 1 shows the expected lag spectrum for this case. At high frequencies, where the mode time period is much shorter than the light travel time across the shell, scattering from different parts of the shell add incoherently, with a wide range of phases, so the net time delay tends to zero, with some oscillations that depend on the shell structure. At low frequencies, where the period is much longer than the light travel time across the shell, the scattered light adds mostly coherently and we see a mean time delay for the shell. At a frequency where the time period equals the light travel time across the shell, we see a sharp transition between these two regimes, with the time delay even plunging negative for some ranges of frequency. Of course, all the scattered light signals actually are delayed: the negative lag behaviour arises because we are looking in Fourier space, and at this frequency the phases are starting to wrap around by more than 2π radians. If the shell were symmetric and full-covering, the time delays oscillate but stay positive: lags can change sign in the case of a partial-covering shell as shown here.

The behaviour from this simple model is broadly reproduced by a wide range of more realistic scattering scenarios with scattering from a range of radii [3]: a mean lag at low frequencies, transitioning to oscillatory and small time lags at high frequency. The detailed oscillatory structure tells us about the reverberation structure and geometry, but the basic signature that we should look for is the dramatic change in lag at some characteristic frequency, the value of which tells us the size

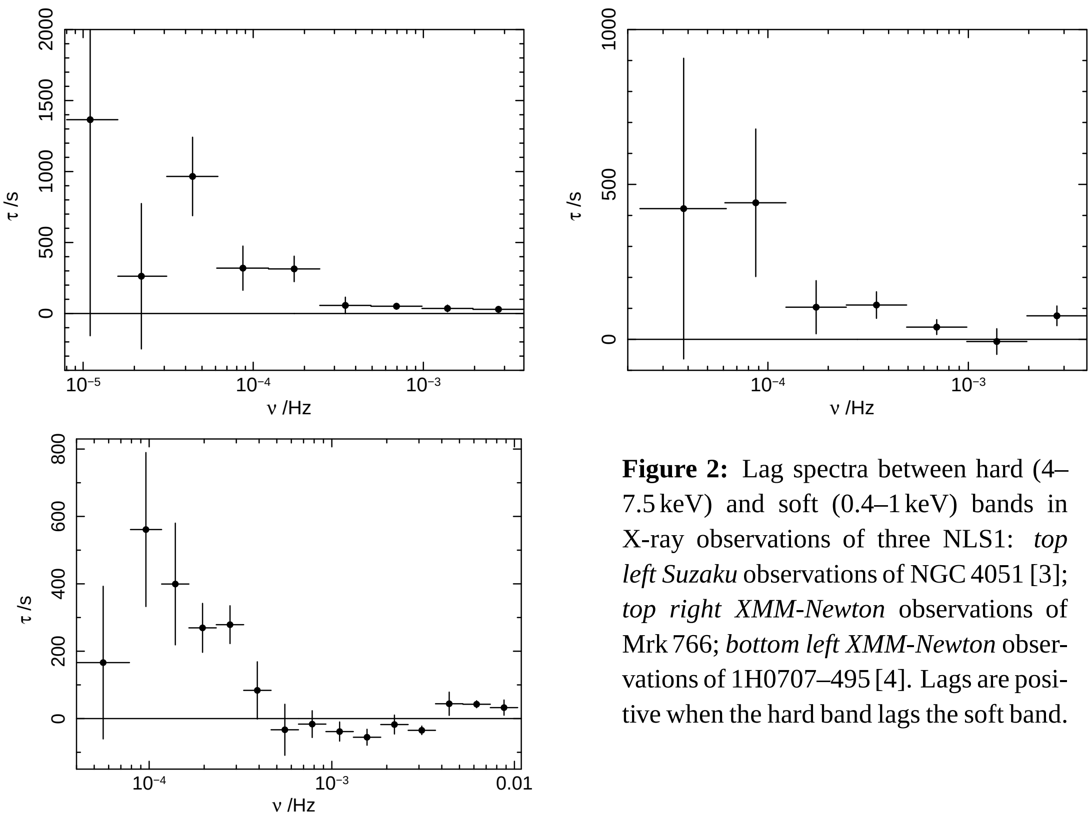

Figure 2: Lag spectra between hard (4–7.5 keV) and soft (0.4–1 keV) bands in X-ray observations of three NLS1: *top left Suzaku* observations of NGC 4051 [3]; *top right XMM-Newton* observations of Mrk 766; *bottom left XMM-Newton* observations of 1H0707–495 [4]. Lags are positive when the hard band lags the soft band.

