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Detection of broad iron K lines in active galaxies

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ABSTRACT

X-ray spectra of Seyfert 1 galaxies obtained by the *Ginga* satellite showed the presence of a fluorescent iron line and a hard continuum tail, which are commonly interpreted as the signature of cold matter irradiated by the X-ray source. This matter could be in the form of either an accretion disc immediately around the central black hole or an outer torus at a radius of about a parsec. Here we use spectra of two such active galaxies taken with the *ASCA* satellite at higher spectral resolution to show, clearly, that the Fe lines are broad. Gaussian model fits show for IC4329A ($z=0.016$) that the line is centred at 6.19 keV in the observer's frame and has a FWHM of $>20\,000$ km s^{-1}, and for NGC 5548 ($z=0.017$) that the line is at 6.15 keV with a FWHM of $>35\,000$ km s^{-1}. The line centroids are shifted by <0.2 keV with respect to the expected rest-frame energy of a fluorescent line from cold material. The widths are considerably larger than the full widths of the optical or UV lines found in these objects of $\sim 15\,000$ km s^{-1}. The intrinsic line profiles are not well determined, but are consistent with models of lines from the inner regions (<100 Schwarzschild radii) of accretion discs inclined at $\sim 20°$–$30°$. The discovery of such broad lines now opens up the immediate surroundings of accreting black holes for detailed study.

Key words: accretion, accretion discs – black hole physics – galaxies: active – galaxies: individual: IC 4329A – galaxies: individual: NGC 5548 – X-rays: galaxies.

1 INTRODUCTION

Fluorescent iron line emission has now been detected in over 20 active galactic nuclei (AGN) by *Ginga* (Pounds et al. 1990; Matsuoka et al. 1990; Piro, Yamauchi & Matsuoka 1990; Nandra & Pounds 1994). The equivalent widths of the iron lines are typically about 150 eV for narrow lines. Together with a hard continuum component, this is the signature of reflection of X-rays by cold matter in the source (Guilbert & Rees 1988; Lightman & White 1988; George & Fabian 1991; Matt, Perola & Piro 1991). This matter may be in the form of either a disc under the X-ray source or a torus of material beyond the optical/UV broad-line region (Awaki et al. 1991; Ghisellini, Haardt & Matt 1994; Krolik, Madau & Zycki 1994). While some of the *Ginga* X-ray spectra are best fitted with broad lines (George, Nandra & Fabian 1990; Nandra & Pounds 1994), the origin of the broadening is ambiguous, possibly a complex of lines as in Seyfert 2 galaxies such as NGC 1068 (Marshall et al. 1993; Ueno et al. 1994) or incorrect modelling of the continuum. The much better resolution of the Solid state Imaging Spectrometers (SIS) on *ASCA* at the Fe K line energy (2 per cent, which is 9 times better than the *Ginga* detectors) now enables us to examine any such possibility in detail. Preliminary *ASCA* results on MCG-6-30-15 (Fabian et al. 1994a) and NGC 5548 (Fabian et al. 1994b) have already indicated that the lines are truly broad. Here we use improved response matrices for the detectors to confirm and extend those results. The data were obtained in the Performance Verification (PV) phase of *ASCA* [see Tanaka, Inoue & Holt (1994) for a brief discussion of *ASCA*].

2 OBSERVATIONS AND ANALYSIS

The two SIS detectors were in 4 CCD mode and observed NGC 5548 on 1993 July 27 and IC4329A on 1993 August

15, both for about 25 ks. The exposure times for the 2 Gas Imaging Spectrometers (GIS – all instruments operate together) were slightly longer. The count rates were between 1 and 3 count s^{-1}. The data were cleaned of extraneous signals by following standard procedures. IC4329A declined in intensity by 10 per cent during the observation, while NGC 5548 varied in a sinusoidal fashion by ± 5 per cent on a time-scale of 5 h.

The spectra of neither source can be fitted by a simple, absorbed power law. Both objects showed evidence for complex structure at low energies, and a high-energy tail similar to that seen by *Ginga*. Details of the continuum modelling and a detailed analysis of the low-energy spectral features will be reported in later papers. In this work we concentrate on the Fe K line region. It is obvious from the residuals (Fig. 1) and known from previous work (e.g. Nandra & Pounds 1994) that both of these objects emit a 6.4-keV Fe K line of equivalent width $EW\sim 100$–200 eV. The line is obviously broad in the raw *ASCA* spectra.

