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Discovery of high-frequency iron K lags in Ark 564 and Mrk 335

E. Kara,1* A. C. Fabian,1 E. M. Cackett,2 P. Uttley,3 D. R. Wilkins1 and A. Zoghbi4,5

1Institute of Astronomy, Madingley Rd, Cambridge CB3 0HA, UK
2Department of Physics and Astronomy, Wayne State University, Detroit, MI 48201, USA
3Astronomical Institute ‘Anton Pannekoek’, University of Amsterdam, Postbus 94249, 1090 GE Amsterdam, the Netherlands
4Department of Astronomy, University of Maryland, College Park, MD 20742, USA
5Joint Space-Science Institute (JSI), College Park, MD 20742-2421, USA

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ABSTRACT
We use archival XMM–Newton observations of Ark 564 and Mrk 335 to calculate the frequency-dependent time lags for these two well-studied sources. We discover high-frequency Fe K lags in both sources, indicating that the red wing of the line precedes the rest-frame energy by roughly 100 and 150 s for Ark 564 and Mrk 335, respectively. Including these two new sources, Fe K reverberation lags have been observed in seven Seyfert galaxies. We examine the low-frequency lag-energy spectrum, which is smooth, and shows no feature of reverberation, as would be expected if the low-frequency lags were produced by distant reflection off circumnuclear material. The clear differences in the low- and high-frequency lag-energy spectra indicate that the lags are produced by two distinct physical processes. Finally, we find that the amplitude of the Fe K lag scales with black hole mass for these seven sources, consistent with a relativistic reflection model where the lag is the light travel delay associated with reflection of continuum photons off the inner disc.

Key words: black hole physics – galaxies: active – X-rays: galaxies.

1 INTRODUCTION
The soft time lag (where soft band variations lag behind corresponding variations in the hard band) has revealed a new perspective through which to study the X-ray emission mechanisms of supermassive black holes. Since a tentative finding in Ark 564 (McHardy et al. 2007) and the first robust discovery in 1H0707−495 (Fabian et al. 2009), the soft lag has been detected in nearly 20 other Seyfert galaxies (e.g. de Marco et al. 2011; Emmanoulopoulos, McHardy & Papadakis 2011; Zoghbi & Fabian 2011; Cackett et al. 2013; De Marco et al. 2013; Fabian et al. 2013; Zoghbi et al. 2013) and one black hole X-ray binary (Uttley et al. 2011). Additionally, studying the high-frequency soft lag as a function of energy (as first done by Zoghbi, Uttley & Fabian 2011) has allowed us to directly compare the lag-energy spectrum with the time-integrated energy spectrum in order to understand which spectral component contributes to the lag at a particular energy (see Kara et al. 2013a for details).

Recently, the lag-energy spectrum has revealed the lag associated with the broad iron K line. This was first discovered in the bright Seyfert galaxy NGC 4151 by Zoghbi et al. (2012). In that work, they not only discovered the Fe K lag, but also used a frequency-resolved approach to show that at lower frequencies (i.e. longer time-scales), the rest-frame energy of the Fe K line lagged behind the continuum, while at higher frequencies (i.e. shorter time-scales from a smaller emitting region), the longest lag comes from the red wing of the Fe K line. This is consistent with relativistic reflection off the inner accretion disc, where the reflected emission lags the continuum roughly by the light travel time between the corona and the accretion disc.

An alternative interpretation has been proposed by Miller et al. (2010), in which the X-ray source is partially covered by optically thick clouds that are hundreds of gravitational radii from the source. In this case, the long, low-frequency hard lag is the reverberation between the source and the distant reflector, and the soft lag is simply the byproduct of taking the Fourier transform of the sharp-edged response function of clumpy reverberating material. This alternative interpretation has not yet been shown to be able to explain the observed broad Fe K lag at high frequencies. Furthermore, the soft lag has also been observed in an X-ray binary, where there is no evidence for distant circumnuclear material (Uttley et al. 2011).