of the scattering region.

2.3 Test on optical data

We can test the method on the optical dataset of NGC 4051 [5]. Fig. 1 shows the lag spectrum, showing the expected rapid transition, indicating a total light travel time across the emission line region (from the nearest to the furthest scattering region) of about 5 days, with a mean lag of about 1.8 days, consistent with the previous analysis of this data, but showing here the characteristic frequency-dependent behaviour.

3. X-ray reverberation detected in narrow-line Seyfert 1s

Our goal here is to attempt to detect reverberation in AGN at X-ray energies, using the maximum-likelihood to take full account of the sampling and noise. As we are then observing generally much more highly ionised material, and as many AGN show rapid (ks) X-ray variability, we may be able to probe the environments around the black hole on scales of light-hours rather than light-days.

Unlike the case of optical reverberation studies, it is not possible to isolate a time series of purely emission-line fluxes, because on the required rapid variability timescales, there are insufficient counts to obtain line flux values that are not completely dominated by shot noise. As in the case of optical studies, it also seems likely that a significant component of line emission arises from distances much larger than can be probed by the timescales in the X-ray observations.

Instead, however, we note that any circumnuclear material will Compton-scatter the incident flux, and because of the strong energy dependence of the absorption opacity of moderately-ionised material, we expect high energy photons to be much more efficiently scattered than low energy photons: the latter are mostly absorbed. Thus we can search for reverberation by cross-correlating hard and soft X-ray bands, making them sufficiently broad in energy that shot noise is low, and we should expect to see time delays between the hard and soft bands. In fact, such time delays have been measured for some years already in both AGN and Galactic binary systems, e.g. [6 – 8], but their significance as an indicator of reverberation has not previously been recognised, and the lags have instead been interpreted by a model of emission from radially propagating fluctuations in an accretion disk [9].

Here, we have analysed three AGN that are also NLS1, from *Suzaku* observations totalling 473 ks of NGC 4051 [3] and *XMM-Newton* observations totalling 493 ks of Mrk 766 [10] and 452 ks of 1H 0707–495 [4]. Fig. 2 shows clear transitions from positive lags (hard band lagging soft) at low frequencies to zero lags at high frequencies. The transitions are not as sharp as expected for thin shells of material, indicating that the reverberating material has some depth [3]. The light travel times across the regions in each case are approximately 10 ks, 5000 s and 2000 s respectively, indicating the detection of reverberating material a few light hours from the central source. Some simple models of the lag spectra are presented by [3, 4].

4. 1H 0707–495

One noticeable feature of the lag spectrum of 1H 0707–495 is that the lags are significantly negative at high frequency [11, 12]: i.e. the soft band lags the hard band, contrary to the expectation outlined above. This has been interpreted as evidence for extreme inner-disk reflection from the accretion disk. A model describing such lags ascribes the lagging of the soft band to two effects, both of which are required: (i) a factor > 9 overabundance of Fe; and (ii) amplification of the Fe disk reflection line by the process of “light-bending”, in which light rays near the black hole are preferentially bent onto the accretion disk, which then produces stronger-than-expected reflection [14]. Thus, it is claimed, extremely strong reflection Fe L lines may be produced in the $0.4 - 1$ keV band, which lead to the apparently inverted lag spectrum. Fe L lines are not visible in the spectrum, and the spectral model supposes that the lines are highly relativistically-blurred (a model-dependent view of these line components has been shown by [11]).