The precise strength and width of an emission line are sensitive to the underlying continuum shape. In order to examine the sensitivity of the iron K line to this effect, we model the hard continuum (above 3 keV in IC4329A and above 2 keV in NGC 5548, which is less absorbed) in two ways: first with a single-power-law spectrum; secondly with a semi-analytic reflection model (adapted from Lightman & White 1988). The values of goodness of fit for both models are similar, and both require that the lines be broad at a confidence level exceeding 99 per cent.

The photon index, Γ, Gaussian line energy, E_K, dispersion, σ, and EW for the single-power-law fit to IC4329A are 1.65 ± 0.03, 6.27 ± 0.07 keV, $0.27^{+0.14}_{-0.09}$ keV and 140^{+32}_{-38} eV, respectively. For NGC 5548 the same parameters are 1.79 ± 0.02, 6.19 ± 0.14 keV, $0.46^{+0.20}_{-0.15}$ keV and 188^{+77}_{-59} eV. (All uncertainties are given at the 90 per cent level for one interesting parameter: $\chi^2_{min}+2.71$.) The line energies quoted are as observed; a 6.40-keV iron K line should be redshifted to 6.31 and 6.29 keV in IC4239A and NGC 5548, respectively. When we use the reflection model, we obtain $\Gamma=1.88\pm 0.02$, $E_K=6.26\pm 0.07$ keV, $\sigma=0.22^{+0.16}_{-0.06}$ keV and $EW=142^{+28}_{-40}$ eV for IC4329A, and $\Gamma=1.927^{+0.009}_{-0.005}$, $E_K=6.12\pm 0.18$ keV, $\sigma=0.46^{+0.27}_{-0.19}$ keV and $EW=154^{+61}_{-55}$ eV for NGC 5548. The acceptable ranges for σ and E_K and for σ and line flux are shown in Figs 2 and 3. The 2–10 keV flux from IC4329A is 9×10^{-11} erg cm^{-2} s^{-1}, and that from NGC 5548 is 4.5×10^{-11} erg cm^{-2} s^{-1}. Our results for the emission-line energy and equivalent width are in full agreement with the *Ginga* results (Piro et al. 1990; Nandra et al. 1991).

We note that there is no 7.1-keV absorption feature evident in the spectra, with an upper limit on any sharp 7.1-keV edge being an optical depth $\tau<0.2$. A weak edge of $\tau\sim 0.04$ is expected from the reflection spectrum for a covering factor of 2π (George & Fabian 1991). The required covering fraction of the reflector derived here, however, is larger. The implications are left to a future paper, but we point out here that any such edge should also be broadened, making it more difficult to detect in the *ASCA* spectra.

Prompted by the resemblance of the rough parameters of the Gaussian line fit to those predicted by disc-line models (Fabian et al. 1989; Matt et al. 1992), which incorporate the broadening due to Doppler and gravitational shifts from the surface of an accretion disc, we have fitted these models to the data. We find for both of these objects that the disc-line fits are as good as the Gaussian fits (same reduced χ^2) and that, of the five free parameters, inner and outer radii (R_{min}, R_{max}), initial energy, inclination and line flux, only three can be constrained by the *ASCA* data. We have therefore fixed the initial line energy at 6.4 keV, as expected from a 'cold' disc, and derived the inclination of the disc, fixing R_{min} at $3R_S$ and R_{max} at $1000R_S$, where R_S is the Schwarzschild radius. For IC4329A the fitted inclination is $<24°$, while for NGC 5548 it is between 15° and 38°, close to face-on for both of these objects. Note that a face-on geometry is also

