nature
Vol 459|28 May 2009|doi:10.1038/nature08007

LETTERS

Broad line emission from iron K- and L-shell transitions in the active galaxy 1H 0707-495

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Since the 1995 discovery of the broad iron K-line emission from the Seyfert galaxy MCG–6-30-15 (ref. 1), broad iron K lines have been found in emission from several other Seyfert galaxies[2], from accreting stellar-mass black holes[3] and even from accreting neutron stars[4]. The iron K line is prominent in the reflection spectrum[5,6] created by the hard-X-ray continuum irradiating dense accreting matter. Relativistic distortion[7] of the line makes it sensitive to the strong gravity and spin of the black hole[8]. The accompanying iron L-line emission should be detectable when the iron abundance is high. Here we report the presence of both iron K and iron L emission in the spectrum of the narrow-line Seyfert 1 galaxy[9] 1H 0707-495. The bright iron L emission has enabled us to detect a reverberation lag of about 30 s between the direct X-ray continuum and its reflection from matter falling into the black hole. The observed reverberation timescale is comparable to the light-crossing time of the innermost radii around a supermassive black hole. The combination of spectral and timing data on 1H 0707-495 provides strong evidence that we are witnessing emission from matter within a gravitational radius, or a fraction of a light minute, from the event horizon of a rapidly spinning, massive black hole.

The galaxy 1H 0707-495 has been observed several times by the European Space Agency's X-ray Multi-Mirror Mission (XMM-Newton)[10–12]. The first observation revealed a sharp and deep spectral drop at 7 keV in the rest frame (the source redshift is 0.041) but no narrow emission features. This led to two main interpretations[10]: either the source is partly obscured by a large column of iron-rich material or it has very strong X-ray reflection[11] in its innermost regions where relativistic effects modify the observed spectrum. In other words, the sharp drop is due either to a photoelectric absorption edge or to the blue wing (higher-energy side) of a line partly shaped by relativistic Doppler shifts. The absorption origin requires that the iron abundance be about 30 times the solar value (unless the spectrum is e-folding below 10 keV (ref. 13), in which case the value is reduced), whereas reflection requires that this factor be between 5 and 10. The extreme variability of the source moreover appears to be due to changes mostly in the intensity of the power-law continuum, above 1 keV, which does not make sense in a partial-covering model.

We have analysed the spectral variability of new observations of the source made with XMM-Newton in January 2008. Variations from 1 to 12 counts per second are seen over four XMM-Newton orbits. The difference spectrum between low- and high-flux states is well fitted by a power-law continuum with photon index of 3, with an excess at lower energies (below 1.1 keV). Strong skewed and broad residuals are seen above such a power-law fit to the full source spectrum, peaking around 0.9 and 6.7 keV. The data are well described by a simple phenomenological model consisting of a power-law continuum, a soft black body, two relativistically broad (Laor[14]) lines and Galactic absorption (corresponding to a hydrogen column density of $N_{\mathrm{H}} = 5 \times 10^{20}\,\mathrm{cm}^{-2}$). We show the ratio of the spectrum and the continuum in that model in Fig. 1. This ratio spectrum is clearly dominated by two strong broad emission lines. They are characterized by energies of 0.89 and 6.41 keV (in our frame), an innermost radius of $1.3 r_{\mathrm{g}}$, an outermost radius of $400 r_{\mathrm{g}}$, an emissivity index of 4 and an inclination of 55.7°. (Here $1 r_{\mathrm{g}} = GM/c^2$, where G is the gravitational constant, M is the mass of the black hole and c is the speed of light.) The normalizations of the lines (in photon spectra) are in the ratio of 20:1, and their rest energies correspond well to ionized iron L and K emission, respectively. We have tried using a