However, it has been shown above how lag spectra may easily become negative in some ranges of frequency, even if the hard band always is lagged more than the soft band (see also [4]). The claim of inner-disk reflection ignores the strong positive lags, up to 600 s, that are clearly seen in Fig. 2 and only addresses the lags that are negative by a few tens of seconds. There are substantial difficulties with this explanation:

1. The proposed inner-disk reflection requires two independent mechanisms for generating lags: negative ones at high frequency and positive ones at low frequency. The proposed model requires some fine tuning to allow the inner disk reflection to dominate at high frequencies, but the positive-lag mechanism to dominate at low frequency.

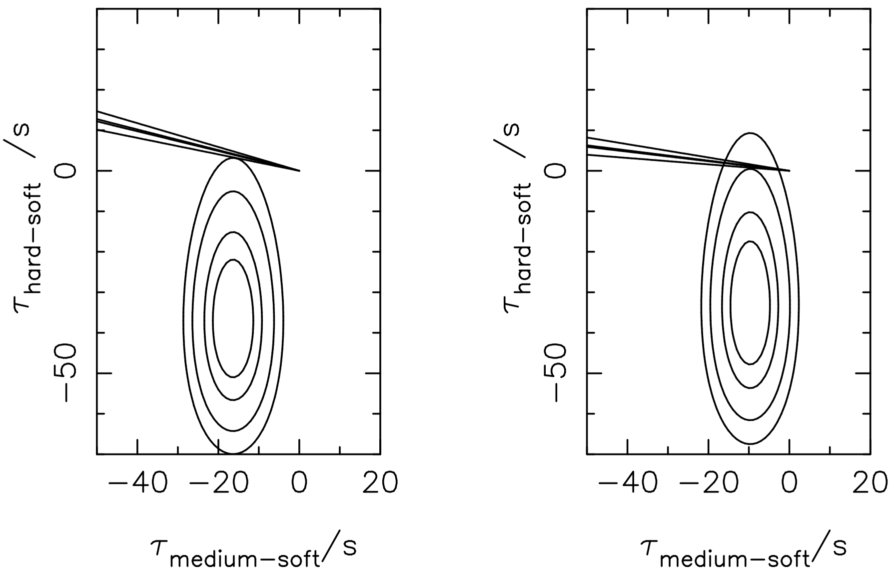

Figure 3: Confidence regions for the time delays between the hard and soft bands (y-axis) *v.* the time delays between the medium and soft bands (x-axis) in 1H 0707–495 at high frequencies ($0.00066 < \nu < 0.0053$ Hz). Contours show the 50, 90, 99 and 99.9 percent confidence regions, to be compared with the inner-disk reflection spectral models - straight lines with a range of slopes indicate the model expectation and the modelling uncertainty (see [4] for full details): *left* the original model of Zoghbi et al. (2010) [12]; *right* the revised model [13], which includes a reverberating black body. In the left panel the band definitions are 0.4–1 keV (soft), 1–4 keV (medium) and 4–7.5 keV (hard) (see [4]): in the right panel the soft band has been modified to be 0.5–1 keV (see text for details). The original inner-disk reflection model is ruled out at 99.9 percent confidence, the revised model is strongly disfavoured at 99 percent confidence.

2. The model requires light-bending to produce sufficient soft-band line emission, which in turn requires the existence of a hypothetical compact source, close to the black hole, but a small distance above the accretion disk. If the positive lags arise from radially-propagating fluctuations in the accretion disk itself, these two mechanisms are mutually exclusive. Either the emission comes from the light-bending “lamp-post”, or it comes from the accretion disk: it cannot arise from both. Such a model could only be tenable if there were some mechanism by which emission from the lamp-post were excited by the accretion disk fluctuations, without those fluctuations themselves producing emission.
3. The proposed distance between source and reflector is $\sim 1\,\mathrm{r}_g$ for a black hole of mass $2 \times 10^6\,\mathrm{M}_\odot$. However, if radiating at the Eddington limit, the black hole’s mass is likely to be about a factor 10 higher [15], so the separation between source and reflector would be $\sim 0.1\,\mathrm{r}_g$, inconsistent with the light-bending model.
4. There is no independent evidence for the highly super-solar Fe abundance that is also required.
5. The analysis of [11, 12] only tested for lags between the soft band ($0.4 - 1$ keV) and the medium band ($1 - 4$ keV). However, if there is substantial Fe L line emission in the soft band, there should be even more line emission in the Fe K band. This was tested by Miller et al. [4] who found that the spectral model of [12] indeed predicted that there should be more