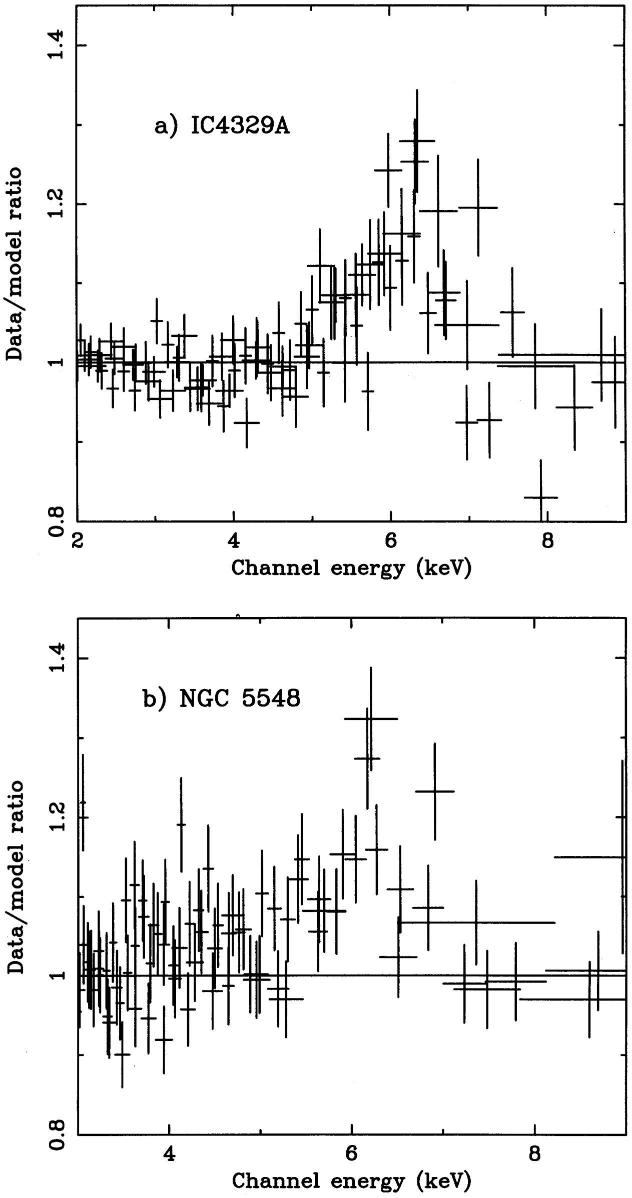

Figure 1. Ratio of data to model for power-law fits to (a) IC4329A and (b) NGC 5548. Data from all four separate detectors are plotted together. The data have been binned on a coarser scale than the intrinsic pulse-height channels to reduce the statistical scatter. The observed energies expected from neutral iron are 6.31 and 6.29 keV respectively. The residual plots clearly show significant line flux extending to the red side of these energies.