Fe K lags have so far been observed in a total of five sources (Zoghbi et al. 2012, 2013; Kara et al. 2013a,b). In this paper, we present the discovery of the Fe K lag in two new sources, Ark 564 and Mrk 335. The two sources are X-ray bright and highly variable, making them the ideal candidates for spectral timing studies. The soft lag was first discovered in both of these sources by De Marco et al. (2013).

Ark 564 (z = 0.0247) was first observed with XMM–Newton in 2000/2001 at the beginning of the mission. In that short observation (10 ks of EPIC-pn exposure), the source was found to have a steep power law ($\Gamma \sim 2.5$) and large amplitude variability on short time-scales (Vignali et al. 2004). In 2005, the source was observed for 100 ks (Arévalo et al. 2006; Papadakis et al. 2007). McHardy et al.
Most recently, Ark 564 was observed for 500 ks with XMM–Newton. Using this long observation, Legg et al. (2012) confirmed a significant soft lag between the 0.3–1 and 4–7.5 keV bands. This frequency-dependent time lag appeared narrower than in other sources, which led the authors to suggest a distant reflection origin. However, we must note that the lag spectrum was not computed between usual the soft, 0.3–1 keV, and medium, 1–4 keV, energy bands as is done in other sources.

Mrk 335 (z = 0.0258) is a remarkably variable source that has been observed in several different spectral states. Mrk 335 was observed for ∼130 ks in 2006 when the source was in a high flux interval (O’Neill et al. 2007; Larsson et al. 2008). Using this long observation, Arévalo, McHardy & Summons (2008) studied the timing properties of Mrk 335 and found that the PSD is well described by a broken power law, with a break at ∼4 Hz, corresponding to the frequency at which there was a sharp cut-off in the hard lag. They concluded that the frequency-dependent time lags were consistent with fluctuations propagating through the accretion flow. Recently, Gallo et al. (2013), using a 200 ks XMM–Newton obtained in 2009 (Grupe et al. 2012), showed that spectral and timing properties of this 200 ks observation were consistent with blurred reflection from an accretion disc around a rapidly spinning black hole (a > 0.7). Additionally, Suzaku observations of Ark 564 and Mrk 335 find high black hole spin for both objects using broad-band spectral fitting with relativistic reflection (Walton et al. 2013).

The paper is organized as follows. The observations and data reduction in this analysis are described in Section 2. We review the Fourier method for calculating the lag in Section 3 and present the results in Section 4. Finally, we discuss the results in Section 5, and show how these results fit in with the growing sample of AGN with Fe K lags.

2 OBSERVATIONS AND DATA REDUCTION

For the analysis of these two sources, we use all of the archival data from the XMM–Newton observatory (Jansen et al. 2001), shown in Table 1. The data for both sources were reduced in the same way using the XMM–Newton Science Analysis System (SAS v.11.0.0) and the newest calibration files. We focus on the data from the EPIC-pn camera (Strüder et al. 2001) because of its faster readout time and larger effective area at high energies. The MOS data yield consistent results, but as the addition of the MOS data does not change or improve the overall lag spectra, they were not included in the analysis.

The data were cleaned for high background flares, and were selected using the conditions PATTERN ≤ 4 and FLAG = 0. The source spectra were extracted from circular regions of radius 35 arcsec centred on the maximum source emission. If pile-up was present, then an annular region was used to exclude the innermost source emission. Pile-up was an issue for some observations in Ark 564, and for consistency, we chose the same size excision radii used in Legg et al. (2012). The majority of the observations were taken in prime small window imaging mode, and for this mode, the background spectra were chosen from circular background regions, also of 35 arcsec radius. For observations taken in full window imaging mode (only the 2009 observations of Mrk 335), the background regions were made as large as possible, sometimes as large as twice the radius of the source region. The background subtracted light curves were produced with the tool EPICLCCORR. The light curves were all binned with 10 s bins.

3 THE FOURIER METHOD

To compute the time lags, we use the Fourier technique outlined in Nowak et al. (1999). This gives us time lags as a function of temporal frequency (i.e. time-scale−1).

