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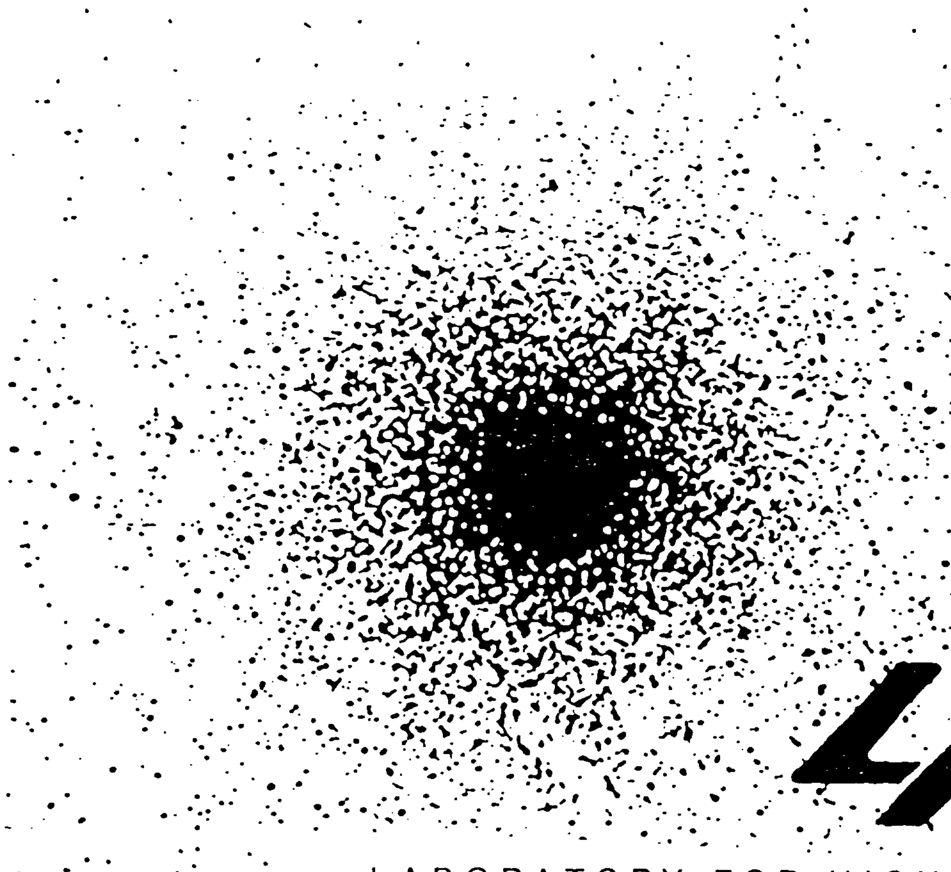

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Detection of Broad Iron K lines in Active Galaxies

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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 disk 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 centered at 6.19 keV in the observers frame and has a FWHM of $> 20,000$ km s^{-1} and for NGC 5548 ($z = 0.017$) 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 disks inclined at $\sim 20 - 30$ degrees. The discovery of such broad lines now opens up the immediate surroundings of accreting black holes for detailed study.

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 et al. 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 either in the form of a disk under the X-ray source or a torus of material beyond the optical/UV broad- line region (Awaki et al. 1991; Ghisellini, Haardt & Matt 1991; 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 being due to a complex of lines as in Seyfert 2 galaxies such as NGC1068 (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 percent, 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 et al 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 25ks. 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 ct s^{-1}. The data were cleaned of extraneous signals 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 timescale of 5 hours.

