XMM-Newton spectral properties of the Narrow-Line Seyfert 1 galaxy IRAS 13224–3809

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ABSTRACT
We report on the first XMM-Newton observation of the highly X-ray variable, radio-quiet, Narrow-Line Seyfert 1 galaxy IRAS 13224–3809 obtained during the guaranteed time programme with a 64 ks exposure. The most remarkable spectral feature is a sharp drop, by a factor \(\sim 5\), in the spectrum at 8 keV. This is a similar, but stronger, feature to that which we found in 1H 0707–495. Significant flattening of the hard X-ray spectrum occurs when the source flux decreases. The flattening of the spectrum can be modelled as an increase in the column density of the absorbing material and/or its covering fraction. Below \(\sim 1.5\) keV the spectrum is dominated by a giant soft X-ray excess, and at around \(\sim 1.2\) keV there is a significant absorption feature detected, most probably due to ionized Fe L absorption. The new X-ray spectral properties detected with XMM-Newton in IRAS 13224–3809 support a partial covering interpretation, i.e. the presence of dense material inside the accretion-disc region partially obscuring the emission from the accretion disc. However, the sharpness of the feature, if due to photoelectric absorption, is surprising and may require an alternative explanation. One possibility which does fit the whole spectrum is that it is dominated by ionized reflection rather than absorption. The unusual spectral properties detected with XMM-Newton from Narrow-Line Seyfert 1 galaxies increase the known spectral complexity of active galactic nuclei and should further stimulate a combined theoretical and observational effort to achieve a better understanding of the physics of the innermost regions of AGN.

Key words: galaxies: active, AGN – galaxies: individual: IRAS 13224–3809 – X-rays: galaxies

1 INTRODUCTION

ROSAT, ASCA and XMM-Newton have shown many Narrow-Line Seyfert 1 galaxies (hereafter NLS1s; see Osterbrock & Pogge 1985 and Goodrich 1989) to have remarkable X-ray properties compared to Seyfert 1 galaxies with broader Balmer lines. In X-rays NLS1s are generally characterized by strong soft X-ray excesses, steep hard power-law continua and extreme X-ray variability (e.g. Puchnarewicz et al. 1992, Boller, Brandt & Fink 1996, Brandt & Boller 1998, Vaughan et al. 1999, Brandt, Mathur & Elvis 1997). With the arrival of XMM-Newton spectra a new feature was added: a sharp spectral drop above 7 keV without any significant Fe-K line emission in the NLS1 1H 0707–495 (Boller et al. 2002; Fabian et al. 2002). In the case of 1H 0707–495 two physical interpretations were discussed: (i) a partial covering scenario (following Rees 1987; Celotti, Fabian & Rees 1992; Brandt & Gallagher 2000) in which the sharp drop is interpreted as Fe absorption in high column density clouds (Boller et al. 2002) and (ii) a reflection-dominated accretion-disc spectrum (Fabian et al. 2002). Both models provide acceptable spectral fits to the 1H 0707–495 data. The very high iron overabundance in the Boller et al. (2002) interpretation was reduced to a more realistic value by the reanalysis of Tanaka et al. (2003).

IRAS 13224–3809 is one of the most interesting members of the NLS1 class due to its remarkable X-ray variability, huge soft X-ray excess (Boller, Brandt & Fink 1996) and high optical Fe II to H/β line ratio (Boller et al. 1993). Indeed, IRAS 13224–3809 is among the most X-ray variable Seyfert 1 galaxies known. The first systematic monitoring in soft X-rays in 1996 showed persistent, rapid, giant-amplitude count rate variability. Over the course of the observations the maximum observed amplitude of variability was of a factor of \(\sim 60\), and a variation by about a factor of 57 in just two days was observed. The ionizing luminosity rises from about \(1.5 \times 10^{43}\) erg s\(^{-1}\) to about \(8.3 \times 10^{44}\) erg s\(^{-1}\), roughly equivalent to a typical Seyfert 1 like MCG–6-30-15 abruptly increasing its soft
X-ray luminosity to become almost as powerful as a quasar (Boller et al. 1997).