We start by generating light curves in different energy bands consisting of N observations in 10 s bins (i.e. dt = 10 s). The frequency range is limited at low frequencies by the length of the observation. The high-frequency cutoff is strictly the Nyquist frequency at f = 1/(2dt); however, we are dominated by Poisson noise at frequencies well below the Nyquist frequency.

We take the discrete Fourier transform of each light curve. In this example, we will find the time delay between a soft band light curve, s(t) and a hard band light curve, h(t). The discrete Fourier transform of the soft band light curve is

$$\tilde{S}(f) = \frac{1}{N} \sum_{j=0}^{N-1} s(t_j)e^{-2\pi if t_j/N},$$

where N is the number of time bins in the light curve, s(t), and the frequency, f = j/(Ndt). The soft band Fourier transform can

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be written in the phasor form as the product of its amplitude and complex exponential phase is

\[ \tilde{S}(f) = |\tilde{S}(f)|e^{i\phi}. \]

We take the Fourier transform of the hard band light curve, and then take its complex conjugate

\[ \tilde{H}^*(f) = |\tilde{H}(f)|e^{-i\phi}. \]

which reverses the sign of the phase. The product of \( \tilde{S}(f) \) with the complex conjugate of the hard band, \( \tilde{H}^*(f) \), is known as the cross-product \( \tilde{C}(f) \) and is written as

\[ \tilde{C}(f) = \tilde{H}^* \tilde{S} = |\tilde{H}| |\tilde{S}| e^{i(\phi - \phi_h)}. \]

This gives the phase difference between the soft and the hard band. The overall Fourier phase lag, \( \phi(f) \), is the phase of the average cross-power spectrum. That is,

\[ \phi(f) = \arg\{\tilde{C}(f)\}. \]

The phase lag is then converted back into time to give us a frequency-dependent time lag between the two light curves:

\[ \tau(f) = \frac{\phi(f)}{2\pi f}. \]

It is important to note that the Fourier phase is defined on the interval \((-\pi, \pi)\), and therefore we are subject to phase wrapping, which causes the amplitude of the lag to change sign (Nowak et al. 1999). In other words, a constant lag of amplitude \( \tau \) will change sign when \( \phi = -\pi, \pi \) at the frequency \( f = 1/(2\tau) \) (see Wilkins & Fabian 2013 for a more detailed discussion of phase wrapping).

### 3.1 The transfer function

An important step in understanding the origin of the lag is to characterize the linear transformation that relates two delayed light curves. This function, known commonly in signal processing as the impulse response function \( t_r(\tau) \), relates the continuous hard and soft band light curves such that

\[ s(t) = \int_{-\infty}^{\infty} t_r(t - \tau) h(\tau)d\tau. \]

The Fourier transform of the impulse response function is called the transfer function, \( \tilde{T}(f) \).\(^1\) The linear transformation between the soft and hard bands in the frequency domain is

\[ \tilde{S}(f) = \tilde{T}(f) \tilde{H}(f). \]

Given this relation between the soft and hard bands, the cross-spectrum can just be written as

\[ \tilde{C}(f) = |\tilde{H}(f)|^2 \tilde{T}(f). \]

Therefore, the lag is derived from the phase of the transfer function. Theoretically, we should be able to directly measure the transfer function over a given frequency range by dividing the cross-spectrum by the hard band power spectrum. In practice, however, statistics are generally too low to allow a direct and unique measure of the transfer function using this method because calculating the transfer function requires a deconvolution of the signal in the two energy bands, which is known to enhance the noise level (see section 13.1 of Press et al. 1992 for further discussion of the deconvolution). Such analyses may be possible with future missions, such as LOFT or Athena+.