The spectra of neither source can be fit 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 is 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; the first is a single power law spectrum, the second a semi-analytic reflection model (adapted from Lightman & White 1988). The goodness of fit of both models is similar and both require that the lines are 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 IC 4329A 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 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 – $\chi^2_{\rm min} + 2.71$). 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 $\Gamma = 1.927^{+0.009}_{-0.015}, E_K = 6.12 \pm 0.18$ 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 intensity are shown in Figs 2 and 3. The 2–10 keV flux from IC4329A is 9×10^{-11} erg cm^{-2} s^{-1} and for NGC 5548 it 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, Yamauchi & Matsuoka 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 $\tau < 0.2$. A weak edge is expected of $\tau \sim 0.04$ is expected from the reflection spectrum for a covering factor of 2π (George & Fabian 1991). However, the required covering fraction of the reflector derived here 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 diskline 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 disk, we have fitted these models to the data. We find for both of these objects that the diskline fits are equally as good as the gaussian fits (same reduced χ^2) and that of the five free parameters, $R_{\rm min}$, $R_{\rm max}$, initial energy, inclination and line flux only three of them can be constrained by the ASCA data. We have therefore fixed the initial line energy at 6.4 keV, as expected from a "cold" disk and derived the inclination of the disk, fixing $R_{\rm min}$ at $3R_{\rm S}$ and $R_{\rm max}$ at 1000 $R_{\rm S}$, where $R_{\rm S}$ is the Schwarzschild radius. For IC4329A the fitted inclination is < 24 degrees while for NGC 5548 it is between 15-38 degrees, close to face–on for both of these objects. Note that a face–on geometry is also inferred from the equivalent widths of the lines observed here and with Ginga, the strength of the reflection continuum component from Ginga (Piro, Yamauchi & Matsuoka 1990; Nandra et al. 1991) and fits to the OSSE continuum for IC4329A (Madejski et al 1994). Whilst these results are suggestive of a disk, it is by no means certain that other geometrical configurations of cold material could not produce the observed line width.

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) we derive a inclination angle of 31^{+6}_{-4} degrees with $EW \sim 450$ eV, if the original line is fluorescent and the radial variation of the emissivity $\propto R^{-\alpha}$ with $\alpha = 3$ (maximizing the relativistic effects). The sharp dependences in this model allow a determination of α if $R_{\rm min}$ is kept fixed at 1.238 $R_{\rm S}$; 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 I galaxies is broad is in general agreement with the rapidly evolving ideas about the geometry of the central region of active galaxies (see Mushotzky, Done & Pounds 1993 for a review). The most plausible broadening mechanisms are the 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 objects (Fig. 1) the observed line extends to lower energies than 6.4 keV (in the rest frame). Fitting 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. NGC 5548 gives a similar result.

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 $\xi = L/nR^2 >> 1000$, where the X-ray luminosity, gas density and its distance 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 that most line photons are 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 disk 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 combination of a 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 disk models. If the line width, of 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 disks about Schwarzschild black holes. Data which 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 refine the constraints on the geometry and dynamics of the region responsible for the Fe K line.

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Figure captions

Figure 1: Ratio of data to model for power law fits to a) IC4329A and b) NGC 5548. 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 line width (σ of the best fitting gaussian) vs. 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-fit 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 line width, σ, vs. 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-fit 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.