Due to its extreme X-ray spectral and timing properties, IRAS 13224–3809 was observed during the XMM-Newton guaranteed time programme. In this paper we discuss the results obtained from the 64 ks observation.

2 X-RAY OBSERVATIONS AND DATA ANALYSIS

IRAS 13224–3809 was observed with XMM-Newton (Jansen et al. 2001) on 2002 January 19 during revolution 0387 for about 64 ks. During this time all instruments were functioning normally. The EPIC pn camera (Strüder et al. 2001) was operated in full-frame mode, and the two MOS cameras (MOS1 and MOS2; Turner et al. 2001) were operated in large-window mode. All of the EPIC cameras used the medium filter. The two Reflection Grating Spectrometers (RGS1 and RGS2; den Herder et al. 2001) also gathered data during this time. The Observation Data Files (ODFs) were processed to produce calibrated event lists using the XMM-Newton Science Analysis System (SAS v5.3). Unwanted hot, dead or flickering pixels were removed as were events due to electronic noise. Event energies were corrected for charge-transfer losses. The latest available calibration files were used in the processing. Light curves were extracted from these event lists to search for periods of high background flaring. A significant background flare was detected in the EPIC pn camera approximately 20 ks into the observation and lasted for 5 ks. This segment was removed and ignored during the analysis. The total amount of good exposure time selected was 55898 s and 58425 s for the pn and MOS detectors, respectively. The source plus background photons, normalized to the source cell size, is 68.

3 X-RAY SPECTROSCOPY

3.1 Mean spectral properties

3.1.1 Discovery of a sharp spectral feature

In Fig. 1 we show the time-averaged spectrum of IRAS 13224–3809. We have fitted the 2–7 keV energy band with a simple power-law, which is extrapolated into the soft and hard bands for illustration purposes. The most obvious features are the strong soft X-ray excess emission below about 1.5 keV and the presence of a sharp spectral drop at ∼ 8 keV. If the 2–12 keV spectrum is fitted by a simple power-law plus edge model, the edge energy is 8.2 ± 0.1 keV (Fig. 2). The energy of the edge is significantly different from that of the neutral iron absorption edge at 7.1 keV. The flux absorbed by the edge is $4.6 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$. The edge cannot be constrained by the MOS data as the spectrum is background dominated above about 6 keV.

Some positive residuals can be seen at around 6.8 keV (in the rest frame of the object). They are consistent with emission from H and He-like iron with a total equivalent width of about 200 eV. The detection of this emission, judged from an F-test, is marginal (at about the 2.5σ confidence level). The strength of the line, when compared with the flux of photons which is absorbed and the likely fluorescent yield (Krollik & Kallman 1987), indicates that the absorber covers a solid angle $\Omega/4\pi \lesssim 0.2$. 

![Figure 1](image1.png)  
*Figure 1. EPIC pn spectrum of IRAS 13224–3809. A simple power-law model, fitted only in the 2–7 keV range, has been extrapolated into the soft and hard bands to illustrate the sharp spectral feature at ∼8 keV, and the soft X-ray excess emission. The photon index in the 2–7 keV band is (1.9 ± 0.1).*

![Figure 2](image2.png)  
*Figure 2. Simple power-law plus edge fit to the 2–12 keV energy range. The edge parameters are $\tau = 1.6^{+0.5}_{-0.5}$ and $E = 8.2 \pm 0.1$ keV.*
3.1.2 A partial covering model

The observed spectrum shows little low-energy absorption and is consistent with interstellar absorption only. On the other hand, there is what appears to be a deep absorption edge at 8.1 – 8.2 keV which would correspond to the K-edge of Fe XVIII–XX. The sharpness of the edge requires that the ionization states of Fe are confined to a narrow range. The absence of strong (narrow) emission at 6.6 keV is in contradiction with an explanation in terms of a distant reflector. The observed features can be explained in terms of absorption if allowance is made for partial covering (i.e. a patchy absorber).