A common approach to studying the response function is to model the impulse response function (e.g. Reynolds et al. 1999) and compare the phase lag of the response function to the observed lags. This technique has been done by Wilkins & Fabian (2013) using general relativistic ray tracing simulations from the source, to the accretion disc and finally to the observer. In this inner disc reflection model, the hard lag is produced by a different mechanism (i.e. propagation effects through corona that cause the soft photons to arrive before the hard photons). Therefore, the hard lags require a different response function. Miller et al. (2010) also used this technique of assuming a response function that fits the observed lag. They use a top-hat response function of length \( \Delta \tau \) where \( \Delta \tau \) corresponds to the maximum light travel delay between the X-ray source and a line-of-sight distant reflector. The sharp edge in this response function was shown to reproduce the high-frequency soft lag observed in a 500 ks observation of 1H0707−495.

### 3.2 Computing the lag-energy spectrum

The lag-energy spectrum is an important tool in directly comparing the lag with the time-integrated energy spectrum. We use the lag-energy spectrum as a way to see what parts of the spectrum contribute to the lag at specific frequencies.

The lag-energy spectrum is computed by measuring the frequency-dependent lag (described above) between the light curves of narrow energy bins (\( \Delta E/E < 0.12 \)) and a reference band light curve (e.g. Zoghbi et al. 2011). The choice of reference band does not change the shape of the lag-energy spectrum, but it does change where the zero-point occurs. For this analysis, we chose the reference band to be the entire energy range, from 0.3 to 10 keV, excluding the small energy bin itself, so as not to have correlated errors (as discussed further in Zoghbi et al. 2013).

We note, therefore, that the interesting lag is not the absolute lag amplitude, but rather the relative lag between the energy bins. We read the lag-energy spectrum from bottom to top, the lower valued/more negative lag precedes the higher valued lag.

### 4 RESULTS

#### 4.1 Ark 564

The light curves of Ark 564 in Fig. 1 show a bright and highly variable source over the 500 ks observation, making it a good candidate for searching for time lags. Fig. 2 shows the lag as a function of temporal frequency, using the technique described in Section 3. The top panel shows the lag between the soft band (0.3–1 keV) and a hard band (1.2–4 keV). The bottom panel shows the lag between the soft band and a hard band (4–7.5 keV), as first shown in Lagg et al. (2012). Note the different scales on the y-axis. The two panels show different lag amplitudes, but the frequency of the soft lag is the same, independent of the amplitude of the hard lag. We note that the transition from positive to negative lag is not steep, as would be expected from an impulse response function with a sharp edge.

The amplitude of the lag between the soft and medium band is \(-95 \pm 31 \) s at [3.5–4.5] \times 10^{-4} Hz. Assuming a black hole

\(^1\) The term ‘transfer function’ is often used in astronomy to describe the linear transformation in the time domain. However, according to conventional signal processing terminology, the ‘transfer function’ only refers to this linear transformation in the frequency domain. Therefore, strictly speaking, the ‘transfer function’ as typically known in astronomy, is actually called the ‘impulse response function’. In this paper, we will adopt this correct terminology.

The light curves were all generated with circular source extraction regions with 35 arcsec radii. However, for the lag and spectral analysis, we accounted for pile-up by extracting annuli where needed. Note that the earlier observation (obsid 0206400101; leftmost panel) is longer, and is shown with a different x-axis scaling.

The lag as a function of temporal frequency for Ark 564. The lag is measured between 0.3–1 keV and 1.2–4 keV (top) and between 0.3–1 keV and 4–7.5 keV (bottom). The amplitudes of the soft and hard lags are much larger in the bottom panel. However, we note that the frequency of the soft lag is the same for both energy ranges. The inset shows the 0.3–1 to 1.2–4 keV lag using only the 100 ks observation from 2005 (black points) overlaid with the 1σ contours from the 2011 lag-frequency spectrum in blue. The 2005 soft lag is not significant, but is consistent with the new observations.

The inset in the top panel of Fig. 2 shows the lag between 0.3–1 and 1.2–4 keV using the 100 ks observation from 2005 in black points overlaid with the 1σ contours of the 2011 lag-frequency spectrum in blue. The 2005 soft lag is not significant, but is consistent with the new observations.