FIGURE 1a

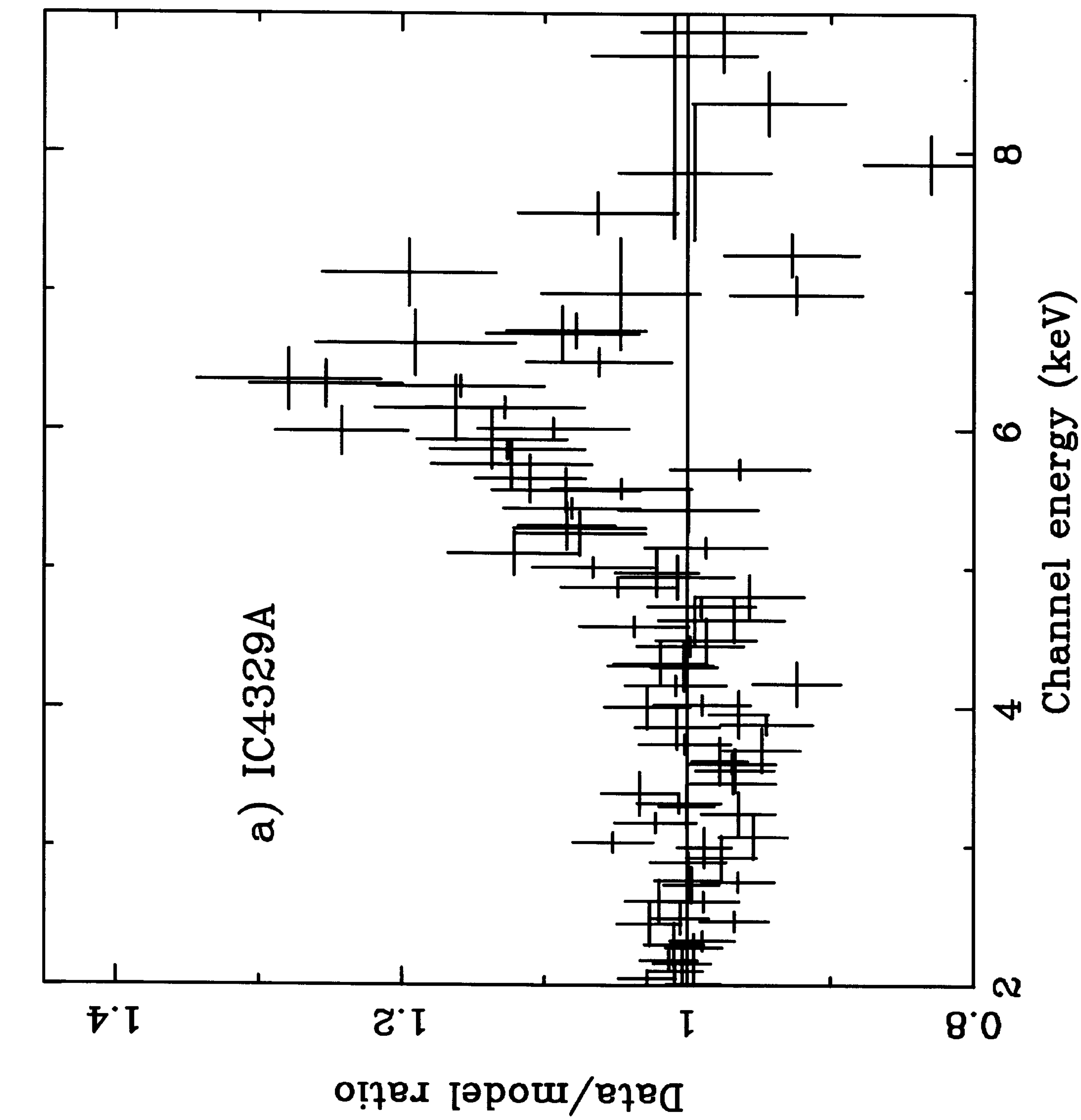

FIGURE 1b

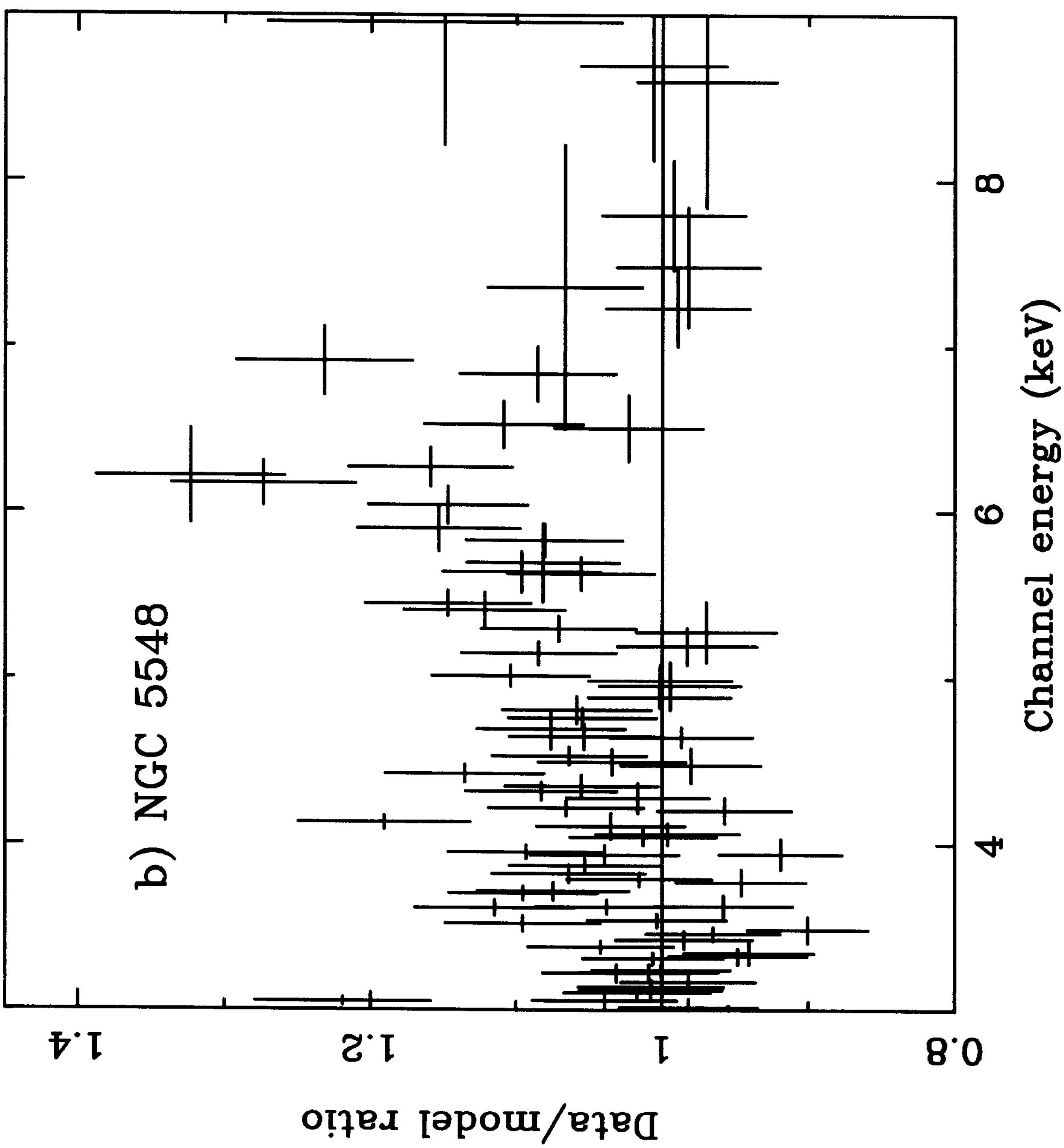