hard band reflection than in any other band, and therefore that the lags between the hard band and either the soft or medium bands should be positive, as usually expected when the hard band dominates the reflection. It was shown that the lags between these bands in fact remain negative at high frequencies (see Fig. 2), and the inner-disk reflection model was ruled out at 99.9 percent confidence [4] (Fig. 3).

Notwithstanding the above difficulties, a revised inner-disk reflection model has been presented, in which a component of soft-band black body emission previously included is now also supposed to have reverberation time delay [13]. This leads to further difficulties for the model:

6. Normally it is supposed that thermal radiation from the accretion disk is upscattered to the X-ray regime, and the thermal emission should therefore *lead* the non-thermal emission in its variations. In the proposed model, the thermally-emitting material does not intrinsically vary, but reflection from its outer layers responds to the varying non-thermal source (invisible propagating fluctuations in the accretion disk are still required to produce the positive lags at low frequencies). The spectrum of such reflection would not be a black body and should be modelled following [16]. It should also be relativistically-blurred. Neither effect has been included. Furthermore, any reflection variations would be substantially diluted by the thermal emission [16].
7. The proposed thermal component only produces significant emission below 0.5 keV, so we may readily repeat the test shown in Fig. 3 excluding the regime below 0.5 keV. We find that although the confidence intervals are broader because of the loss of data, the inner-disk reflection model is still excluded at confidence level 99 percent, even though this model was designed to circumvent this difficulty.

Our conclusion is that the inner-disk reflection model is not viable. In principle, the negative lags may be produced as an artifact of the Fourier filtering shown in Fig. 1: however, it is difficult to obtain lags that remain negative over a broad range of frequencies. An alternative explanation is that all the bands being cross-correlated contain both direct and scattered components, with differing transfer functions in each band. Simple top hat transfer function models can reproduce the observed lag spectrum between the various energy bands [4]. We should also take account of the finite size of the X-ray emission region: this is likely to be a Compton upscattering corona with size of order ks and with intrinsic time delays of order tens of seconds (e.g. [17]).

5. Conclusions

X-ray observations of highly-variable NLS1 AGN reveal time delays between variations at hard photon energies with respect to soft photon energies. The time delays have values of hundreds of seconds at low variation frequencies but fall to values close to zero at high frequencies. The transition frequencies occur at $\sim 10^{-4}$Hz. Such a lag spectrum signature is expected in models of reverberation, where the transition occurs at a time period comparable to the light crossing time of the reverberating region. This indicates the existence of scattering material at distances of a few light hours from the central source, equivalent to a fews tens to a few hundreds of gravitational radii. Simple reverberation models have been presented elsewhere [3, 4]. It seems likely that the global covering factor of the scattering material must be high (~ 50 percent) in order to achieve a sufficient amount of scattered light.

One NLS1, 1H 0707–495, displays soft band lags at high frequencies, which we interpret as being due to scattered light present at all photon energies in this source. An alternative model ascribing the soft-band lags to inner disk reflection is strongly disfavoured by consideration of the full energy dependence.

The large-scale reverberation explanation is supported by spectral evidence that there are substantial zones of partially-covering, absorbing circumnuclear material [18]. Further work is needed to create models that reproduce both the timing behaviour and the observed high resolution spectra (e.g. [19, 20]).

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