As a check, we show the statistical significance of a model Gaussian to the feature at 6.4 keV. We fit a function to the data, $\tau(E) = a + bE + ce^{-(E-E_0)^2}$, shown as the red line in Fig. 3. This function was modelled on the lag-energy spectra of 1H0707–495 and IRAS 13224–3809, where there are clear indications of a Fe K feature. We compared this model to one of just a line without the additional Gaussian. Comparing these two nested models yields an $F$-statistic, i.e. $\Delta \chi^2 / \chi^2$, of 5.5. Therefore, the Gaussian model is the high frequencies, even where we see the lag is zero. Including this 100 ks observation into our analysis does not change the average lag-frequency spectrum or the lag-energy spectrum, and so we choose to present the results from only the four orbits from 2011, in order to make a direct comparison with the results presented in Legg et al. (2012).

The high-frequency lag-energy spectrum ($[3.2–5.2] \times 10^{-4}$ Hz) in Fig. 3 has the same general profile as the high-frequency lag-energy spectra seen in 1H0707–495 and IRAS 13224–3809. The high-energy lag spectrum is very similar to these other two sources, with a clear local maximum at 6 to 7 keV, the energy of the Fe K line and a dip at 3–4 keV. At 0.3–0.5 keV, we see a larger delay than in the other two sources, which may be indicative of ionization differences or more contribution from reprocessed blackbody emission from the irradiated accretion disc that causes a larger contribution of delayed emission relative to the direct emission.
preferred with 98.2 per cent confidence. We notice, however, that in
this source, the 0.3–0.5 keV band diverges from a linear relation.
If we avoid the soft excess, and only fit the functions between 0.5
and 10 keV, the Gaussian model is preferred with 99.94 per cent
confidence.

In Fig. 4, we show the low-frequency hard lag dependence on
energy for two slightly different frequency ranges. The lowest fre-
cency range \([0.6–1.1] \times 10^{-4}\) Hz in blue) shows a simple power-law
shape, while the slightly higher frequency range \([1.1–2] \times 10^{-4}\)
Hz in red) is flat until 1 keV, when it turns upwards and follows the
same power-law behaviour.

In the first reported results on this 500 ks observation of Ark
564, Legg et al. (2012) showed possible weak non-stationarity
in the light curves. We at first half of the observation (obsid 201–501) and the second half (obsid 601–901), taken a few weeks
later. They reported a different frequency dependence of the soft lag
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with propagating fluctuations in the disc that are transferred to the corona (Kotov, Churazov & Gilfanov 2001; Arévalo & Uttley 2006). In the partial covering model, it is the long, low-frequency lags that are interpreted as reverberation, now between the X-ray source and the distant reflector. In this model, the high-frequency lag is a mathematical artefact due to phase wrapping (Miller et al. 2010).

The high-frequency Fe K lags, as detected here in Ark 564 and Mrk 335 (Figs 3 and 8, respectively), are key to breaking the degeneracies between these two models. The broad Fe K line is an indicator of reflection in both models, however, we only observe a

Fe K reflection feature in the high-frequency lags, not in the low-frequency lags (i.e. Figs 4 and 9). In the case of partial covering, where the low-frequency lags are associated with reflection, it is not clear why the Fe K reflection feature is only seen at high frequencies. Furthermore, it is not clear how to reproduce the Fe K structure at high frequencies, if it is simply due to phase wrapping.

Variations of the partial covering model have been proposed to explain the lag-frequency spectrum of Ark 564 (using a small system of absorbing clouds at 100\(r_g\) or less, modelled as a single top-hat response function; Legg et al. 2012) and for 1H0707−495 (using an extended wind from tens to hundreds of gravitational radii, modelled as several top-hat functions of different widths; Miller et al. 2010). While these different partial covering models can explain the lag-frequency spectra, neither has been shown to self-consistently explain the low- and high-frequency lag-energy spectra.