A partial-covering model was therefore fitted to the data. The model comprised a multi-component disc (MCD) model for the soft component, and a partially covered power-law for the hard continuum. In addition, this model required a further absorption feature around 1.2 keV (see Section 3.1.3), which is included by subtracting a Gaussian line. A good fit was obtained (χ²/ν = 510/471) using two absorbed power-laws, but a very steep slope, Γ ≃ 2.5, was required, which appears extremely high given the present values found in AGN (c.f. Fig. 1 of Brandt, Mathur & Elvis 1997). Allowing for an exponential cut-off in the power-laws did not significantly improve the fit (χ²/ν = 509/470) but gave a more reasonable spectral slope. This model is illustrated in Fig. 3. The best-fit parameters were as follows: the MCD (colour) temperature kT = 0.16 keV, Γ = 2.0, Eout = 4.4 keV, and the column densities (and covering fractions) of the line-of-sight absorbers were NH ≃ 1.2 × 10²² cm⁻² (0.06) and ≃ 1.5 × 10²³ cm⁻² (0.77). The Fe abundance was about 10×solar with a 90 per cent confidence lower limit of 2×solar. The average effective slope of the cut-off power-law over 1 – 5 keV is approximately Γ = 2.5.

The temperature and (absorption-corrected) luminosity of the disc require that its inner radius is only about one gravitational radius for a 10⁶ M☉ black hole. Assuming the soft X-ray excess is physically described by a MCD model then the object would be super-Eddington when bright.

3.1.3 Detection of Fe L absorption

A broad absorption feature at E = 1.19 ± 0.02 keV, with an intrinsic width σ ≃ 0.12 keV, is required in the above model with high significance (Fig. 4). The equivalent width is approximately EW ≃ 1.20 × 10⁻¹³ erg cm⁻² s⁻¹. The RGS1 spectrum is consistent with, but does not constrain, the presence of an absorption feature (no data were collected from RGS2 in that energy range). Other features in the RGS spectra can not be constrained with the available photon statistics.

In the case of 1H 0707–495 (Boller et al. 2002) we noted that the sharp drop at 7.1 keV could be the blue wing of a strong, relativistically-blurred iron emission line. This would require some unusual geometry or situation in order that such a strong line is produced; the spectrum needs to be reflection-dominated. Fabian et al. (2002) discuss one possibility involving a corrugated inner accretion disc; an alternative would be gravitational light bending (e.g. Martocchia, Matt & Karas 2002; Fabian & Vaughan 2003). The spectrum of IRAS 13224–3809 can also be fitted by such a model (see Fig 5). Fitting the 2–12 keV spectrum with a power-law continuum plus an emission line with a Laor (1991) profile worked well with an emissivity index q = 6.2 ± 1.2, inner and outer radii of r_in = 1.3_{-0.1}^{+0.2} and r_out > 180 gravitational radii for the disc, and an inclination of i ≃ 60 ± 3 deg. The disc inclination and emissivity were covariant in the fitting, and a wide range of inclination angles was possible. The equivalent width of the line is unusually high at 5.6 keV. To see whether such a strong line can be produced, we used a grid of ionized slab models produced by D. Ballantyne (using the code described by Ross & Fabian 1993). With the abundances of metals at 7 times solar and Galactic absorption we obtain a fit over the entire range from 0.4 – 12 keV with a χ²/ν = 1.3. Some sharp deviations at the 2–3σ level occur at ~ 6 keV and again at ~ 8 keV. As with 1H 0707–495 this model requires the X-ray spec-
3.2 Flux-dependent spectral properties

The 0.3 – 12 keV light curve of IRAS 13224–3809 shows strong and rapid variability with flux changes by about a factor of 10 (Fig. 6). We have divided the light curve into four different flux states: (i) two high states with count rates above 2.5 counts s\(^{-1}\) (time intervals less than 20 ks and greater than 30 ks after the beginning of the observations); (ii) a medium state with count rates between 1.5 and 2.5 counts s\(^{-1}\); and (iii) low state below 1.5 counts s\(^{-1}\).