FIGURE 2a

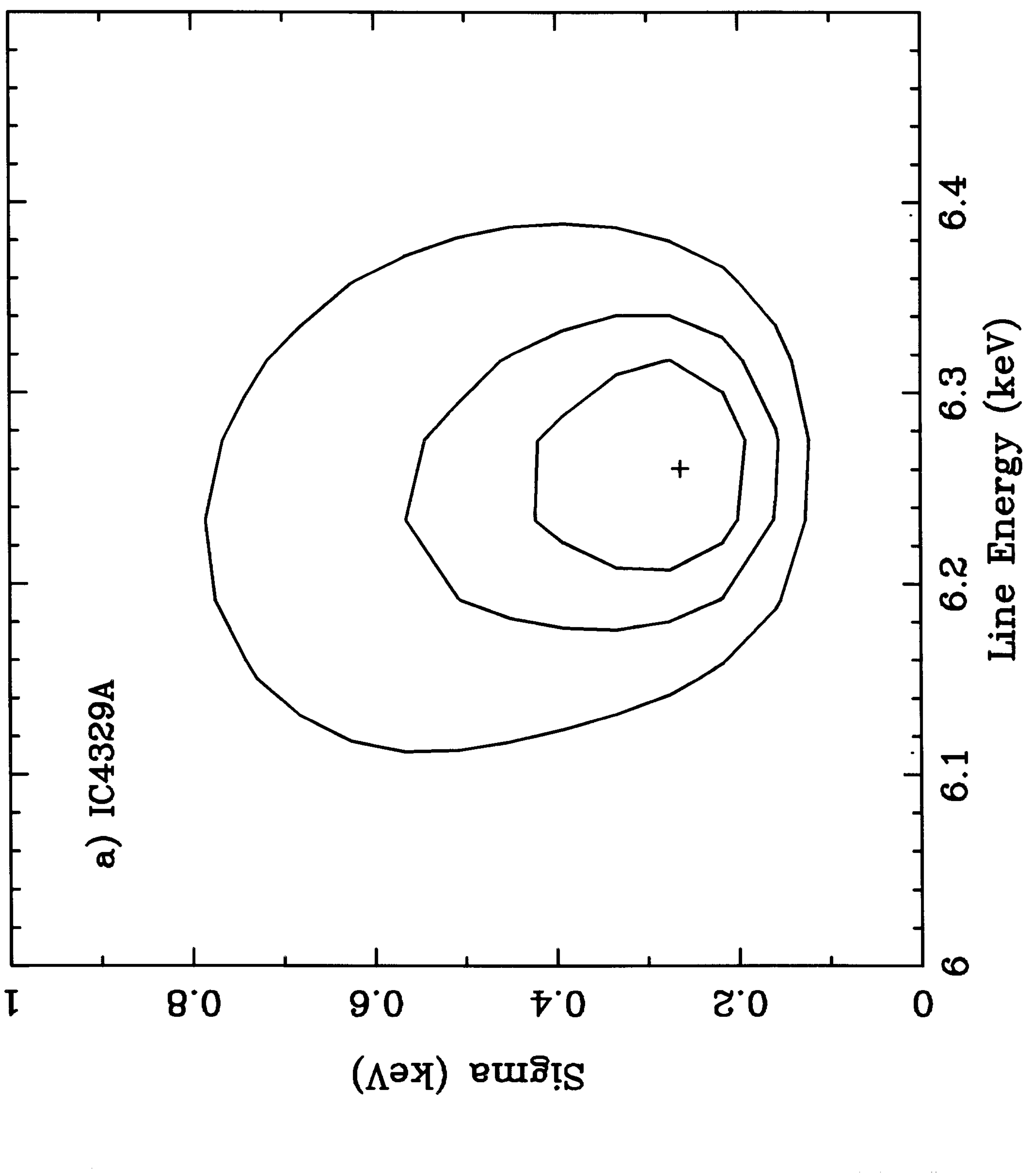

FIGURE 2b

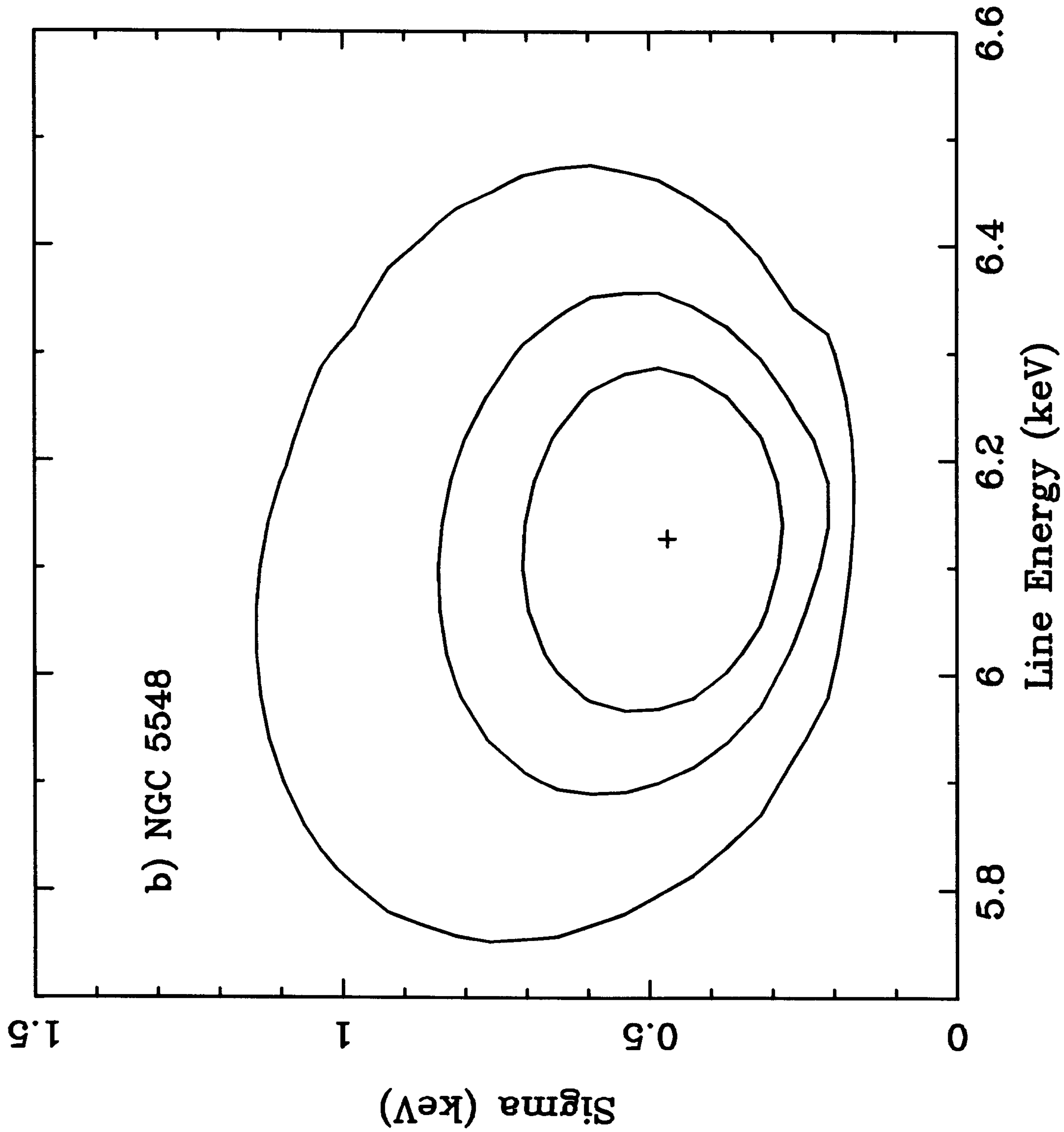