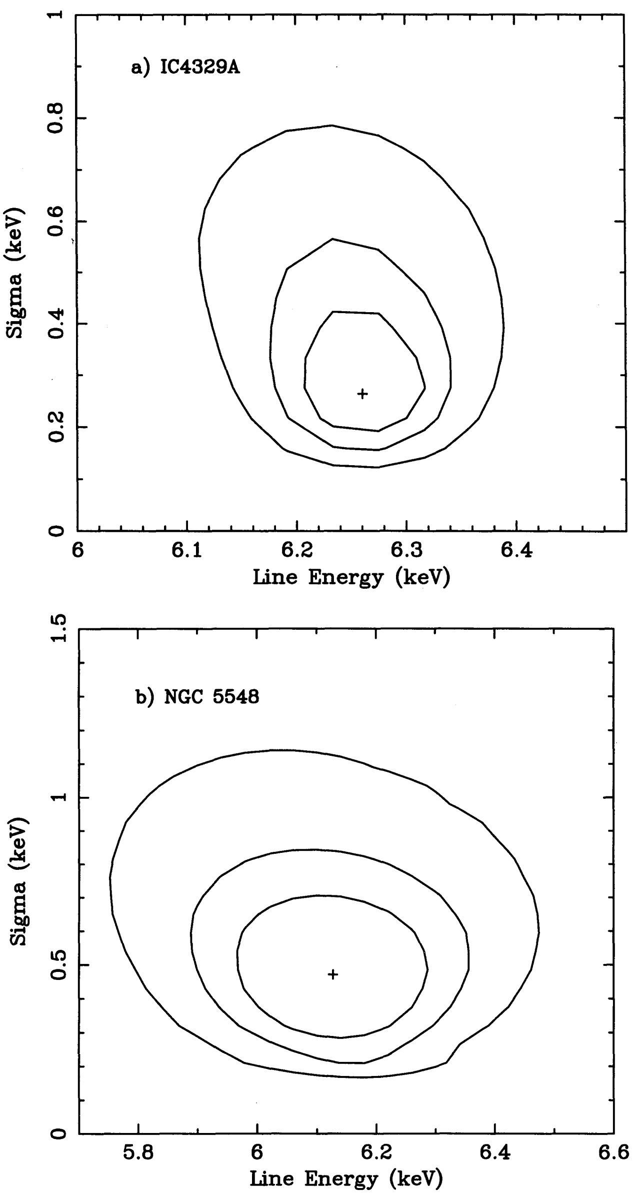

Figure 2. Probability contours of linewidth (σ of the best-fitting Gaussian) versus observed centroid energy, E_K, for (a) IC4329A and (b) NGC 5548. The contours are 68, 90 and 99 per cent confidence for two parameters of interest ($\Delta\chi^2 = 2.30$, 4.61 and 9.21 respectively). The best-fitting values are marked with crosses. A continuum consisting of a power law and reflection component has been used in deriving these contours, which show a very clear preference for intrinsic broadening of the line.

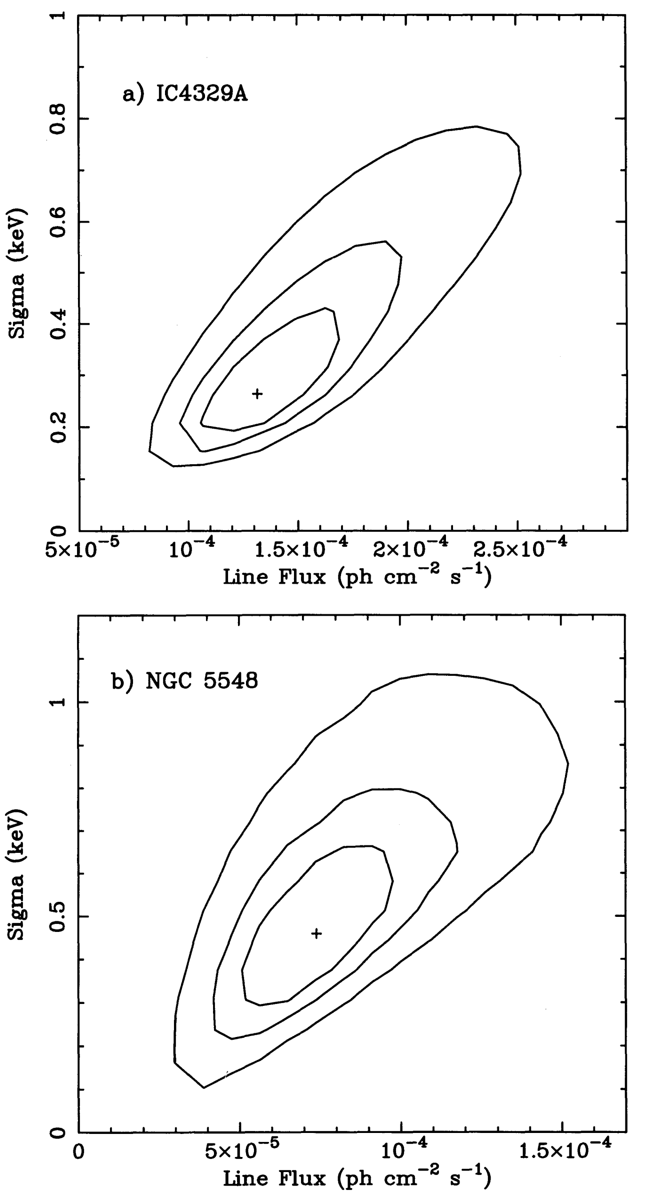

Figure 3. Probability contours of linewidth, σ, versus line flux for (a) IC4329A and (b) NGC 5548. The contours represent 68, 90 and 99 per cent confidence for two interesting parameters. The best-fitting values of the line fluxes (marked with crosses) correspond to equivalent widths of 142 and 154 eV respectively. For these model fits, the equivalent width is proportional to the line flux over the range of interest. A continuum model including reflection has been used.

inferred from the equivalent widths of the lines observed here and with *Ginga*, the strength of the reflection continuum component from *Ginga* (Piro et al. 1990; Nandra et al. 1991) and fits to the *OSSE* continuum for IC4329A (Madejski et al. 1994). Whilst these results are suggestive of a disc, it is by no means certain that other geometrical configurations of cold material cannot produce the observed linewidth.