### 5.1 Partial covering view of lag-energy spectra

Here, we calculate the expected low- and high-frequency lag-energy spectra given the simple single top-hat response function, similar to the one concluded in Legg et al. (2012). In that work, the authors conclude that the lag-frequency spectrum between the soft band (0.3–1 keV) and the hard band (4–7.5 keV) can be explained as a single top-hat response function in the hard band lagging behind a delta function in both bands. The top panel of Fig. 2 shows the lag-frequency spectrum between the soft (0.3–1 keV) and medium bands (1–4 keV), which has a shorter low-frequency lag than the low-to-high lag-frequency spectrum, but has the same turnover frequency from hard-to-soft lags. This has been explained in the partial covering scenario of distant absorbers as a dilution effect (Miller et al. 2010). In this case, the source photons scatter through a medium whose opacity decreases with increasing

Figure 6. Mrk 335 broad-band light curve from 0.3–10. keV in 200 s bins. Note the logarithmic y-axis. The 2006 observation (left) is \(\sim 10\) times brighter than the 2009 observations (middle, right).

Figure 7. The Mrk 335 lag as a function of temporal frequency between 0.3–0.8 keV and 1–4 keV for the 2006 observations. The inset shows the lag as a function of frequency for just the 2009 low-flux observations. No lag was detected, and therefore we did not use these observations in the lag-energy analysis.

Figure 8. The Mrk 335 lag-energy spectrum in the frequency range \([1.9–6.7] \times 10^{-4}\) Hz. Only the data from 2006 were used as no lag was present in the 2009 observation. The red line shows the best-fitting linear model plus a Gaussian at 6.4 keV.

Figure 9. The low-frequency lag-energy spectrum of Mrk 335 in the low-frequency range \([0.4–1.6] \times 10^{-4}\) Hz. Like Fig. 4 the profile appears smooth and very different from the high-frequency lag-energy spectra.
energy, and therefore the fraction of scattered photons increases with energy (as demonstrated by the top-hat response function whose amplitude increases with energy). This causes the amplitude of the low-frequency hard lag to increase with energy, but does not change the turnover frequency.

We illustrate this partial covering scenario in Fig. 10 by computing the lag-frequency spectrum and the low- and high-frequency lag-energy spectra for a single top-hat response function whose amplitude increases with energy. This assumes that the reflector’s response to the direct emission is uniform over a distribution of time delays, with a width of \( \Delta \tau \), and centred at \( t_0 \). For this demonstration, we choose \( \Delta \tau = t_0 = 100 \) s. The solid line in panel (a) shows the energy spectrum of the scattered light, steadily increasing with energy. We also include the case where the amplitude of the response function is not simply steadily increasing with energy (as shown by the dotted line with a clear feature at 6 to 7 keV). Panel (b) depicts the frequency-dependent lag between the direct emission and the reflected emission at 10 keV. Here, the soft lag is an artefact of taking the argument of the Fourier transform of the sharp-edge response function. The solid blue and red lines in panel (c) show the resulting lag-energy spectrum for low \( ([1–2] \times 10^{-3} \text{ Hz}) \) and high frequencies \( ([3.5–4.5] \times 10^{-4} \text{ Hz}) \), respectively. The increase in low-frequency lag with energy is a direct result of an increasing amount of dilution (i.e. an increasing fraction of scattered light). The high-frequency lag, as a relic of the hard lag, is therefore also affected by dilution, and we see a mirror image in the high-frequency lag-energy spectrum. We note that if the lag-energy dependence is due to a change in the width of the response function (rather than just a change in the amplitude of the low-frequency hard lag), is therefore also affected by dilution, and we see a mirror image in the high-frequency lag-energy spectrum. We note that if the lag-energy dependence is due to a change in the width of the response function (rather than just a change in the amplitude of the low-frequency hard lag), is therefore also affected by dilution. However, the most negative point at 8 to 10 keV.

We have shown here that the response function proposed in Legg et al. (2012) can explain the low-frequency lag-energy spectrum (Fig. 4), but cannot reproduce the Fe K feature seen clearly in the high-frequency lag-energy spectrum (Fig. 3). We conclude that the high-frequency lag must have a different response function (and a different physical mechanism) from the low-frequency lag.