Evidence in support of partial covering is obtained from a comparison of the spectra between a high-flux level and a low-flux level. The high-flux and low-flux spectra are constructed from those intervals were the source count rate is \(\geq 2.5\) counts s\(^{-1}\) and \(\leq 1.5\) counts s\(^{-1}\), respectively. The average fluxes of the two are different by a factor of three. These two spectra were fitted simultaneously with the same spectral model as in section 3.1.2 (i.e. a MCD and a cut-off power-law model, and two absorbed power-law components). The Fe abundance was fixed at 3\(\times\) solar. A good fit (\(\chi^2/\nu = 667/631\)) was obtained, as shown in Fig. 7. The best fitting parameters were as follows: \(kT = 0.16\) keV, \(\Gamma = 2.0\), \(E_{\text{cut}} = 4.0\) keV. The column densities (and covering fractions) of the absorbers for the high-flux spectrum were \(N_{\text{HI}} \approx 1.0\) (0.66) and \(N_{\text{HI}} \approx 20\) (0.53), and those for the low-flux spectrum were \(N_{\text{HI}} \approx 3.1\) (0.53) and \(N_{\text{HI}} \approx 23\) (0.87), where the column is in units of \(10^{22}\) cm\(^{-2}\). Thus when the flux dropped the absorption increased.

4 DISCUSSION

IRAS 13224–3809 shows an unusual combination of spectral features: (i) a sharp spectral drop by a factor of \(\sim 5\) at \(\sim 8\) keV, (ii) marginal Fe K emission lines, (iii) a flattening of the spectrum above 3 keV towards low flux states, (iv) strong soft X-ray excess emission, (v) a significant Fe-L absorption feature at around 1.2 keV.

The most plausible explanation for the spectral features (i) to (iii) appears to be provided by a partial-covering scenario. The soft X-ray excess is most probably due to a higher temperature of the accretion disc as often seen in NLS1s. Presently it is not clear whether the Fe-L absorption feature is physically connected with the partial covering scenario. The lack of strong emission lines can be explained if the absorber subtends only a small solid angle as seen from the central black hole. An immediate consequence, given the variability in the absorber, is that the absorber must be located close to the central black hole, maybe even within the accretion disc region as suggested by e.g. Rees (1987), Celotti, Fabian & Rees (1992) and Brandt & Gallagher (2000). The flattening of the spectrum provides strong evidence for partial covering, as an increased absorbing column and/or a larger covering fraction is expected when the source flux is low. Although the partial coverer model explains the data well, the present photon statistics above the edge still do not allow us to constrain precisely the iron abundance, nor can we disentangle the unique contribution of the covering fraction or the absorbing column.

The sharpness of the feature, if due to a photoelectric edge, is surprising. At 8.2 keV the absorbing matter must be partially ionized (the threshold energies for Fe XIX–XXIII are 7.93, 8.07,
8.21, 8.35 and 8.49 keV) in which case a range of ionization states is expected. These make the observed edge broad rather than sharp (e.g. Palmeri et al. 2002). Alternatively the feature may be a neutral edge in approaching matter (say in a wind or jet along the line of sight, e.g. Chartas et al. 2002). The velocity of the matter is then required to be $0.15c$. A further possibility if the absorption is by approaching matter is that the feature is the start of a trough due to resonance absorption (e.g. Krolik et al. 1985, with Fe XXV/XXVI instead of O VIII). There is then a significant outflow of mass and kinetic energy from the object.

The extreme spectral properties detected with XMM-Newton increase the known spectral complexity in active galactic nuclei and should further stimulate a combined theoretical and observational effort to improve our understanding of the physics of the innermost regions of AGN. To more precisely constrain the form of the sharp spectral feature in IRAS 13224–3809 and distinguish between different models we need a much stronger signal above 8 keV. This may be possible if the source is observed during one of its giant amplitude fluctuations.

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