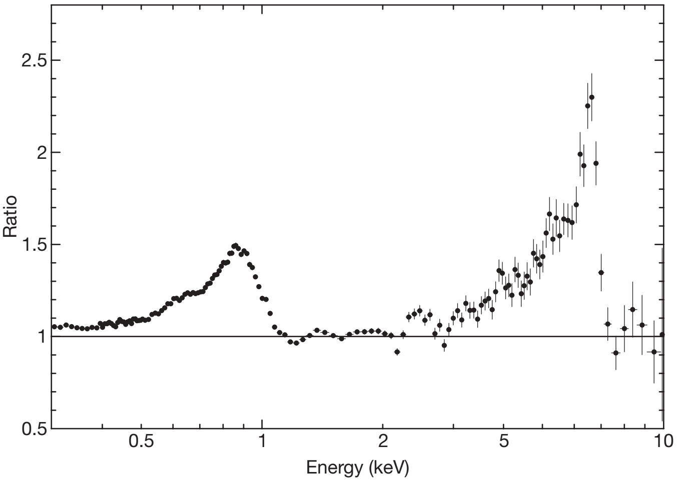

Figure 1 | Ratio of the observed spectrum and a simple phenomenological model. **The model consists of a power law, a black body and two broad emission lines. The data are from all four XMM-Newton orbits and the normalizations of the broad lines have been set to zero to make the plot. Ionized iron L and K emissions peak in the rest frame around 0.9 keV and 6.5–6.7 keV with equivalent widths of 180 and 970 eV, respectively. Error bars, 1σ.**

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variety of continuum models and always obtain similar results. The data have also been fitted with a self-consistent model reflection spectrum[15] (Fig. 2; see Supplementary Information for more details), which reproduces the correct relative fluxes for the lines. Iron is almost nine times more abundant than in the Sun, and the other elements have the solar abundance values. Perhaps a dense nuclear star cluster has led to the formation of massive white dwarf binaries that have enriched the nucleus with type Ia supernova ejecta rich in iron (such an explanation has been proposed for globular star clusters[16]).

The presence of broadened and skewed lines other than the iron K line is a prediction of the disk reflection model that we have now confirmed. Furthermore, we have shown that the relative strengths of the observed iron L and K lines agree well with predictions based on atomic physics. Whereas it is possible to construct a partial-covering, absorption-dominated model[10,12] for the prominent K-shell iron feature, the L-shell absorption edge of ionized iron required around 1 keV is accompanied by an unacceptably strong absorption feature around 0.75 keV from an unresolved transition array of iron ions Fe IX–Fe XI. Previous work[10,12] on absorption models for 1H 0707-495 have been unable to account for the spectral structure around 1 keV without invoking emission. The strong variability, and shape, of this emission component points to the inner regions of the flow and, thus, to a reflection solution.

The source fractional root-mean-square variability is roughly constant below 1 keV, increases abruptly at 1 keV and then drops back to the soft level above 4 keV, in agreement with the expectation of the two-component model (reflection plus power law) used to fit the data. Both components vary in amplitude, but the power law does so by nearly twice as much as the reflection. The nonlinear behaviour of the variability in accreting black holes[17] is considered to be due to the cumulative random effects of the orbital variations from many radii effectively multiplied together. On the shortest timescales, light-crossing effects will become important, as the light path for the direct primary radiation is shorter than that for the reflected radiation. This effect is seen for the first time in the frequency-dependent lags (Fig. 3). The large positive lag for variations lower in frequency than 0.6 mHz (timescales greater than 30 min) is probably due to the inward drift of accretion fluctuations through the emitting region[18], causing the density and, thus, the ionization state of the irradiated disc to respond first. Variations higher in frequency than 0.6 mHz show a negative lag in the sense that the soft reflection-dominated band follows the hard power-law-dominated band by about 30 s. This is in the opposite sense to a Comptonization lag produced by up-scattering of photons (or to any model where the spectral drop at 1 keV is instead produced by absorption that is responding to the changing continuum), and is explained by reverberation. If the lag time corresponds to the natural length of about hr_g, where we expect h to be between two and five, then we deduce a mass for the black hole of about $7 \times 10^6 h^{-1} M_\odot$ ($M_\odot$, solar mass), which is reasonable for this source (no definitive mass is known; see, for example, ref. 19) and implies that the accretion rate is only just below the Eddington limit. The breadth of the iron lines implies (using the methods of ref. 8) that the black hole has a high spin, of dimensionless spin parameter $a = cJ/GM^2 > 0.98$, so much of the emission should originate from within a few gravitational radii. Iron L-line emission should be detectable in similar sources[20] with high iron abundances, thereby enabling reverberation studies to be made.