5.2 The growing sample of Fe K lags

High-frequency Fe K lags have now been discovered in seven Seyfert galaxies. Fig. 11 shows the lag-energy spectrum for four of the seven sources (1H0707−495, IRAS 13224−3809, Ark564 and Mrk 335) with 68 per cent confidence contours. Since the zero-point is arbitrary and these sources have different lag amplitudes, the lag-energy spectra have been scaled to the 3 to 4 keV band. We focus on the overall shape, rather than the value of the lag. The four sources show very similar Fe K features, with a dip at 3 to 4 keV, a peak at 6 to 7 keV, and the most negative point at 8 to 10 keV.

As the zero-point is arbitrary, the lags have been scaled to the 3 to 4 keV band. The Fe K lag profile is the same in all four sources, but the lags at the soft excess do not share a common shape.
At these high energies, we avoid complexities caused by the soft excess, but what is interesting is that we still see the same mass scaling relation as found for the lags of the soft excess (De Marco et al. 2013). This points to a common origin of both the soft excess and the broad Fe K lag at small distances from the X-ray corona.

Lastly, we comment briefly on the apparent weak non-stationarity in the light curves (as noted by Legg et al. 2012, through the lag-frequency spectrum and PSD). Fig. 5 shows that the first half of the 500 ks observation peaks at the rest frame of the Fe K line, presumably from a larger emitting region, while at slightly higher frequencies, the second half shows a broader lag peaking at 4 to 5 keV, the red wing of the Fe K line from a smaller emitting region. While the non-stationarity of the light curves is not currently well understood, it does provide tantalizing evidence for further behaviour that will be accessible either through much deeper observations or future observatories.

The case for relativistic reflection continues to grow with recent discoveries of the Fe K reverberation lag (Zoghbi et al. 2012) that is now seen in seven sources, flux-dependent reverberation lags (Kara et al. 2013b), the black hole mass scaling relation with lag (De Marco et al. 2013), and reverberation lags in a black hole X-ray binary (Uttley et al. 2011) and possibly a neutron star (Barret 2013). The work presented here on Ark 564 and Mrk 335 support a relativistic reflection model and is not consistent with partial covering. The study of X-ray reverberation lags is quickly developing and is revealing a new perspective through which to probe strong gravity.

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Figure 12. The amplitude of the Fe K lag versus $M_{BH}$ for the seven Seyferts with detected Fe K reverberation lags. See Table 2 for details about the sources. The light crossing times at 1 $r_g$ and 6 $r_g$ as a function of mass are shown as red and green lines, respectively.

Table 2. Details of the black hole mass for the seven sources with an observed Fe K lag.

<table>
<thead>
<tr>
<th>Object</th>
<th>$\log(M_{BH})$</th>
<th>$M_{BH}$ reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ark 564</td>
<td>6.2 ± 0.5</td>
<td>Zhang &amp; Wang (2006)</td>
</tr>
<tr>
<td>1H0707–495</td>
<td>6.31 ± 0.5</td>
<td>Bian &amp; Zhao (2003)</td>
</tr>
<tr>
<td>NGC 7314</td>
<td>6.70 ± 0.5</td>
<td>Schulz, Knaie &amp; Schmidt-Kaler (1994)</td>
</tr>
<tr>
<td>IRAS 13224–3009</td>
<td>6.76 ± 0.5</td>
<td>Zhou &amp; Wang (2005)</td>
</tr>
<tr>
<td>Mrk 335</td>
<td>7.15 ± 0.12</td>
<td>Peterson et al. (2004)</td>
</tr>
<tr>
<td>NGC 4151</td>
<td>7.65 ± 0.03</td>
<td>Bentz et al. (2006)</td>
</tr>
<tr>
<td>MCG-5-23-16</td>
<td>7.92 ± 0.4</td>
<td>Oliva et al. (1995)</td>
</tr>
</tbody>
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