FIGURE 3a

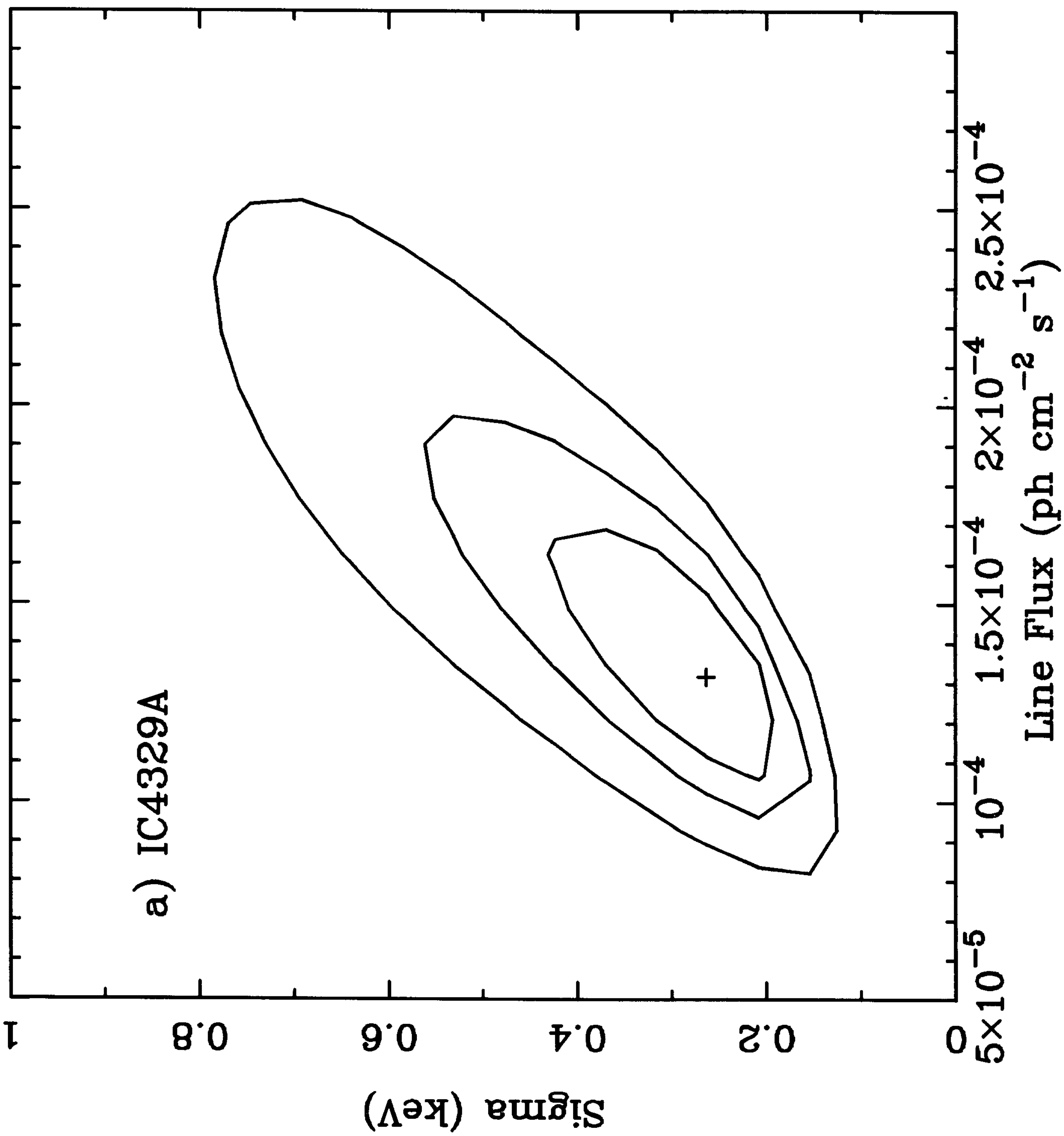
a) IC4329A
Line Flux (ph cm^-2 s^-1)
Sigma (keV)
5×10^-5
10^-4
1.5×10^-4
2×10^-4
2.5×10^-4
0
0.2
0.4
0.6
0.8
1

FIGURE 3b