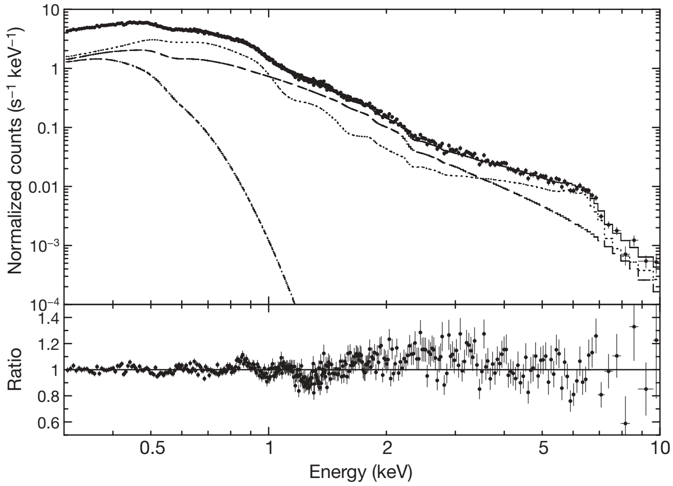

Figure 2 | Spectrum of the first orbit showing the best-fitting self-consistent, relativistically blurred reflection model. The ratio of the data and the model is shown in the lower panel. The total exposure time for this spectrum is 102 ks, with the source changing flux continuously and by more than a factor of two every few kiloseconds. The offset in the 1.5–4-keV band is due to the simplicity of using only two components in the 1–10-keV band despite the high variability of the source. The addition of a further reflection component with higher ionization parameter considerably reduces this offset. This is to be expected if the ionization changes with time or flux. The contributions of the power-law, reflection and black-body components are indicated by the dashed, dotted and dash–dot lines, respectively. Error bars, 1σ.

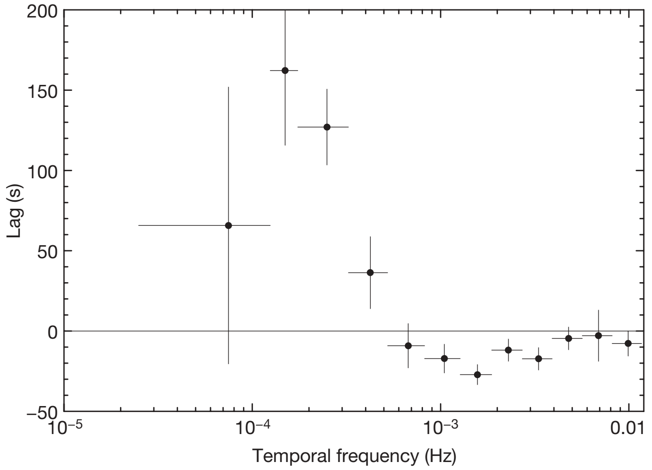

Figure 3 | Frequency-dependent lags between the 0.3–1-keV and 1–4-keV bands. A negative lag, such as that found above frequencies of 6×10^{-4} Hz or timescales shorter than 30 min, indicates that the harder flux, which is dominated by the power-law continuum, changes before the softer flux, which is dominated by reflection (particularly the iron L line). Error bars, 1σ.

Received 9 December 2008; accepted 13 March 2009.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

Acknowledgements A.C.F. thanks the Royal Society for support. This work is based on observations made with XMM-Newton, a European Space Agency (ESA) science mission with instruments and contributions directly funded by ESA member states and the USA (NASA). A.Z. acknowledges the support of the Algerian Higher Education Ministry and the UK Science and Technology Facilities Council (STFC). C.S.R., W.N.B., G.M., G.P. and R.C.R., and A.J.B. acknowledge support from the US National Science Foundation, NASA, the Spanish Ministerio de Ciencia e Innovacion, the French National Research Agency and the UK STFC for support, respectively.

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