Kerr metric models produce blueshifted lines (Laor 1991), except when they are observed at very low inclination or the emissivity function is very broad. Fitting the IC4329A data (the set with the best signal-to-noise ratio), we derive an inclination angle of 31^{+6}_{-4} deg with $EW \sim 450$ eV, if the original line is fluorescent and the radio variation of the emissivity is $\propto R^{-\alpha}$ with $\alpha = 3$ (maximizing the relativistic effects). The sharp dependences in this model allow a determination of α if $R_{\min}$ is kept fixed at $1.238 R_S$; we find $\alpha = 2.15^{+0.55}_{-0.25}$ and $EW \sim 240$ eV (similar to the Gaussian case).

3 DISCUSSION

The discovery that the Fe K line in these two Seyfert 1 galaxies is broad is in general agreement with the rapidly evolving ideas about the geometry of the central regions of active galaxies (see Mushotzky, Done & Pounds 1993 for a review). The most plausible broadening mechanisms are the Doppler effect, transverse Doppler effect and gravitational redshift. We can rule out multiple line components, as seen in Seyfert 2 galaxies and X-ray binaries, by noting that for both NGC 5548 and IC4329A (Fig. 1) the observed line extends to lower energies than 6.4 keV (in the rest frame). Fitting of the IC4329A data with two narrow components gives (rest frame) energies of 6.38 and 5.62 keV. Since the only other likely line-emitting components are He and H-like Fe which are at higher energies, this low-energy feature cannot be due to multiple lines. A similar result is obtained for NGC 5548.

Broadening due to Comptonization requires that the spectrum pass through a Thomson depth (or more) of cool gas ($kT<0.5$ keV) in order that the scattering does not over-broaden the line ($\Delta E/E=\sqrt{2kT/mc^2}$). The gas must also be completely ionized, since no strong absorption is seen. It cannot therefore be associated with the reflecting matter. From simple photoionization considerations (Kallman & McCray 1982), the ionization parameter $\xi=L/nR^2\gg 1000$, where the X-ray luminosity, the gas density and the distance of the gas from the source are L, n and R respectively. If the thickness of the gas is $\Delta R<R$, and since $L\sim 10^{44}$ erg s^{-1} for our sources and the column density $N=n\Delta R>2\times 10^{24}$ cm^{-2}, then, in order for most line photons to be scattered, $R<5\times 10^{14}\Delta R/R$ cm, which for a black hole of mass $>10^7$ M$_\odot$ is less than $200\Delta R/R$ Schwarzschild radii. Since the original Fe line photons must originate within such a region, and therefore have the intrinsic broadening of a disc line, we consider that any effect of Comptonization is small and that the dominant broadening effects are Doppler and gravitational.

We have presented here unambiguous evidence that the iron line in at least two, and probably three (Fabian et al. 1994a), Seyfert 1 galaxies is broad. The rest-frame energy of the line is consistent with slightly redshifted cold iron. The large physical width, combined with cold Fe, indicates that the line is originating in rapidly moving material which is not strongly ionized, in accord with simple accretion disc models. If the linewidth, FWHM $>20\,000$ km s^{-1} for IC4329A and $>35\,000$ km s^{-1} for NGC 5548, is associated with a Keplerian velocity, most of the line radiation must originate within 100 Schwarzschild radii, much further in than any of the optical/UV emission lines or any other diagnostic feature. The first two moments of the line profiles are qualitatively well-described by models of discs around Schwarzschild black holes. Data that increase the signal-to-noise ratio in the line by a factor of ~ 3 are necessary to determine further moments of the line profile, and thus to refine the constraints on the geometry and dynamics of the region responsible for the Fe K line.

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